Electrical Wiring Fundamentals

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For Engineers,
Technicians
and Students

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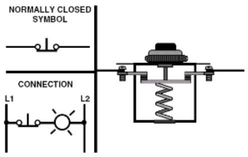


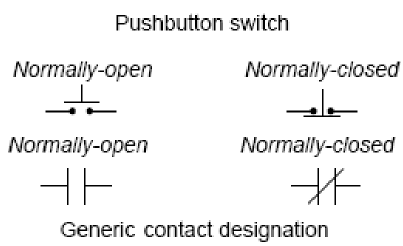
CHAPTER 1

Control Switches

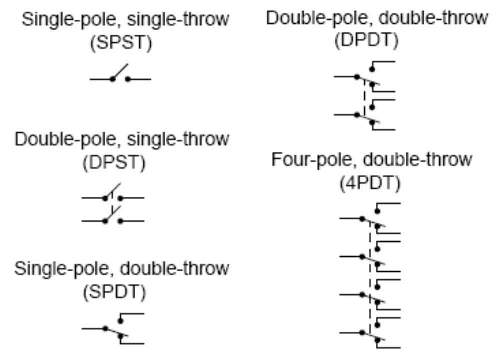
1.1 Switches and Pushbuttons

Switches: are identified by the number of conductors (poles) they connect to, and the number of positions (throws) they can switch to. Switches are also rated for voltage and power and must be operated within their limits.
Single-pole, single-throw (SPST)
Single-pole, double-throw (SPDT)
Double-pole, double-throw (DPDT)
Double-pole, single-throw (DPST)
Triple-pole, single-throw (3PST): These are used to interrupt current to three-phase circuits and motors.
Isolating switch: is connected upstream of a power circuit and is NOT horsepower rated and so it is not meant to interrupt current flow. Isolating switches are not meant to control motor loads. Rather once a motor has been properly shut off, an isolating switch can be used for lockout purposes.

Fig.1 Some types of switches.



Pushbutton switch and their generic contact designations.

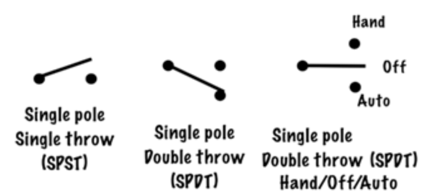


Some common switch configurations and their designations

Fig.2 Terminal symbol, type and contact form.

Pushbuttons: are momentary contacts that come available as either normally open (NO) or normally closed (NC) contacts, although many pushbuttons come with both NO and NC sets of contacts.

Pushbuttons contacts



Single-pole, single-throw (SPST) & Single-pole, double-throw (SPDT) contacts

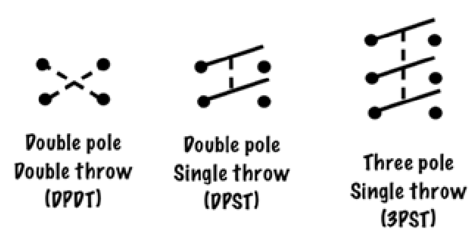


Fig.3 Single-pole, single-throw (SPST) Double-pole, double-throw (DPDT) Double-pole, single-throw (DPST) contacts.

1.2 Symbols & Applications of Basic Switches

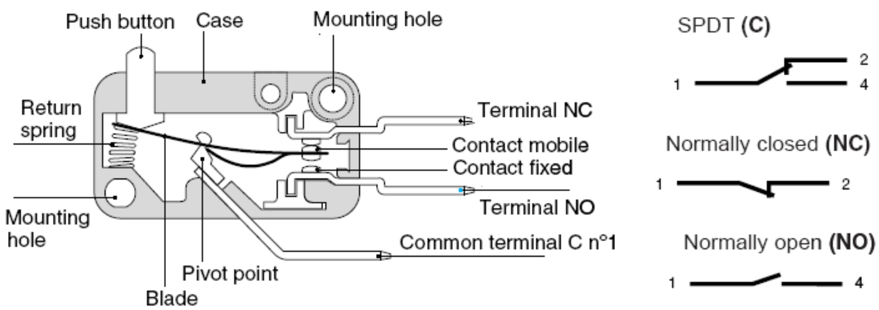


Fig.4 Single-pole changeover switch.

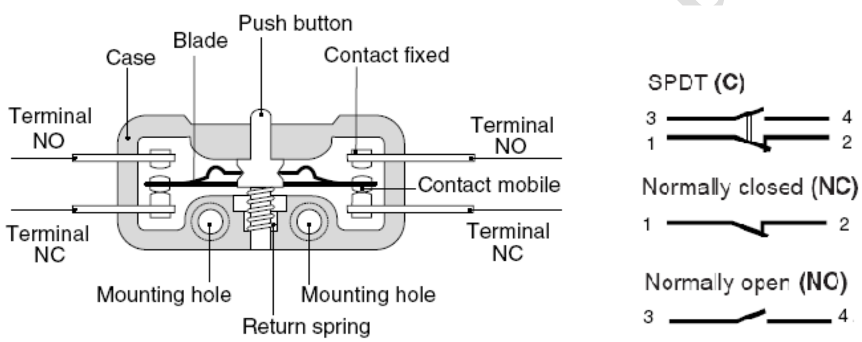


Fig.5 Double-pole changeover switch.

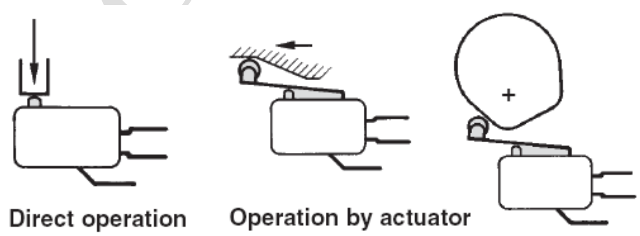
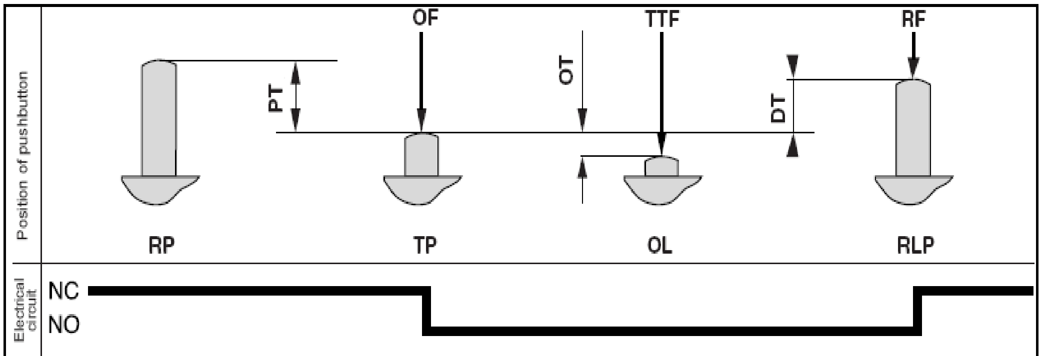


Fig.6 Methods of actuation of a snap switch.



Forces		OF Operating Force Maximum force which must be applied to the operating device to displace the rest position RP to the tripping point TP.	TTF Total travel force Force required to displace the operating device from its rest position RP to its overtravel limit position. (We only specify this value if it is higher than the operating force. When not quoted, it is equal to or less than the operating force). MOF Maximum overtravel force The maximum force which can be applied to the operating device, without damaging it, in the end of travel position where it is in abutment internally or against the face of the case.	RF Release force Force to which the operating force must be reduced to allow the snap-action Mechanism to return to its release position RLP.
Positions	RP Rest position Position of the operating device when no external mechanical force is applied. Also described as "height at rest".	TP Tripping point Position of the operating device relative to the fixing point (hole, face) at the moment when the microswitch trips.	OL Overtravel limit Position of the operating device when an extreme force has moved it to the effective end of the available travel.	RLP Release position Position of the operating device at the moment when the snap-action mechanism trips on its return to its original position
Travel		PT Pre-travel Distance between the rest position RP and the tripping point TP.	OT Overtravel Distance between the tripping point TP and the overtravel limit OL.	DT Differential travel Distance between the tripping point TP and the release position RLP.

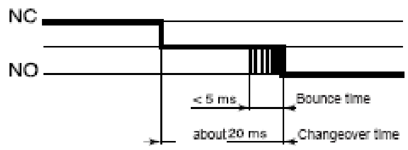
Fig.7 Mechanical characteristic of a typical snap switch.

The reference point for the figures given for travel and forces is a point F situated on the button in the case of a plain microswitch, or, generally, 3 mm in from the end of a plain actuator.

The reference point for the positions is one of the fixing holes, unless otherwise indicated.

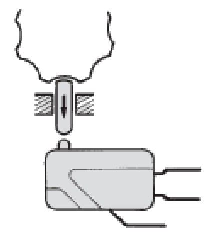
Changeover time

This is the time taken by the mobile contact when moving from one fixed contact to another until it becomes fully stable (contact bounce included). This time is a function of the contact gap, the mechanical characteristics of the snap action and the mass of the mobile element. However, thanks to the snap-action mechanisms employed, the time is largely independent of the speed of operation.
It is normally less that 20 milliseconds (including bounce times of less than 5 ms).



Mechanical durability

This is an average value indicating the purely mechanical performance of a switch when not subject to any electrical load.
It may be useful for evaluation purposes in cases where the power levels involved are very low and the electrical life is thus close to the mechanical life.



Mounting - Operation

- To conform to the leakage paths and air gaps in the standard EEC24 - EN/IEC 61058 - EN/IEC 60947:
  - An insulation pad must be inserted between the switch and the fixing surface if the latter is metal.
  - Manual operation of a metal actuator must only be carried out with the help of a secondary actuator made of insulating materials.
- The installer must ensure adequate protection against direct contact with the output terminals.

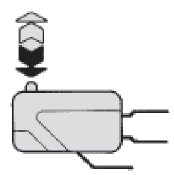


Fig.8 Mechanical characteristic of a typical snap.

1.3 Technical Guide for Basic Switches

Classification	Conditions	Descriptions
Electrical conditions	Voltage	AC, DC, and voltage value
	Current	Normal value, inrush value, and inrush time
	Circuit configuration	Number of poles and contact configuration
	Load	Power factor, time constant, induction, and non-induction
	Electrical life	Minimum life, mean life, and guaranteed life
Mechanical conditions	Operating characteristics (force)	O.F., R.F.
	Operating characteristics (motion)	P.T., O.T., M.D.
	Operating characteristics (position)	F.P., O.P., R.P.
	Accuracy	Repetition accuracy and repetition deviation
	Speed	Collision, high speed, low speed, and crawling (min. and max. values)
	Operating frequency	Cycling per minute (CPM)
	Actuation	Self-release and force release
	Actuation method	Cam, lever, bimetal, and bellows
Environmental conditions	Environment	Temperature, humidity, altitude, and pressure
	Atmosphere	Liquid, gas, fine powder, corrosive, explosive, etc.
	Vibration and impact	Frequency, amplitude, scale, and level of variation
	Installation	Degree of splash, spray and drip, and complete immersion, etc.
Mounting conditions	Dimensions and weight	Space and weight limitations
	Mounting method	Screw, bolt, and fastening method
	Terminal	Screw terminal, solder terminal, and quick connector terminal

Fig.9 Technical Guide for Basic Switches.

1.4 Operating Characteristics

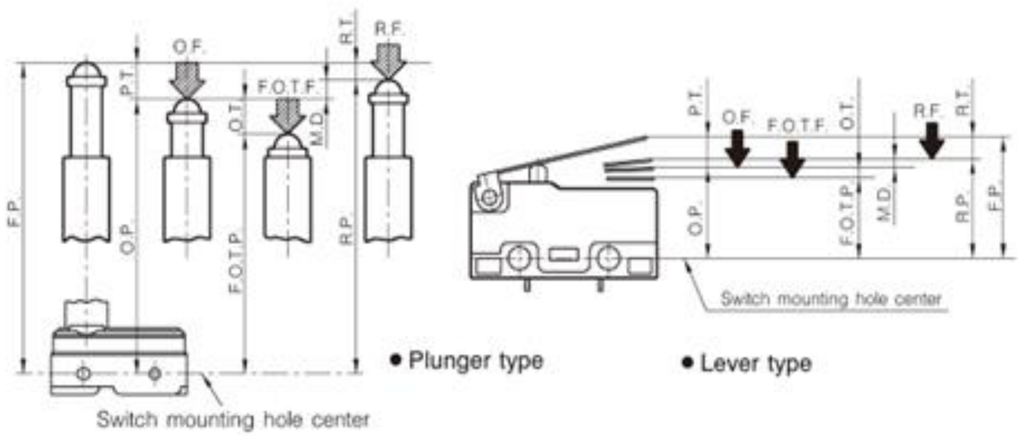


Fig.10 Actuator. The actuator comprises part of the switch. The external force applied to the actuator is transmitted to the switch's internal spring mechanism to operate the moving contact and perform opening/closing of the switch.

F.P. (Free Position)
Distance from the switch mounting hole center to the actuator tip when no external force is applied. "Position" referred to from here on refers to this distance.

O.P. (Operating Position)
Position of actuator at which the moving contact snaps from the free position when an external force is applied on the actuator.

F.O.T.P. (Final Overtravel Position)
Position at which the actuator is pressed until it can no longer operate.
This is sometimes abbreviated as "T.T.P".

R.P. (Return Position)
Position of actuator at which the moving contact snaps from the operated position to the free position when an external force is decreased.

P.T. (Pretravel)
Actuator travel from free position up to operated position.

O.T. (Overtravel)
Actuator travel up to the final overtravel position fro tuator operated position.

M.D. (Movement Differential)
Actuator travel from the operated position to the retu sition.

F.O.T.F. (Full Overtravel Force)
Amount of force applied when the actuator is pressec full overtravel position.
This is sometimes abbreviated as "T.T.F."

R.F. (Release Force)
Amount of force applied to the actuator at the mom contact is made to snap at the return position.

1.5 Types of Actuators

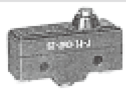
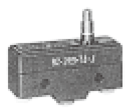
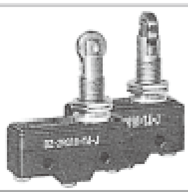
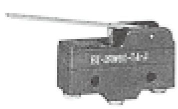
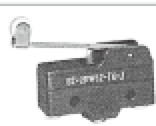
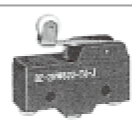
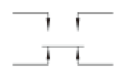
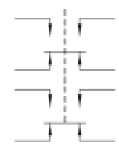
Shape	Name	Features and Conditions of Use
	Pin plunger	This actuator is used in objects having small movement such as thermostats and gages. This actuator has accurate operating characters.
	Short plunger	This actuator is ideal for when a large O.T. is required and the actuator operates in linear motion in the same direction as plunger movement and when the startup angle is 20° or less.
	Fine plunger	This actuator is ideal for when a large O.T. is required in linear motion in the same direction as plunger movement.
	Panel mount plun ger	This actuator is for panel mounting, and is ideal as a manual or mechanical push-button. This actuator has an extremely large O.T., and the O.P. can be adjusted by changing the mounting position.
	Panel mount rolle plunger	This actuator is a roller plunger for mounting on a panel, and is ideal for fast movement.
	Lever	This actuator is ideal for operation by small forces. It is desirable that this actuator is used for cams and dogs having slow move-ment. Lever vibration is absorbed by a return spring.
	Roller lever	This actuator is ideal for operation having small force. It is desirable that this actuator is used for cams and dogs having fast movement.
	Short roller lever	This actuator is ideal for operation on rotary cams having fast movement.

Fig.11 Types of Actuators.

1.6 Circuit Configuration

Name	Single-Pole Double-Throw	Single-Pole Normally-Open	Single-Pole Normally-Closed	Double-Circuit Double-Break	Four-Circuit Double-Break
Code	SPDT (1c)	SPNO (1a)	SPNC (1b)	2CKT-DB	4CKT-DB
Symbols					

Note:

SPDT ...... Single-Pole Double-Throw.
SPNO ...... Single-Pole Normally-Open.
SPNC ...... Single-Pole Normally-Close.
2CKT-DB ...... Two-Circuit Double-Break.
4CKT-DB ...... Four-Circuit Double-Break.

Fig12 Circuit Configurations.

1.7 Selection Guide for Contact Materials & Mechanisms Circuits

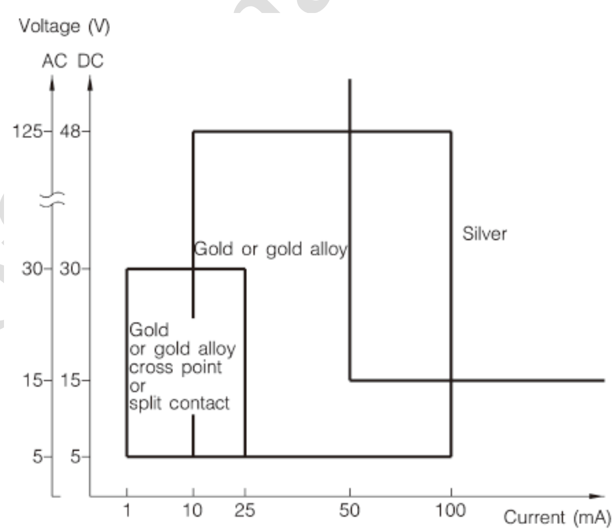


Fig.13 Selection guide.

1.8 Detent Action Rotary Switches

1. Construction

A typical detent action rotary switch is shown in Fig14, while Fig.15 shows a cut away view exposing its basic components. A mounting plate (1) connects a detent assembly (2) to one or more contact decks (3) and finally a position limiting stop plate (4). These assemblies are bolted together along with a steel shaft (5) and a handle (6). The detent assembly contains a star wheel and up to four spring-loaded ball bearings providing snappy positive indexing. Spring return switches use a coil spring in place of the star wheel/spring/ball bearing arrangement.

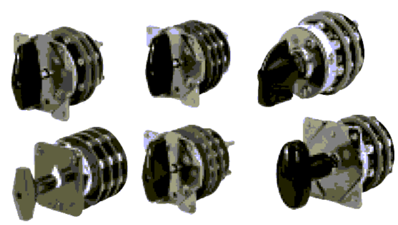


Fig.14 An overview of typical detent-action switches.

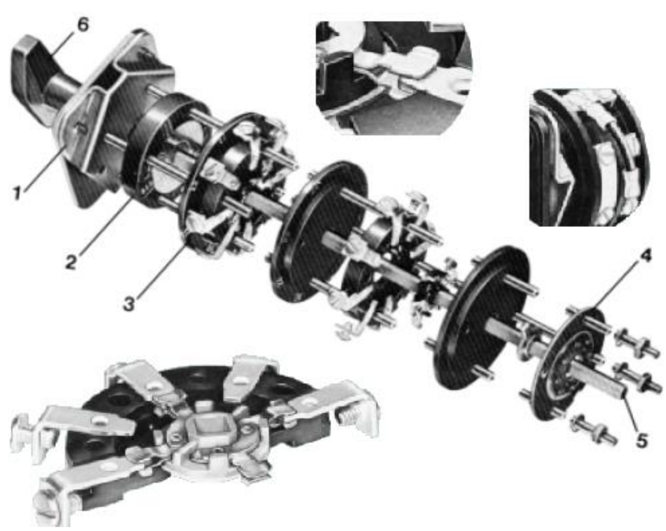


Fig.16 Construction details of a typical detent action switch.

Mounting plate (1)	Contact decks (3)	Steel shaft (5)
Detent assembly (2)	Position limiting stop plate (4).	Handle (6).

2. Contact Diagrams

Contact diagrams are shown for 8 position switches. The handle is shown in the 12 o'clock (0^{o}) position. Contacts can be either make-before-break (shorting) or break-before-make (non-shorting) assembly. Some of the switching assemblies are shown in Figs. 3-11 as follows:

1. Two pole per section, double break switching (Fig.16).
2. One pole per section, provides 'OFF' and 7 tap positions (Fig.17).
3. The configuration shown in Fig.18 allows any one circuit to be opened while the rest are closed, with make-before-break (shorting) action.
4. One pole per section; double-break switching (Fig.19).
5. Cumulative tap switching with make-before-break action (Fig.17).
6. Double break switching (Fig.18).
7. Three pole per section with double break switching (Fig.19).
8. This configuration allows pair of circuit to be fed from common source (Fig.20).
9. This configuration is the same as configuration 2 except first position is ON (Fig.21).

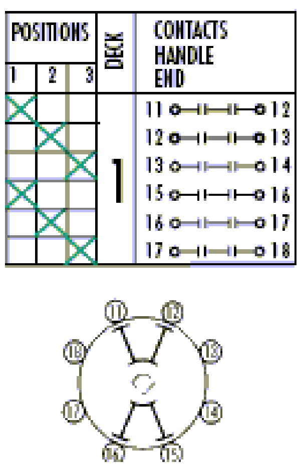


Fig. 16 Two pole per section, double break switching assembly.

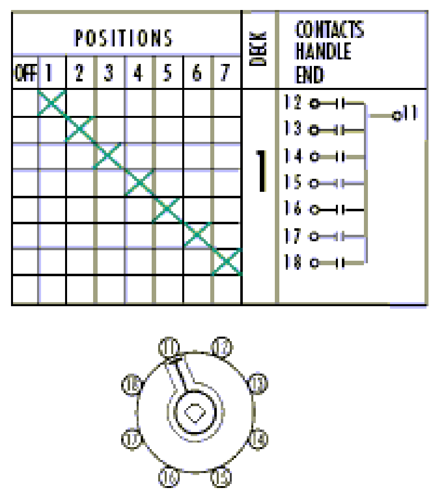


Fig. 17 One pole per section, provides 'OFF' and 7 tap positions.

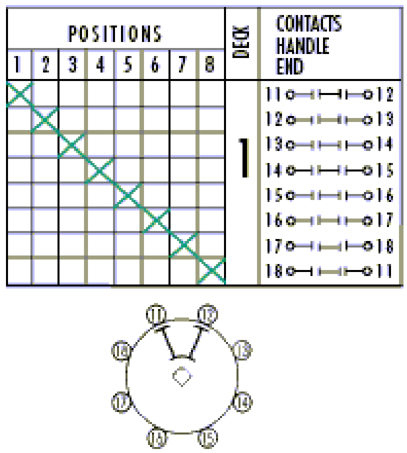


Fig.18 One pole per section, double break switching.

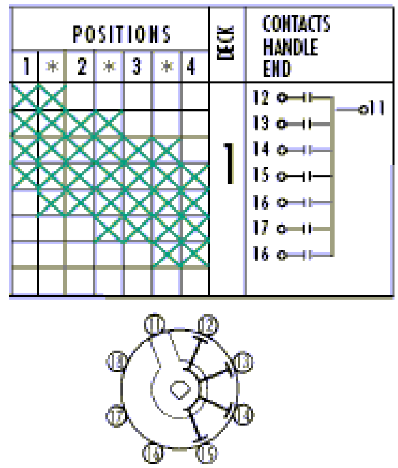


Fig.19 Cumulative tap switching with make-before-break action.

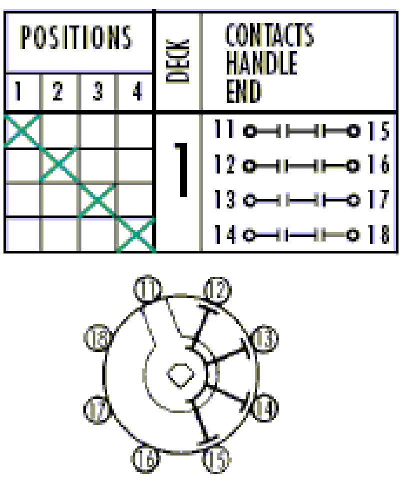


Fig.20 Double break switching.

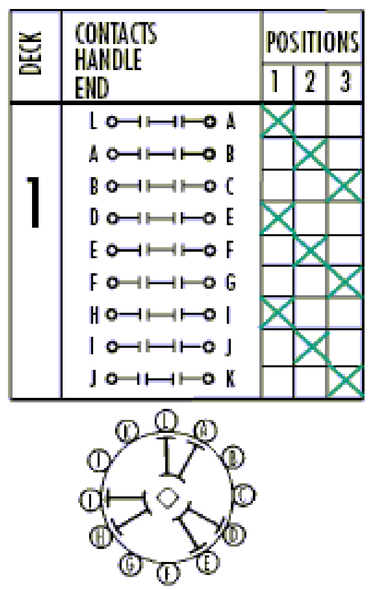


Fig.21 Three pole per section with double break switching.

1.9 Snap Action Rotary Switches

1. Construction

Fig. 22 An overview of typical snap-action switches.

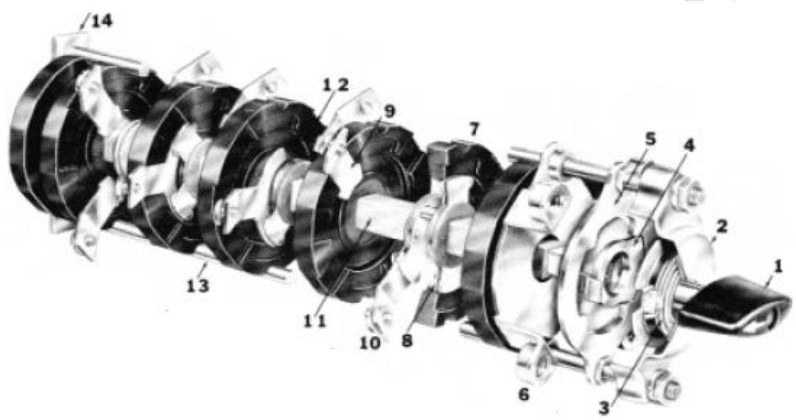


Fig.23 Construction details of a typical snap-action switch.

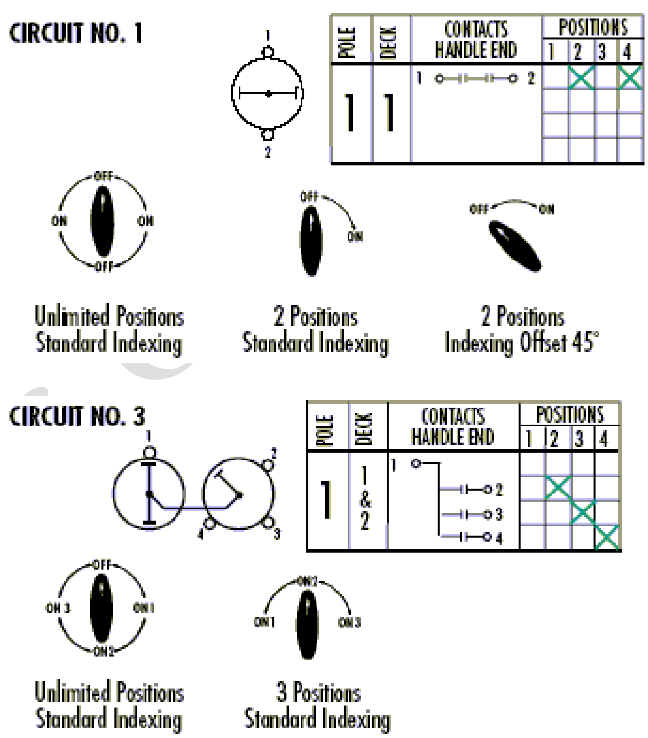
Operating handle (1)	Locking-plate (5)	Connecting terminals (10).
Snap-drive mechanism cover (2)	Mounting bracket (6)	Insulated shaft (11).
Powerful coil spring (3).	Molded insulating disks (7)	Radial grooves (12)
Indexing plate (4)	Spring-metal blades (8)	Side securing rods (13)
	Stationary contacts (9)	Back plate (14)

An overview and the construction details of a typical snap-action switch is shown in Figs.22 and 23. In Fig.23, the electrical system comprises two or more stationary contacts (9) and one or more sets of movable contacts. These are pairs of spring-metal blades (8) that make high-pressure, low-resistance contact on both faces of the stationary contacts while bridging two or more of these contacts. The stationary contacts fit in radial grooves (12) in the rim of molded insulating disks (7), withing which the movable contacts are carried on an insulated shaft (11). All "making" and "breaking" of electric circuits takes place within the closed spaces between adjacent disks. Their quick-break action makes these switches particularly suitable for direct-current service. The ends of the stationary contacts extend outside the insulating disks and serve as connecting terminals (10). This one-piece contact/terminal construction minimises series resistance and heating. The mechanical system is designed to provide uniform high-speed "make" and "break", regardless of whether the operating handle (1) is turned rapidly or slowly. Turning the handle through approximately 120^o in either direction winds a powerful coil spring (3). When this is fully wound, the indexing plate (4) is momentarily withdrawn from the locking-plate (5) by an eccentric cam. The drive shaft and movable contacts then snap rapidly to the next position.

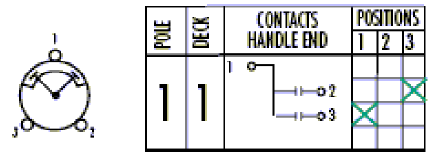
The snap-drive mechanism, mechanism-cover (2), locking plate, mounting bracket (6), insulating disks, and back plate (14) are stacked on side securing rods (13) and bolted firmly together to form a rigid assembly. The handle is keyed to the operating shaft and secured by a screw.

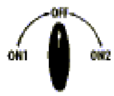
2. Contact diagrams

A typical contact diagrams are shown in Fig.24.



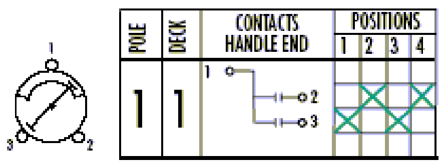
CIRCUIT NO. 6



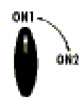


3 Positions
Standard Indexing

CIRCUIT NO. 5



Unlimited Positions
Standard Indexing

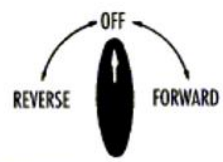


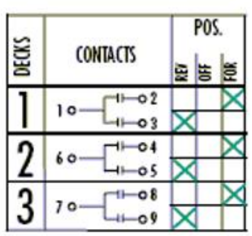
2 Positions
Standard Indexing

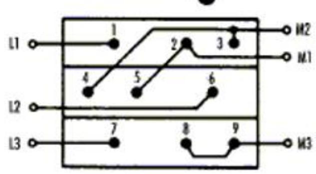
2 Positions
Indexing Offset 45°

REVERSING SWITCH
Three Phase

Break-before-make contacts







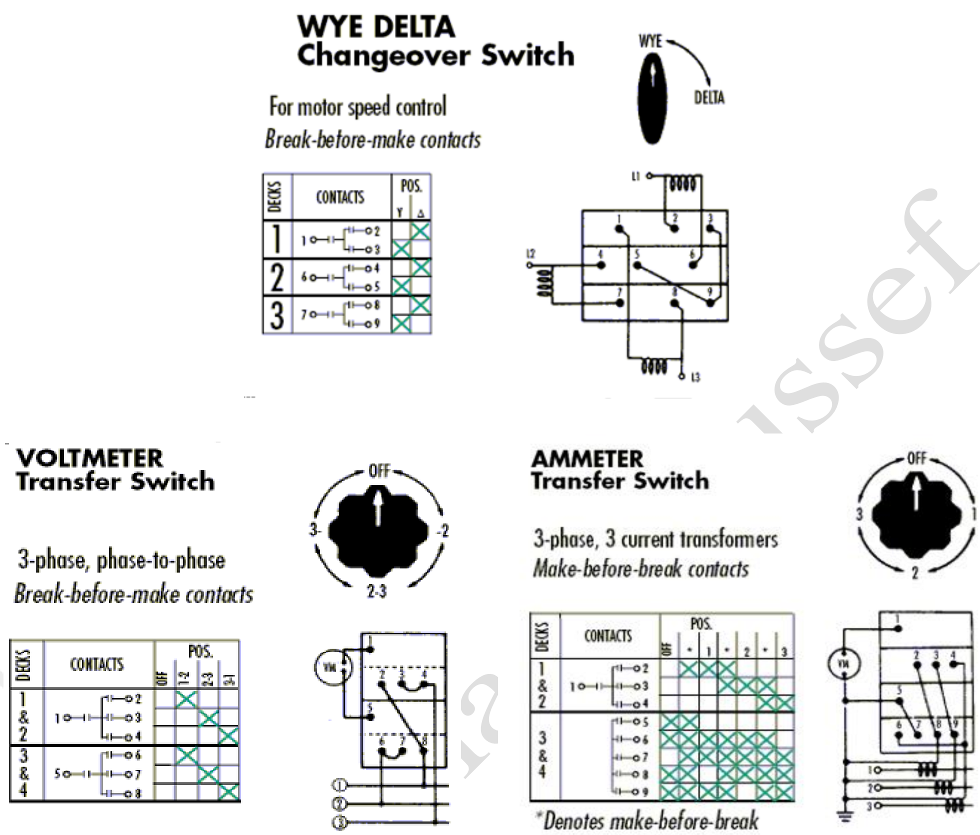


Fig.24 Contact diagrams.

1.10 Lockout-Tagout (LOTO)

Lockout-tagout (LOTO) or **lock and tag** (Fig.25) is a safety procedure which is used in industry and research settings to ensure that dangerous machines are properly shut off and not started up again prior to the completion of maintenance or servicing work. It requires that hazardous power sources be "isolated and rendered inoperative" before any repair procedure is started. "Lock and tag" works in conjunction with a *lock* usually locking the device or the power source with the hasp, and placing it in such a position that no hazardous power sources can be turned on. The procedure requires that a *tag* be affixed to the locked device indicating that it should not be turned on.

Fig.25 Lockout-tagout (LOTO) safety procedure.

Hazardous energy and its isolation

Modern machinery can contain many hazards to workers, from things like electrical, mechanical, pneumatic or hydraulic sources. For example a typical industrial machine may contain things like hot fluids, moving presses, blades, propellers, electrical heaters, conveyor belts with pinch points, moving chains, ultraviolet light, etc.

Disconnecting or making safe the equipment involves the removal of all energy sources and is known as *isolation*. The steps necessary to isolate equipment are often documented in an *isolation procedure* or a *lockout tagout procedure*. The isolation procedure generally includes the following tasks:

1. Identify the energy source(s)
2. Isolate the energy source(s)
3. Lock and Tag the energy source(s)
4. Prove that the equipment isolation is effective

The locking and tagging of the isolation point lets others know not to de-isolate the device.

1.11 Multi-Contact Lockout Relays

Lock-out Relays (LORs) are high speed control relays used primarily as auxiliary relays in applications requiring many contacts. They can take the following forms:

LOR/ER: electric-trip and either manual or electric- reset.
LOR/SR: electric trip and self-reset device.

Lock-out Relays of various types are often used in the electrical power industry. These are control relays for the purpose of tripping and locking out circuit breakers or other devices automatically when a fault or other predetermined condition exists. The lock-out relays are generally used in conjunction with differential relays to protect transformers, buses, and rotating machinery in various electrical systems. Lock-out Relays of known types often have ten or more NO and NC contacts. The relays can be programmed to change sequences such as shutting down a faulty pump and then initiating the action to start-up a standby pump or bypassing a faulty circuit by opening and closing breakers. Known relays of this type are normally latched in the RESET position and trip-out to a TRIP position when commanded. There are then manual-reset, electric-reset, and self-reset versions to get back to the RESET position.

1. Basic Circuit Operation (Manual-reset LOR)

The control of a Lock-out Relay for operation as a relay require a NO contact S1 to command the LOR to TRIP and the electric-reset LOR/ER needs an additional NO contact S2 to initiate the command for RESET. This circuit is self-interrupting with the LOR contacts so S1 need not be concerned with the "break" of the TRIP circuit. On the electric-reset LOR, S2 needs to make only the K1 relay circuit so the burden of LOR/R does not affect S2. Any pilot duty device is acceptable for both S1 and S2.

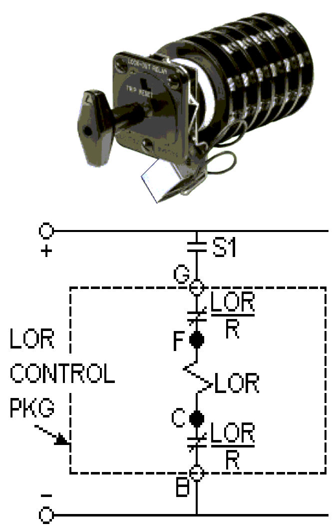


Fig. 26 Manual-reset LOR Control Circuit (shown in RESET position).

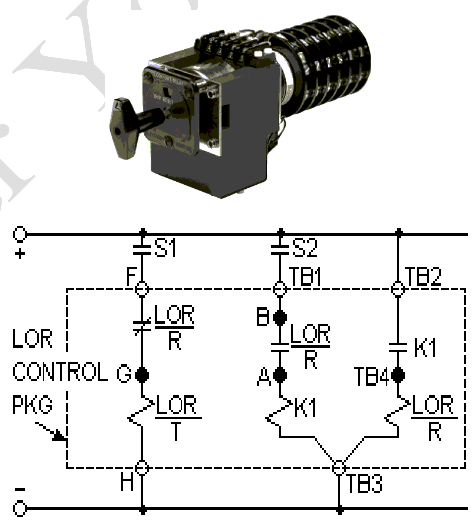


Fig. 27 Electric-reset LOR/ER Control Circuit (shown in the RESET position).

The LOR schematic is shown on Fig.26. The LOR contacts shown are normally closed in the reset position. G and B are tie points to connect the LOR to the control circuit. C and F are internal connection points shown for information.

To command the Lock-out Relay to TRIP, S1 is closed. This completes a circuit across the LOR trigger solenoid, which operates, causing the device to snap to the TRIP position. It locks into this position and remains there indefinitely. When this happens, the LOR contacts open thereby removing the control circuit from the bus.

The unit will stay locked-out in the TRIP position until manually reset. S1 may be any kind of auxiliary contact -- from a breaker, a protective relay, or from another auxiliary device like a relay. The condition of the Lock-out Relay is visible by the handle location and a mechanical target within the nameplate (Black for RESET, Orange for TRIP).

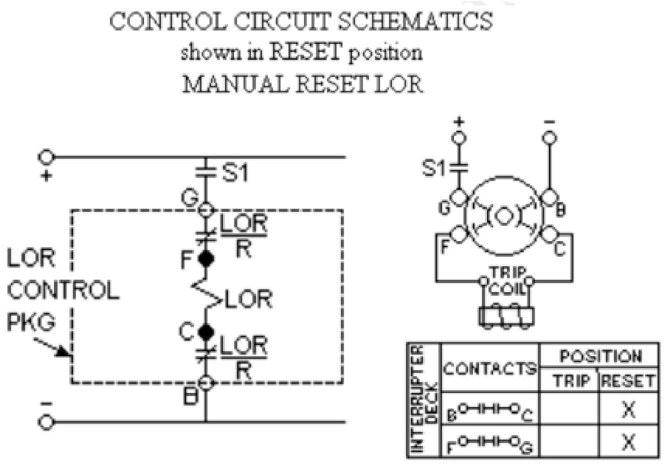


Fig. 28 Design guide for an LOR (Manual Reset)
(control circuit schematics shown in RESET position).

2. Electric-reset LOR/ER Circuit

The LOR/ER schematic is shown on Fig.27. The LOR/R coil form represents the rotary solenoid that is used to reset the LOR/ER electrically. K1 is a relay used to control the rotary solenoid. This enables S2 to be a low level contact. It controls only the K1 relay coil. The K1 contact operates the high current rotary solenoid. TB1, TB2, TB3 are terminal block contacts, and F and H are LOR tie points-- all are for connection to the control bus. G, B, and TB4 are internal tie points shown for information. When the LOR/ER tripped, the Normally Closed (NC) LOR contact in the LOR/T circuit opens removing LOR/T solenoid from the circuit. When this happens, the Normally Opened (NO) cotacts of LOR in the K1 relay circuit closes enabling this circuit to be used. To command the LOR/ER to reset, S2 is closed. This completes the circuit to the K1 relay and it operates closing contact K1. This completes the circuit to the LOR/R rotary solenoid and it indexes to the RESET position. When this happens, the NO LOR contact opens. This opens the circuit on the K1 relay coil. K1 relay drops out opening contact K1 that opens the rotary solenoid LOR/R circuit. At the same time the NC LOR contact, in the linear solenoid LOR/T circuit, closes, setting up the LOR/ER for the next TRIP command. S1 and S2 should be momentary contacts and should not stay closed. If both contacts are closed at the same time, a "pumping" action will result with the LOR/ER indexing back and forth between the RESET and TRIP positions.

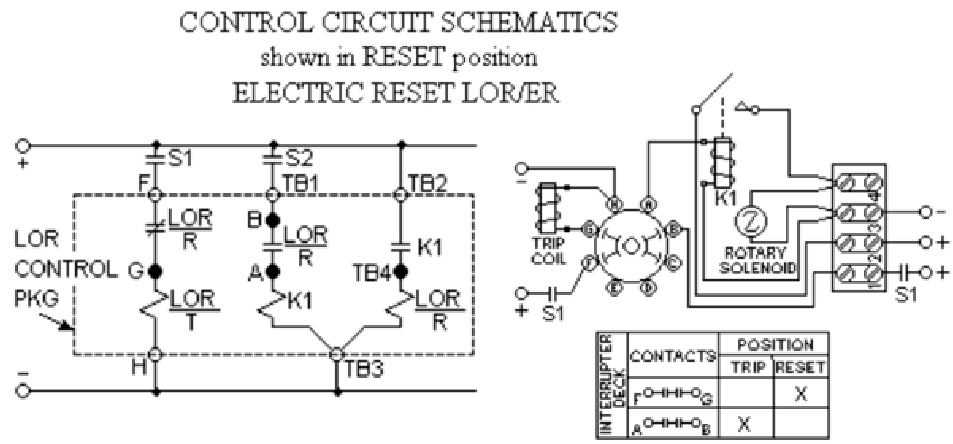


Fig. 29 Design guide for an LOR-ER (wiring diagrams - TRIP & RESET circuits).

3. Self-reset LOR/SR Circuits

The LOR/SR, as shown in Fig. 28 and 29, is in the RESET position. The LOR/T coil is the same linear solenoid that is used in all LOR's, and controls the trigger that locks the LOR/SR in the RESET position. The LOR/R is the same rotary solenoid used in the LOR/ER and is used to electrically reset the LOR/SR. K1 and K2 are two relays with NO contacts used in the control circuit. R1 and R2 make up a bridge circuit on both the INSTANTANEOUS RESET and the TIME DELAY RESET units. In addition the TIME DELAY RESET version has an additional 1E-1F normally open (NO) contact to isolate the K2 coil plus the time delay circuit consisting of R1 and C1-C2-C3-C4 which are wired in parallel. D1 protects the capacitors from a possible incorrect polarity hookup.

1. The INSTANTANEOUS RESET version of the LOR/SR will reset itself within 80 milli-seconds after the fault has cleared itself (S1 opens). This circuit is illustrated in Fig.28. The LOR/SR trips in the same manner as the manual-reset LOR. With S1 closed (simulating the commanded or fault condition) B-A contact closes and E-F contact closes. In this manner E-F and A-B are both connected to the (+) bus so the K1 coil sees no voltage difference and cannot operate. Therefore, the LOR/SR will not reset and may remain in the TRIP position indefinitely while the R1R2 bridge draws only enough milliamps to maintain the voltage balance of the bridge -- and well below the dropout current of any 0.2A target relays that may be part of the circuit. When S1 opens (indicating the fault or predetermined condition has cleared), the R1R2 bridge becomes unbalanced since the E-F contact, although closed, is in the S1 contact circuit. K1 operates, closing contact K1 and K2 operates, closing contact K2 and the rotary solenoid LOR/R operates and indexes to the RESET position completing the cycle. Contact E-F, and A-B then open dropping out relays K1 and K2 (and their contacts). Contact F-G closes setting up LOR/SR for the next command.

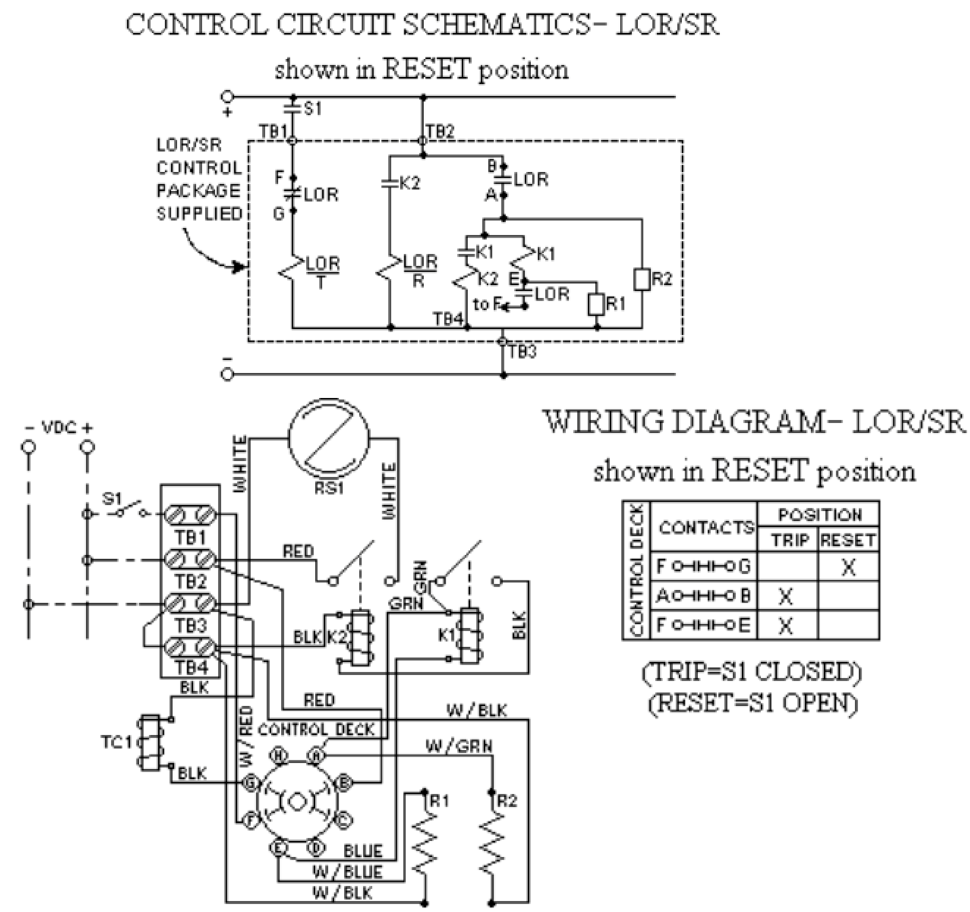


Fig. 30 Design guide for an LOR/SR instant self-reset lock-out relay (control circuit and wiring diagrams - TRIP & RESET circuits).

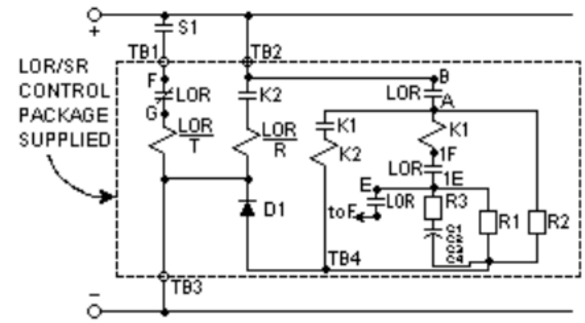
2. The TIME DELAY SELF-RESET (shown in RESET position) version of the LOR/SR, illustrated in Fig. 29, operates in the same manner as the instantaneous reset version except the R3-C1-C2-C3-C4 circuit causes a time delay of from 300 to 600 milliseconds from the time S1 opens until the LOR/SR contacts reclose.

4. Target used with Lock-out Relays

All the Lock-out Relays have a mechanical target as part of the nameplate -one color for RESET and another for TRIP. The standard circuits are shown on Figs. 30 and 31.

CONTROL CIRCUIT SCHEMATICS- LOR/SR

shown in RESET position



WIRING DIAGRAM- LOR/SR

shown in RESET position

CONTROL DECK CONTACTS	POSITION TRIP	POSITION RESET
F o-||-o G		X
A o-||-o B	X	
F o-||-o E	X	
1F o-||-o 1E	X	

(TRIP=S1 CLOSED)
(RESET=S1 OPEN)

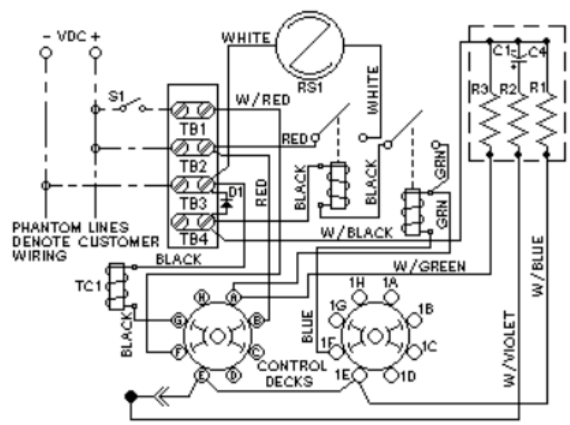


Fig. 31 Design guide for an LOR/SR time delay self-reset lock-out relay (control circuit and wiring diagrams shown in RESET position).

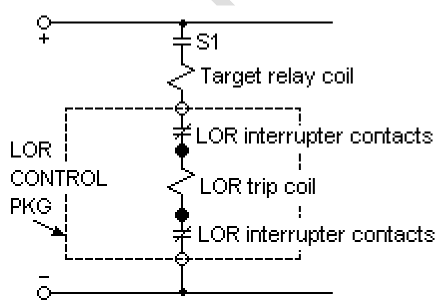


Fig. 32 An LOR circuit with target relay coil.

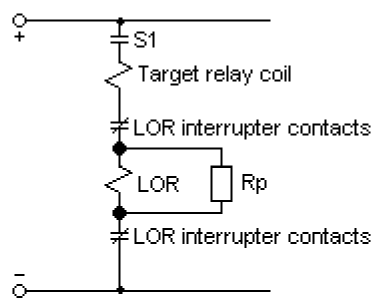


Fig. 33 LOR trip circuit with resistor (Rp) in parallel with LOR trip coil.

5. Contact Deck Arrangement

Specifically, two NO contacts and two NC contacts are provided in each deck, and up to ten decks can be stacked, resulting in a relay with up to forty contacts (twenty NO and twenty NC). The deck arrangement is illustrated in Fig. 32 for the first deck. For multideck units the second digit of the terminal number is the same as shown but the first digit changes to denote the deck number. As an example, terminal 82 is in the eighth deck, directly under terminal 12 and used together with terminal 88. This explains how the LOR's are constructed and is shown as information for the user. Traditional contact charts are normally used, as shown on Fig. 33. Complete design guide for a typical LOR is shown in Figs.34, 35.

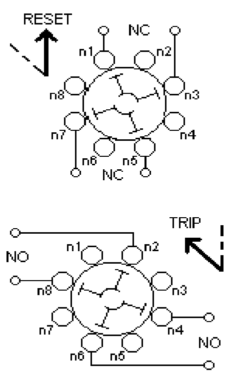


Fig. 34 Basic LOR Deck Layout.

DECK	CONTACTS	POS. TRIP	POS. RESET
1	11 ○—| |—○ 13		X
	12 ○—| |—○ 18	X	
	15 ○—| |—○ 17		X
	16 ○—| |—○ 14	X	
2	21 ○—| |—○ 23		X
	22 ○—| |—○ 28	X	
	25 ○—| |—○ 27		X
	26 ○—| |—○ 24	X	
[illegible]	[illegible] —| |—○ 33		X
9	9[illegible]	X	
	95 ○—| |—○ 9[illegible]		[illegible]
	96 ○—| |—○ 94	X	
10	101 ○—| |—○ 103		X
	102 ○—| |—○ 108	X	
	105 ○—| |—○ 107		X
	106 ○—| |—○ 104	X	

Fig. 35 LOR, LOR/ER, and LOR/SR, Lock-out Relay Contact Chart.

1.12 Latching Switch Relays (LSRs)

Latching switch relays are auxiliary relays used to provide maintained contacts - both Normally Closed (NC) and Normally Opened (NO). They are two position rotary action relays with up to 20 N/O and 20 N/C contacts in a single device. It is manually or remotely operated unit used for a variety of applications; latching relays, reclosing relays, programming relays, and local/remote switches.

1. CONTACT DECK ARRANGEMENT

The blade and terminal configuration enables the use of multiple contacts in the same deck, and simple stacking procedures enable the fabrication of many independent contacts in one relay. Specifically, two N/O contacts and two N/C contacts are provided in each deck, and ten decks can be stacked, resulting in a relay with up to forty contacts. This is shown in Fig.36. The illustration of the basic deck LSR layout is for the first deck. For multideck units the secondary digit of the terminal number is the same as the deck number, e.g. terminal 82 is in the eighth deck, in line under terminal 12 and is a N/O contact used together with terminal 84.

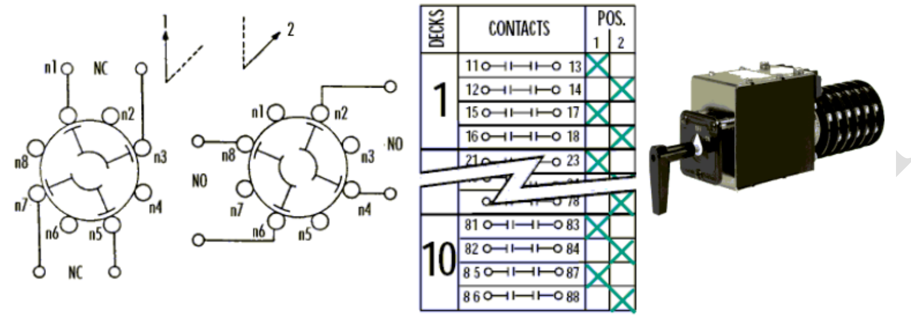


Fig. 36 Contact deck arrangement and contact chart of LSR.

2. LOW LEVEL CONTROL

A shown in Fig. 37, the low level command contacts S1 and S2 close on an interposing relay coil k1 and the rotary solenoid coil LSR is controlled by the relay contact k1. S1 and S2 can be LSR contacts rated less than 1 ampere. The circuit is interrupted by the internal LSR, so S1 and S2 need to "make" the low level circuit only. To command LSR to position 2, S1 is closed momentarily. This completes a circuit to the rotary solenoid LSR and the device indexed to position 2 and latches. When this occurs, LSR/1 contact opens, interrupting the LSR solenoid circuit. The LSR solenoid resets itself and awaits the next command.

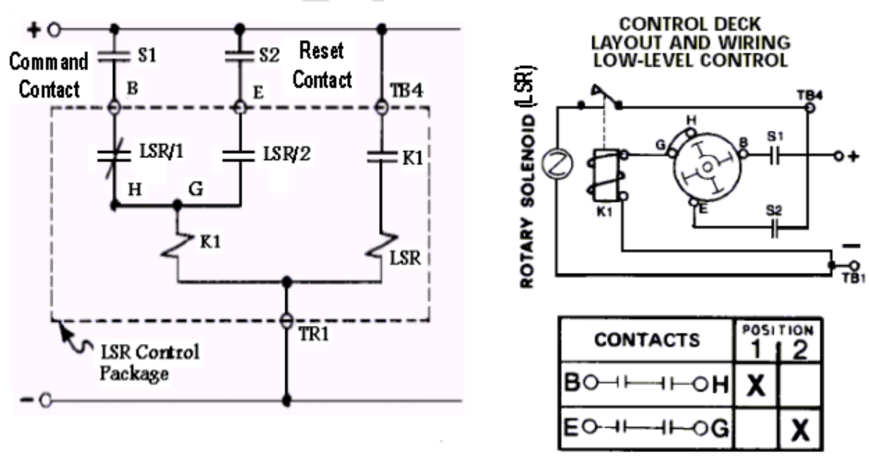


Fig. 37 Latching Switch Relay (LSR) low-level control circuit using interposing relay- Control deck layout and wiring diagrams.

3. DIRECT CONTROL METHOD

As shown in Fig.38, the command contacts S1 and S2 close directly on the full LSR rotary solenoid coil current, so the burden data of this solenoid should be considered in the choice of these control conacts. The internal LSR contacts interrupt the solenoid current however, so S1 and S2 need to "make" the circuit only.

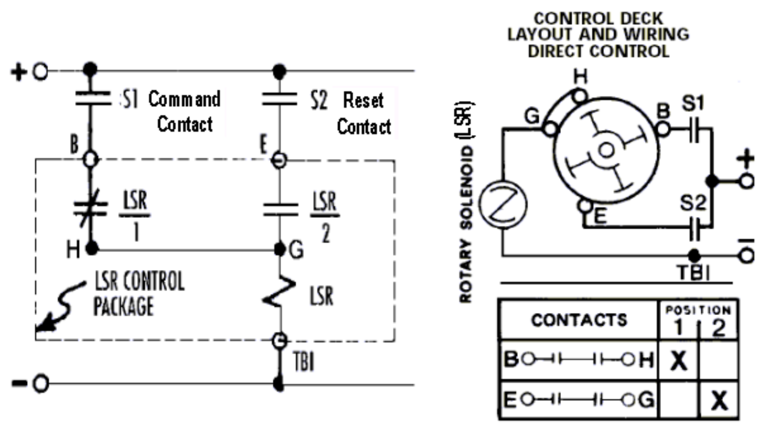
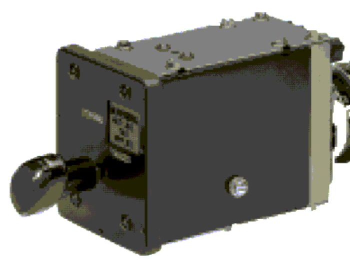


Fig.38 Latching Switch Relay (LSR) direct control circuit with no interposing relay- Control deck layout and wiring diagrams .

1.13 Tagging Relays

Tagging relays allow remote or manual circuit breaker operation for automated power distribution. They feature an eye-catching orange "Warning" hot line tag ensuring personnel safety. Typical control deck layout and wiring diagrams are shown in Fig. 39. Some of their applications are:

1. Distribution automation and safety tagging.
2. Power distribution automation.
3. Enhanced circuit breakers control shcemes.
4. Remote reclosure cut-off.



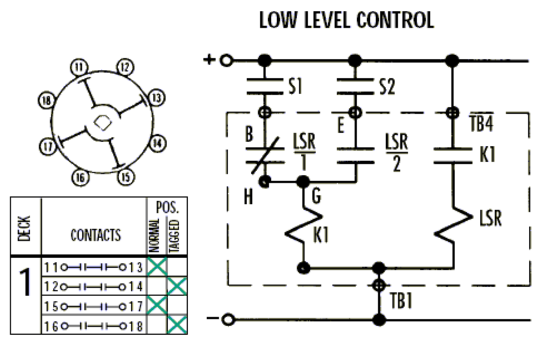
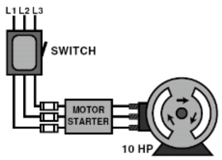


Fig. 39 Control deck layout and wiring diagrams for low level control of tagging relays.



CHAPTER 2

Motor Control Circuits

2.1 Overview

The term “motor control” can have very broad meanings. It can mean anything from a simple toggle switch intended to turn a motor on or off to an extremely complex system intended to control several motors, with literally hundreds of sensing devices that govern the operation of the circuit. The electrician working in industry should be able to install different types of motors and the controls necessary to control and protect them and also to troubleshoot systems when they fail.

In reference to Fig.1, the basic motor control components are:

1. Conductors (copper conductors unless identified for use with a different conductor)
2. Overload Protection (or any other approved means).
3. Controller (any device normally used to start and stop a motor)
4. Disconnecting Means (a motor-circuit switch rated in hp or a circuit breaker)
5. Branch-Circuit Short and Ground-Fault Protection (a circuit breaker or fuse)

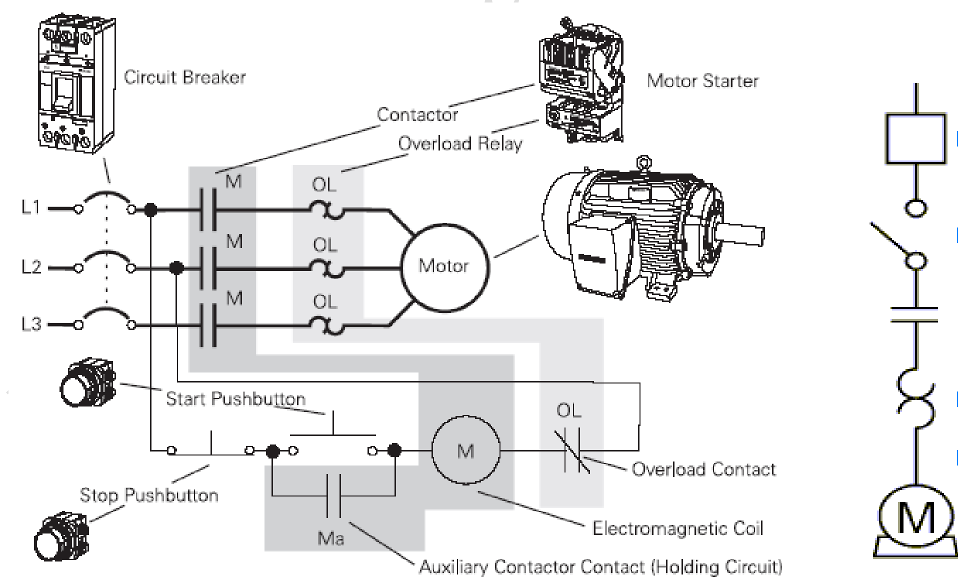


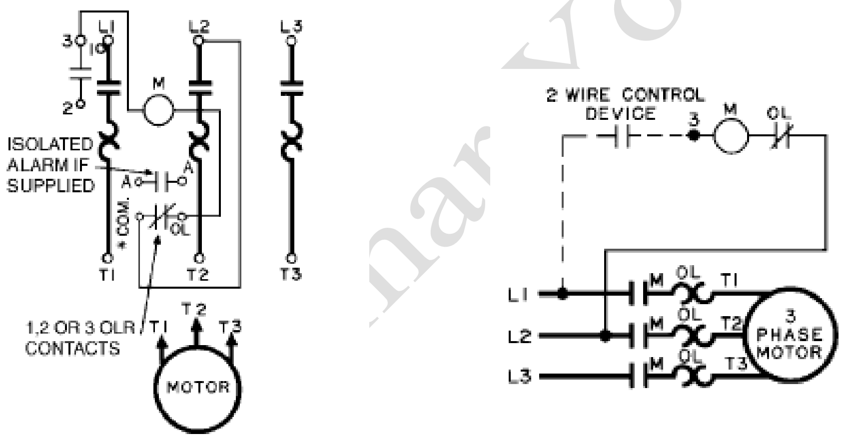
Fig.1 Basic motor control components and branch circuit.

2.2 Wiring Diagram & Elementary Diagram

The **control diagram** is the written language of control circuits. There are three types of control diagrams in use:

1. The **wiring diagram**, which is best, suited for making the initial connections when a control system is first wired or for tracing the actual wiring when troubleshooting.
2. The **line, schematic or ladder diagram** which is the easiest to use in trying to understand the control circuit electrically. It is the simplified circuit illustration
3. The **wireless-connection diagrams** which the most compact type and eliminates confusing lines. Its chief advantage is for installing already-formed wiring harnesses for factory assembly lines.

   Figs. 2 and 3 show a typical wiring, ladder and wireless diagrams.



(a) **(b)**

Fig. 2 (a) Wiring diagram, and (b) its corresponding elementary (ladder) diagram-ANSI symbols.

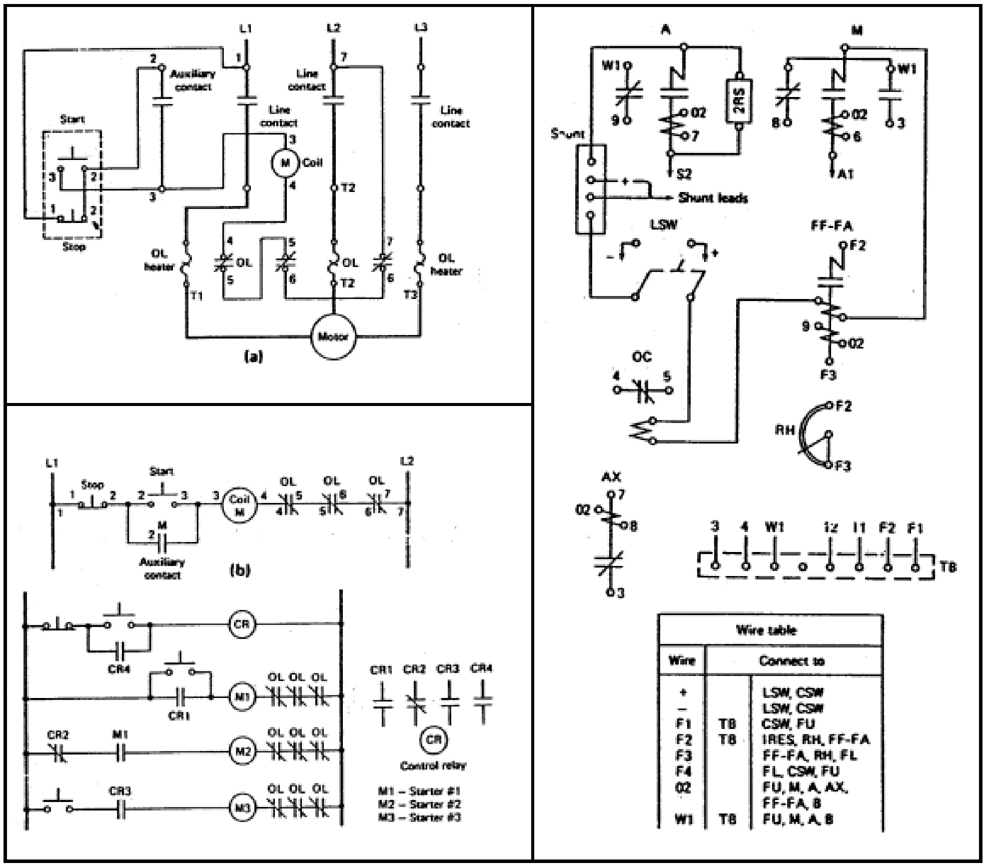


Fig. 3 Motor circuit diagrams (schematic - typical line or ladder , and wireless connection diagrams)-ANSI symbols.

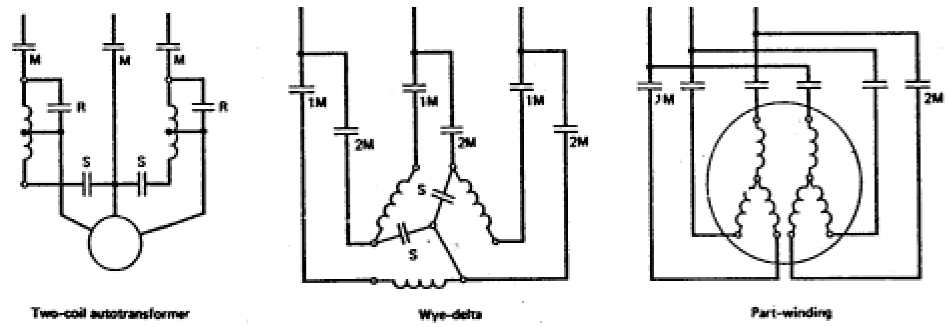
2.3 Control of Motor Starting

1. Full-Voltage Starting

This type of starting control can be an advantage for fans and other devices that otherwise would have to be restarted. For motors up to 10 hp and not over 600 V, the manual across-the-line motor starter may be used to give manual control. Most of these units give overload protection and under-voltage release. This is shown in Fig.4.

2. Reduced -Voltage Starting

Whenever the starting of a motor at full voltage would cause serious voltage dips on the power company lines or the plant wiring, reduced voltage starting becomes almost a necessity (Fig. 5).



Two-coil autotransformer

Contactor sequence			
Contactor	Start	Transition	Run
M	X	X	X
S	X		
R			X

Wye-delta

Contactor sequence			
Contactor	Start	Transition	Run
1M	X	X	X
2M			X
S	X		

Part-winding

Contactor sequence		
Contactor	Start	Run
1M	X	X
2M		X

Fig. 4 Full-voltage starting. **Fig. 5 Reduced voltage starting (star-delta).**

2.4 Traditional Electromechanical Starters

A.C. Induction motors are traditionally started and stopped by applying and removing the A.C. supply. In some cases, a full voltage start is acceptable, but in many situations, the start current must be reduced, and so a reduced voltage starter is employed.

1. Across-the-line starting

The simplest form of motor starter for the induction motor is the across the line type. This starter comprises a switch and an overload protection relay. The switch may be a manually operated load break switch, but more commonly it would be an electromagnetic contactor, which can be opened by the thermal overload relay. Figs.6-8 show different types of non-reversing and reversing-type starters. To start, the contactor is closed, applying full line voltage to the motor windings. The motor will draw a very high inrush current for a very short time, to establish the magnetic field in the iron, and then the current will be limited to the locked rotor current of the motor. The motor will develop locked rotor torque and begin to accelerate towards full speed. As the motor accelerates, the current will begin to drop, but will not drop significantly until the motor is at a high speed, typically about 85% of synchronous speed. The motor load will affect the time taken for the motor to accelerate to full speed and therefore the duration of the high starting current, but not the magnitude of the starting current. Across-the-line starting results in maximum start current and maximum start torque. This may cause an electrical problem with the supply, or it may cause a mechanical problem with the driven load.

A DOL starter connects the three main lines (L1, L2 and L3) directly to the motor terminals when the start button is pressed. The drawing of a DOL starter is generally done in two separate stages. These are called the Power Circuit and the Control Circuit.

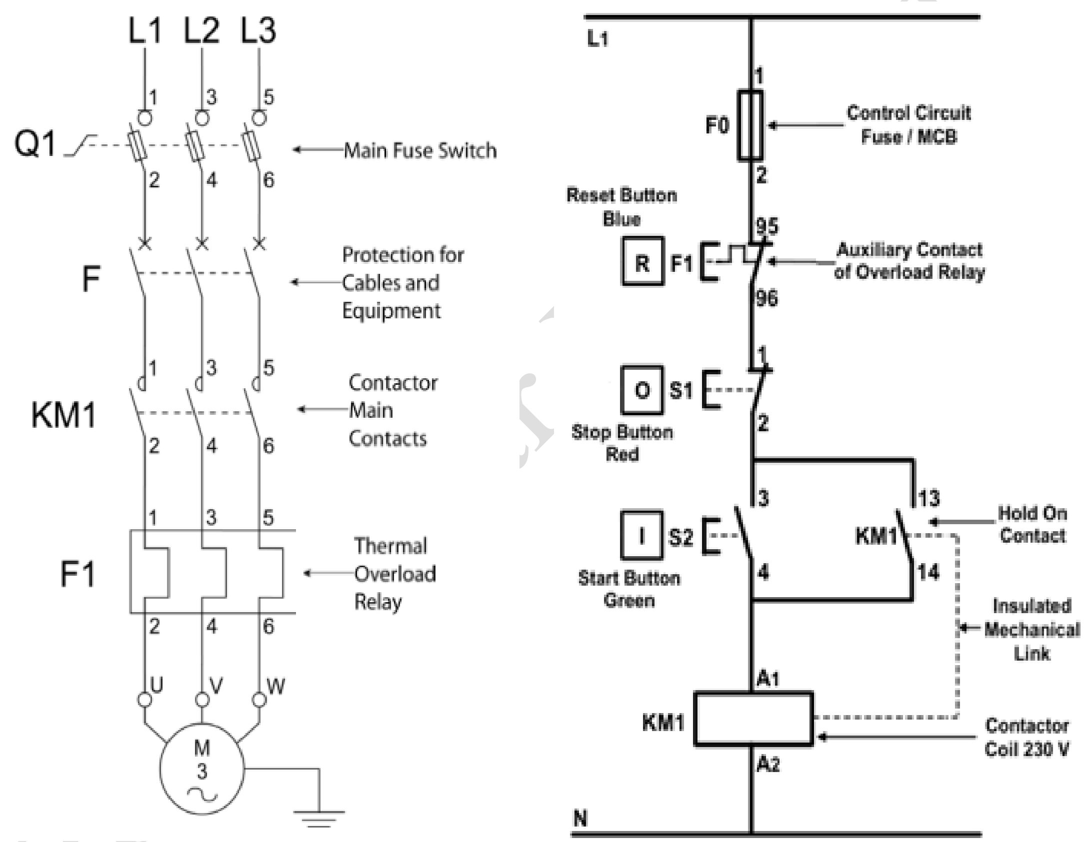


Fig. 6 Across-the- line non-reversing starter, US and international symbols (power circuit - control circuit)-IEC symbols.

Power Circuit

The power circuit shows all the components or parts of components required to handle the load current of the motor. Remember that the motor in question may be a small 1.5 kW (2 HP) or a large 225 kW (300 HP). As the motor power rating increases so too must the current rating of the contactor, overload relay and supply cables. When wiring circuits, the supply should be fed in on the low number terminal and out on the high number terminal. See Fig.6.

Control Circuit
The control circuit shows all the components or parts of components required to control the motor. These components are basically the same regardless of the power rating of the motor in question. Note When wiring circuits, the supply should be fed in on the low number terminal and out on the high number terminal. See Fig.6.

Circuit Description
Refer to the circuit illustrated in Fig.6.
The motor being controlled by KM1 will START if:
1. Supply voltage is present between L1 and N
2. The control fuse F0 is good
3. The normally closed (NC) contact 95 – 96 is closed
4. The stop pushbutton S1 is not operated
5. The start pushbutton S2 is operated
6. The coil is energised by the presence of a voltage and the circuit is complete through the coil to the neutral
7. The auxiliary contact 13 – 14 (NO) is closed by the operation of the coil
8. When the start pushbutton S2 is released current continues to flow through the auxiliary contact 13 – 14 (hold on contact), the coil remains energised and the motor continuesto run.

The motor being controlled by KM1 will STOP if:
1. The control circuit fuse blows or MCB trips or is switched off.
2. The overload trips or F1 is pressed causing 95 – 96 (NC) contact to open
3. The stop button S1 is pressed
4. The voltage reduces to a level which cannot keep the coil energised
5. The supply fails

2) Primary Resistance.
These starters have one or more sets of resistors which, during starting period, are connected in series with the supply to the motor. The function of the series resistors is to limit the starting current drawn by the motor, and thus reduces the starting torque of the motor. This is shown in Fig.9. Once the motor reaches its full speed the resistors are bridged by a contactor to apply full voltage to the motor. An appropriate primary resistance starter will cause the motor to accelerate the load to almost full speed with the resistors in circuit before they are bridged out. In this case, the transition to full voltage only occurs once the impedance of the motor has risen, and the resulting current is much less than the locked rotor current of the motor. Improved starting characteristics with some loads can be achieved by the use of several stages of resistance and

bridging out increasing amounts of resistance as the motor accelerates. The primary resistance starter reduces the voltage applied to the motor terminals while passing the full starting current to the motor. Consequently, there is a very high power dissipation in the resistors, resulting in the requirement for very high power rated resistors. The resistors may be either metallic resistors, or liquid resistors. Metallic resistors have a positive temperature coefficient and as a result, as they heat up, their resistance increases. Liquid resistors, such as saline solution, have a negative temperature coefficient and so consequently, as they heat up, their resistance reduces. The heat build up in the resistors during start, and their temperature dependant resistance characteristics, make it essential the resistors are allowed to fully cool between starts. This restricts the starting frequency and the minimum time between the starts.

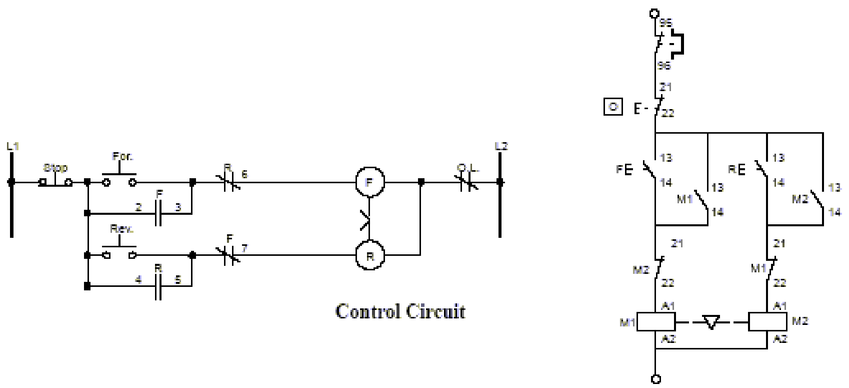


Fig. 7 Across-the-line reversing starter, US and international symbols (power circuit - control circuit).

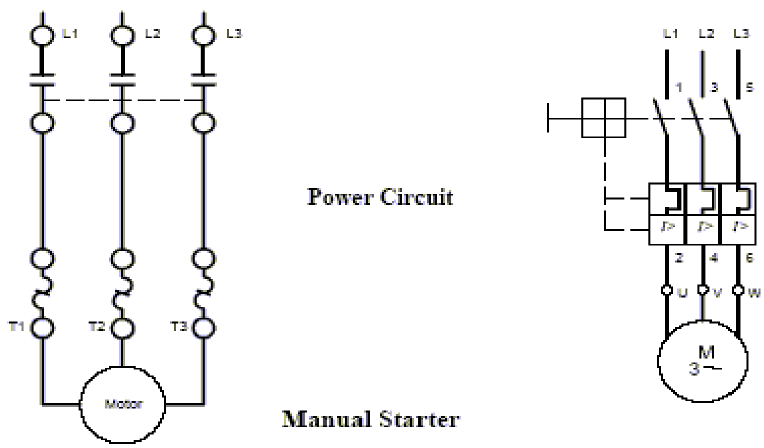


Fig. 8 Manual starter, US symbol (power circuit).

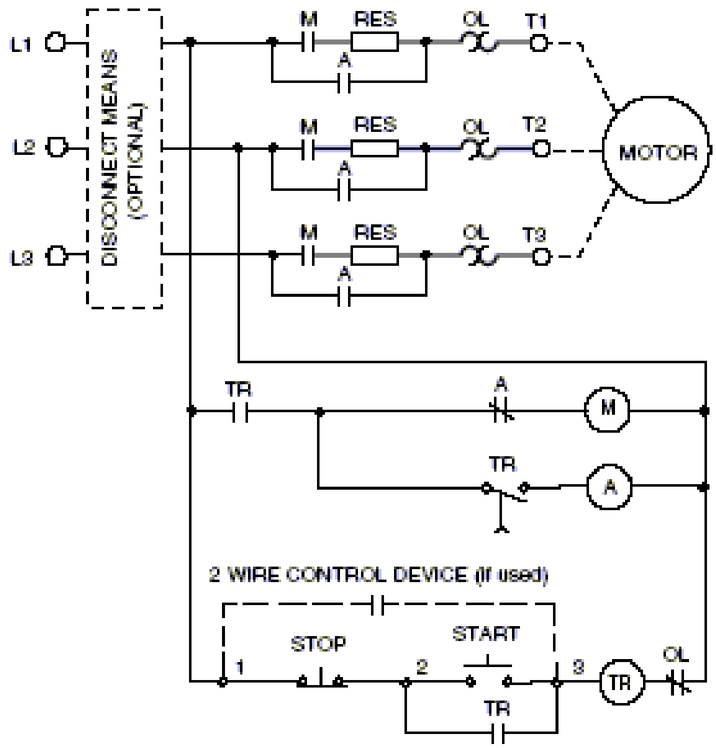


Fig.9 Three-phase primary-resistor reduced voltage starter.

3) Primary Reactance.

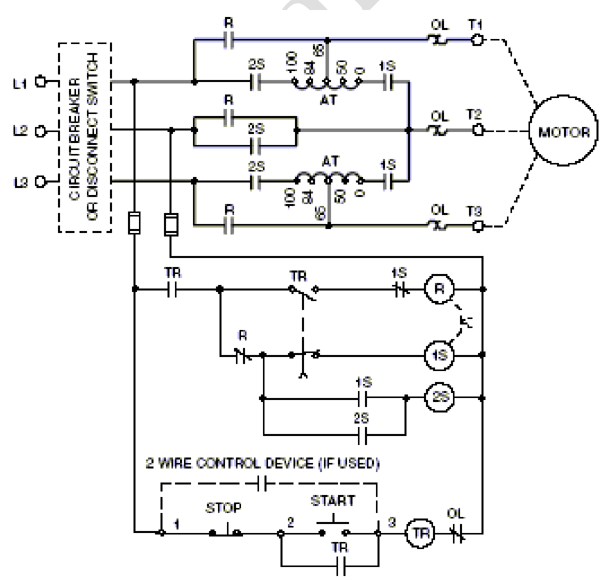
The operation of the primary reactance starter is essentially the same as that of the primary resistance starter, but the use of a three phase reactor in place of the resistors offers the advantage of reduced heat loss and greater ease of start current setting due to the ability to change taps on the reactor.

4) Auto transformer.

An Auto transformer starter uses an auto transformer to reduce the voltage applied to a motor during start. The auto transformer may have a number of output taps and be set-up to provide a ingle stage starter, or a multistage starter. There are two ways of connecting an auto transformer starter:

a. Open Transition starting:

Applying full voltage to the transformer via a contactor, and connect the motor to the tap by means of a contactor. When the motor has accelerated to full speed, or has run out of acceleration torque, the tap contactor opens, disconnecting the motor from the transformer and another contactor closes connecting the motor to the supply. The transformer can now be disconnected from the supply. This format is known as an **open transition** starter and is less than ideal due to the fact that the motor is disconnected for a short period of time during the start period. While the motor is connected and accelerating, there is a rotating magnetic field in the stator which causes flux in the rotor and thus a rotor current to flow. At the instant the motor is disconnected, there is a magnetic field in the rotor which is spinning with-in the stator winding. The motor acts as a generator until the rotor field decays. The voltage generated by the motor is not synchronised to the supply, and so on reconnection to the supply, the voltage across the contactor at closure can be as much as twice the supply voltage resulting in a very high current and torque transient. This open transition switching is often known as the auto-reclose effect as it yields similar characteristics to opening and closing a breaker on a supply to one or more motors. The consequences of open transition switching can be as bad as broken shafts and stripped gears.



Wiring Diagram

Fig. 10 Reduced voltage autotransformer controller. with closed transition starting.

b. Closed transition starting (Korndorffer starter)

Is used to eliminate the current and torque transients. As shown in Fig.10, the closed transition switching is achieved by reconnecting the tap contactor between the transformer and motor, to the star connection of the transformer, hard wiring the motor to the tap, and altering the sequence of contactor control. To start the machine, the main contactor and the star contactors are closed applying reduced voltage to the motor. When the motor has reached full speed, (or run out of acceleration torque) the star contactor is opened effectively converting the auto transformer starter into a primary reactance starter. Next the primary reactance is bridged by a contactor applying full voltage to the motor. At no time does the motor become disconnected from the supply.

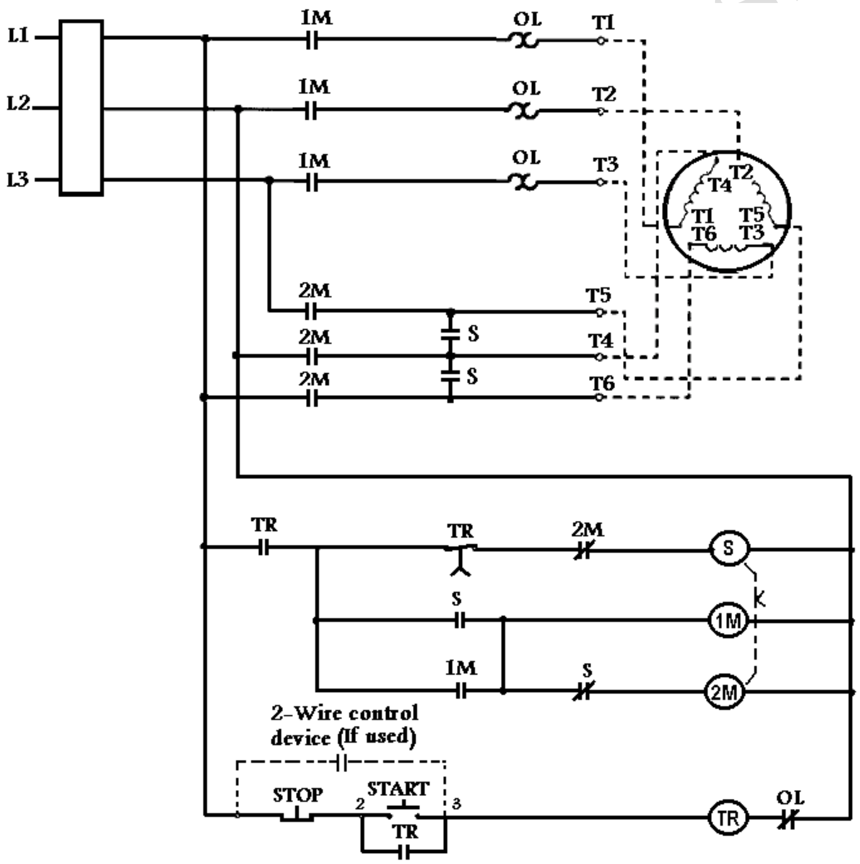
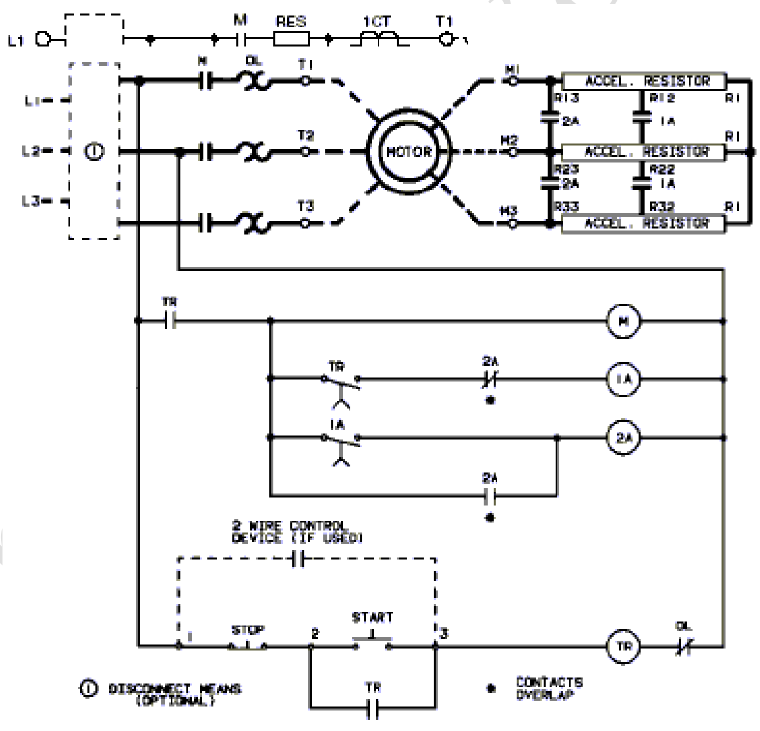


Fig. 11 Y/Δ type Reduced voltage controller with open-transition starting.

c) Star Delta.

The Star Delta starter can only be used with a motor, which is rated for connection in delta operation at the required line voltage, and has both ends each of the three windings available individually. In reference to Fig.11, at start, the line voltage is applied to one end of each of the three windings, with the other end bridged together, effectively connecting the windings in a star connection. Under this connection, the voltage across each winding is 1/(sqrt 3) of line voltage and so the current flowing in each winding is also reduced by this amount. The resultant current flowing from the supply is reduced by a factor of 1/3, as is the torque. i.e. A motor which exhibits a locked rotor current of 600% and an locked rotor torque of 180% will exhibit characteristics of (locked rotor current)$_{star}$ of 200% and (locked rotor torque)$_{star}$ of 60%. To step to full voltage, the star connection is opened, effectively open circuiting the motor, and the ends of the windings are then connected to the three-phase supply in a fashion to create a delta connection. This type of starter is an open transition starter.



Non-Reversing Wound-Rotor Motor Controller w/ 3 Points of Acceleration

Fig.12 Non-reversing wound-rotor motor controller with three points of acceleration.

d) Slip Ring Motors

The Slip Ring motor is essentially similar to the standard cage induction motor except that the winding on the rotor has far more turns and instead of being short circuited, is brought out to a set of slip rings for external connection. This is shown in Fig.12. A very high value of resistance on the rotor termination will give a very low locked rotor current, and a low locked rotor torque. Reducing the termination resistance, will increase both the locked rotor current and the locked rotor torque up to the point where maximum torque is available under locked rotor conditions. A short circuit across the rotor will result in the maximum torque occurring a t a very low slip, and a locked rotor current as high as 1400% for a locked rotor torque of as low as 50%. Typically, the slip ring motor is started by a multistage starter, developing as high as 300% torque at 250% current. By stepping through lower resistor values as the motor accelerates, the maximum torque is kept in step with the actual rotor speed and thus the maximum acceleration of a very difficult load can be achieved in minimum time and with maximum efficiency. The slip ring starter comprises an isolation contactor for the stator circuit, the stator being effectively across-the-line controlled, and a series of rotor resistors and contactors controlled by a sequencer.

2.5 Typical Applications of Motor Control Circuits

1. Two-Wire Low Voltage Release (Fig. 13)

Low voltage release uses a maintained contact pilot device. It is used when a starter is required to function automatically. Only two wires are required to connect the pilot device to the starter.

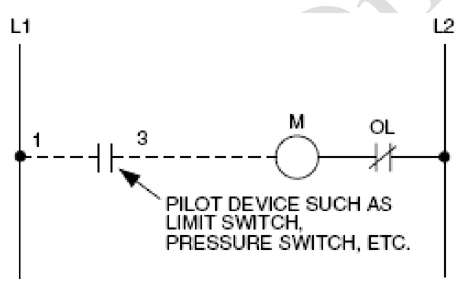


Fig. 13 Two-Wire Low Voltage Release.

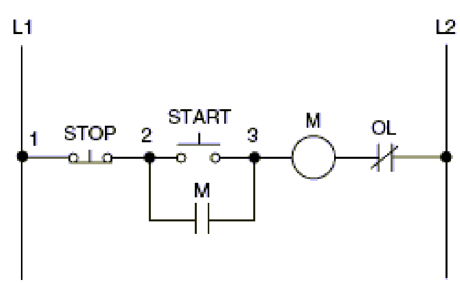


Fig. 14 Three-Wire Low Voltage Protection.

2. Three-Wire Low Voltage Protection (Fig. 14)

Momentary contact push buttons are used to energise the starter coil. The scheme is used to prevent unexpected starting of motors. Three wires are required to connect the pilot device to the starter.

3. Maintained Contact Hand-OFF-Auto Selector Switch (2-Wire Control - Fig.15)
This scheme is used when it is desired to operate the starter manually as well as automatically.

4. Momentary Contact Multiple Push Button Control (3-Wire Control - Fig.16)
This scheme is suitable for remote control of motor starters.

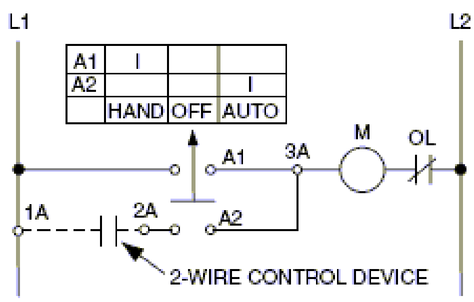


Fig. 15 Maintained Contact with Selector Switch.

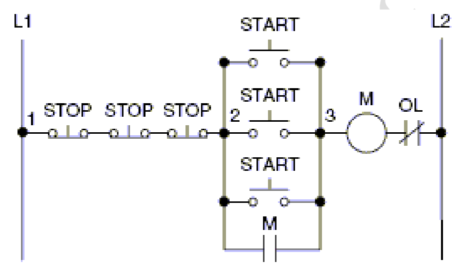


Fig. 16 Momentary Contact with Push Button.

5. Pilot Light Indicator (Motor is Running - Fig.17)
A pilot wire is wired in parallel with the starter coil to indicate the running condition of motor.

6. Pilot Light Indicator (Motor is Stopped - Fig.1)
The pilot light is wired to indicate when the motor is stopped.

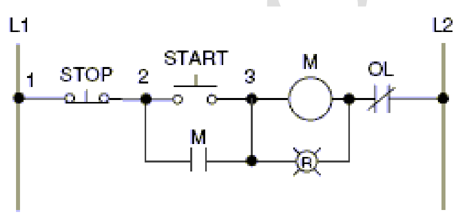


Fig. 17 Pilot Light indication (running).

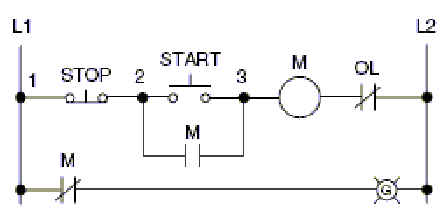


Fig. 18 Pilot Light indication (stopping).

7. Pilot Light Indicator (Push-to-Test - Fig.19)
To test the light bulb, push the cap of the push-to-test pilot light.

8. Illuminated Push Button Indicator (Motor is running - Fig.20)
Start button and pilot light are combined in one unit.

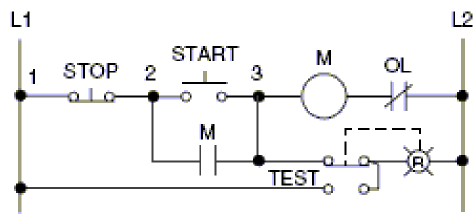


Fig. 19 Pilot Light Indicator (Push-to-Test).

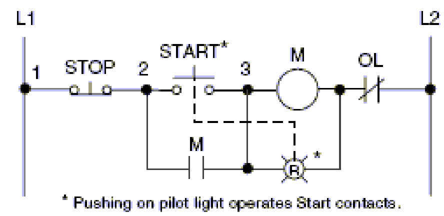


Fig. 20 Illuminated Push Button Indicator.

9. Fused Control Circuit Transformer (Fig.21)

Step down transformer is used to provide a control circuit voltage lower than line voltage. Over current protection is provided for the control circuit.

10. Fused Control Circuit Transformer and Control Relay (Fig.22)

This scheme is used with starter coils with high VA rating. A control relay CR with a low VA rating can be connected so the NO relay contact controls the starter coil on the line side.

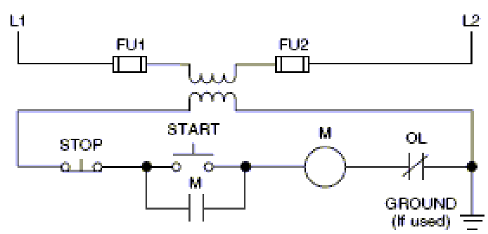


Fig. 21 Fused Control Circuit Transformer

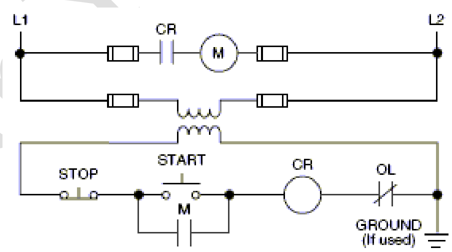


Fig. 22 Fused Control Circuit Transformer and Control Relay.

11. Jogging: Selector Switch & Start Push Button (Fig.23)

Jogging (inching) is a momentary operation of a motor from rest for the purpose of accomplishing small movements. The selector switch disconnects the holding circuit contact, then press the start pushbutton to jog.

12. Jogging: Selector Push Button (Fig.24)

In the run position, normal 3-wire control is accomplished. In the jog position, the holding circuit is broken, depressing the pushbutton to jog.

13. Jogging: Control Relay (Fig.25)

When the jog pushbutton is pressed, the starter coil M is energised and no holding circuit forms, thus jogging can be obtained.

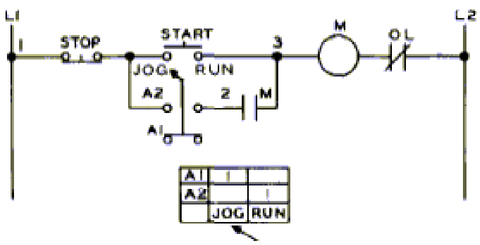


Fig. 23 Jogging.

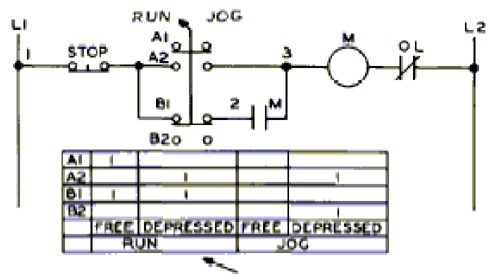


Fig. 24 Jogging with Selector Push Button

14. Jogging: Control Relay for Reverse Starter (Fig.26)

To jog the motor in the forward F or reverse R direction, whether the motor is at standstill or rotating.

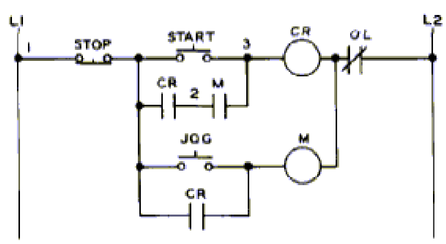


Fig. 25 Jogging with Control Relay.

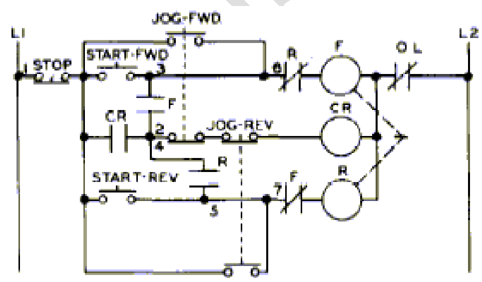


Fig. 26 Jogging with Control Relay for Reverse Starter.

15. Reverse Starting (Fig.27)

Forward-Reverse-Stop pushbutton station. Limit switches may be used to stop the motor at a certain point in either direction.

16. More than 1 starter, 1 Push Button Station Controls all (Fig.28)

To control more than one starter using only one start-stop station.

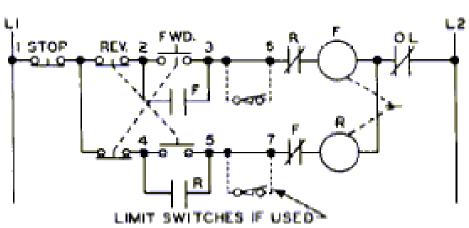


Fig.27 Reverse Starting.

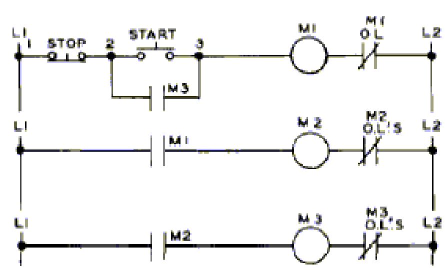


Fig.28 More than one starter control.

17. Reverse Starter Multiple Push Button Station (Fig.29)
In case of more than one forward-Reverse-Stop pushbutton station are required.

18. Reverse Starter + Pilot Lights Direction indicator (Fig.30)
Pilot lights are connected to indicate which direction the motor is running.

19. Multiple-station and alternate control (Fig.31)
To start and stop motors from more than one location. This can be done by wiring the stops in series and the starts in parallel. Note that only one seal contact is needed. Pressing any one-start button will energise the M contactor. Pressing any one-stop button will de-energise M and unseal the M contactor M-1.

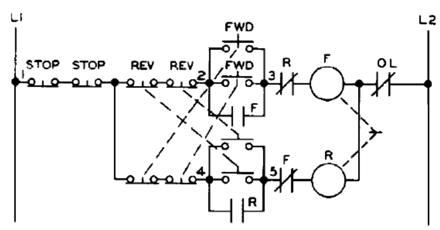


Fig. 29 Reverse Starter Multiple Push Button Station.

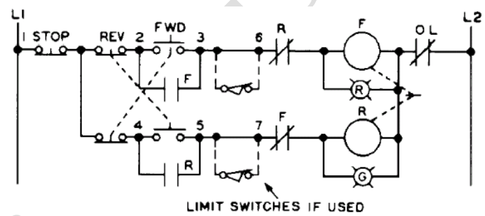


Fig. 30 Reverse Starter with Direction indicator.

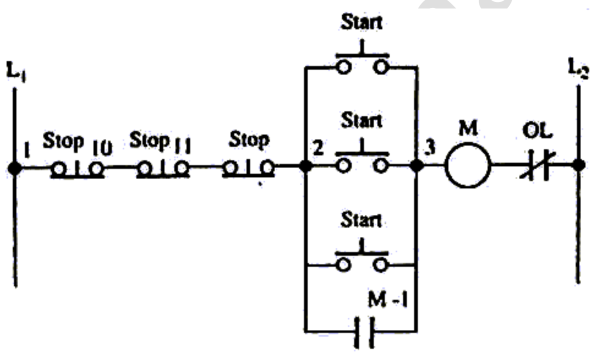


Fig. 31 Multiple Start/Stop control.

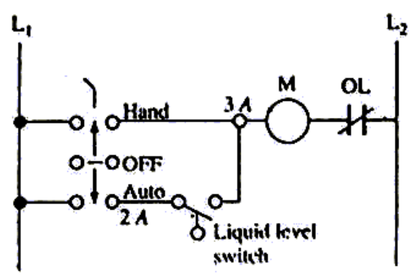


Fig. 32 Hand/Automatic control.

20. Hand/Automatic control (Fig.32)
A typical application is a sump pump. For normal daily operation, the pump should go ON when the liquid-level switch closes, indicating water is to be pumped out. For servicing or checking, the pump should stay OFF. For periodic checks to make sure the pump works, switching to hand position will make the pump run. If it does not run in the hand position, it will not run when it rains.

A three-position selector switch is used to select hand, OFF, or automatic. During normal operation, the switch is in the automatic position.

21. Start/stop seal control (Fig.33)

This kind of control is shown in Fig.35

22. Two speed motor starters (Fig.34)

The circuit is shown in Fig. 36 for both 3-phase and single-phase. The two contactors must be interlocked to prevent motor damage. There is a start button for each speed, and there is a master stop button. The high-speed and low-speed coils are electrically interlocked by NC contacts from the opposite coil. The CR relay and its circuit are included to make sure that the motor is started initially at low speed.

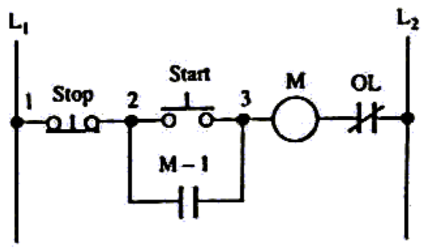


Fig. 33 Start/Stop Seal Control.

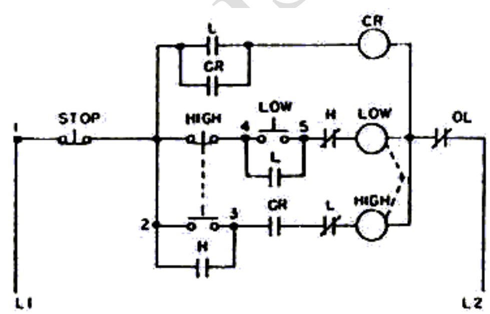


Fig. 34 Two speed magnetic starter.

23. Jogging control (Fig.35)

Jogging (inching) is a momentary-ON control capability with one pushbutton. Jogging is used for a final adjustment of a machine's position. Jogging can be accomplished by the use of a selector switch that disables the seal circuit as shown in Fig.35, for a normal start/stop seal, the selector closes a path from A_2 to 2 causes the start button to be a momentary-ON, or jog, button. The disadvantage of this circuit is that a selector has to be changed to choose between jog and seal-ON.

In some control circuits, it is desirable to choose either jog or seal-ON directly, like in Fig.38. Push jog and momentary operation continues as long as the jog push button is depressed. Release JOG and the motor goes OFF. Push start and the circuit seals ON. If the motor is running sealed, pushing jog turns it OFF, as the button leaves the top contact, the circuit is in the jog mode. This circuit is a questionable one to use. Suppose the jog push button is down. When it is let up, the motor is expected to go OFF. If the jog button returns up quickly, before M-1 opens, the motor will seal ON. This result is a particular possibility for a large contactor that drops out slowly. Therefore, this circuit is not generally used

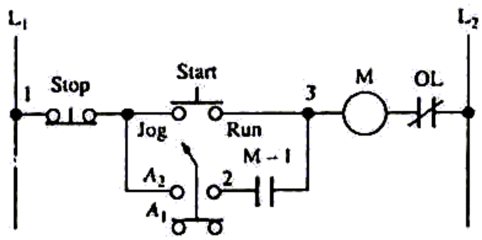


Fig. 35 Start/Stop /Jog control with selector switch.

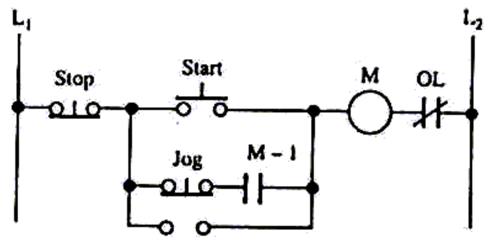


Fig. 36 Questionable Start/Stop /Jog circuit.

A better circuit, to prevent this unwanted seal-ON with the jog button return, is shown in Fig. 37. It is necessary to push stop to go from run/seal to jog, which was not required in the previous circuit. This circuit requires an added logic relay for the control circuit. Pressing start energised CR, which energised M through CR-2. Contacts CR-1 and M-1 complete the seal circuit. Depressing jog during running has no effect. If the motor is stopped, pushing jog causes M to go ON momentarily, with no possibility of sealing taking place

24. Pilot light indication

By wiring a light in parallel with the motor starting coil as shown in Fig.38. There are many possible pilot light configurations. This is shown in Figs.39a,b, where a push button is supplied to check the light (push-to-test), or another variation is the pilot light is ON when the motor is not ON.

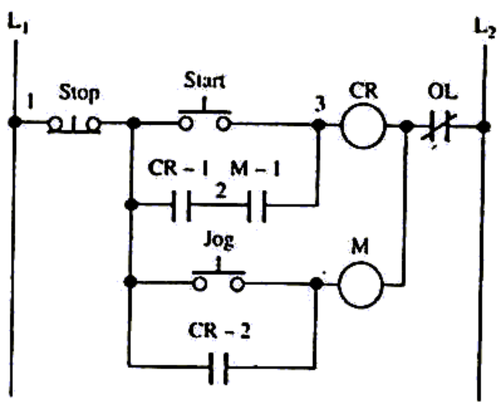


Fig. 37 Start/Stop /Jog control with selector switch.

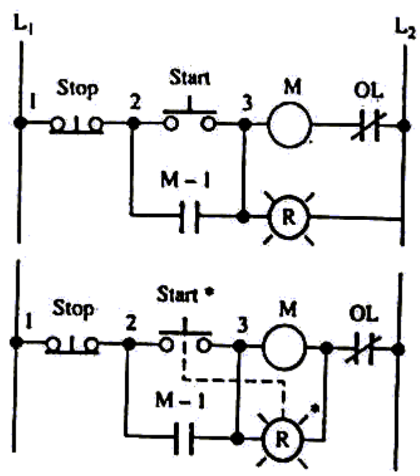


Fig. 38 Pilot lights for run indication.

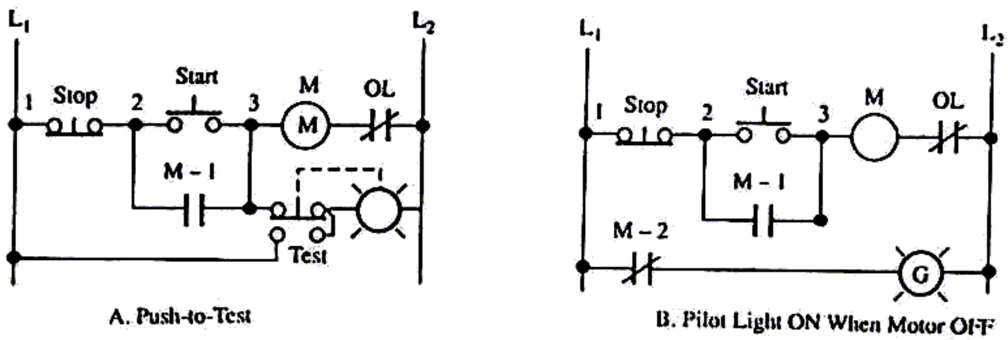


Fig. 39 Pilot light variations.

26. Dual Speed Motor Operation (Figs.40-41)

Two contactors, one for high speed and one for low speed are needed. The circuit in Fig. 44 can be started up in either low or high speed. Also, it can go directly from low to high speed. However, before the motor can go from high to low speed, stop must be pushed. If the motor is going at high speed, pressing the low-speed button will have no effect, as stop button must be depressed first.

The circuit in Fig.45 is used when the motor must start initially at low speed, e.g. a motor driving a big flywheel. This circuit requires an extra electromechanical relay for control (CR), called compelling relay. Pressing the high button will not start the motor initially, as contact CR-2 is open. However, if the motor has been running at low speed, the CR relay is energised and sealed. Contact CR-2 is closed. In that situation, pressing the high button runs off low (the upper section of the push button) and energises the high contactor. Note that the motor can be started in low when it is at rest.

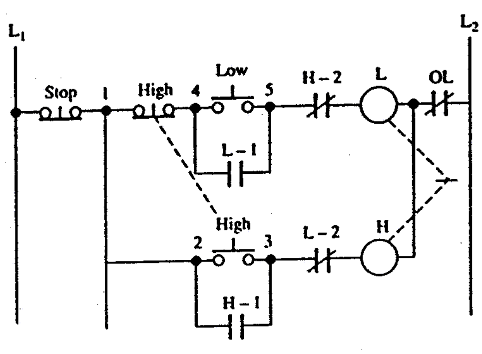


Fig. 40 Two-Speed control that requires low-speed start.

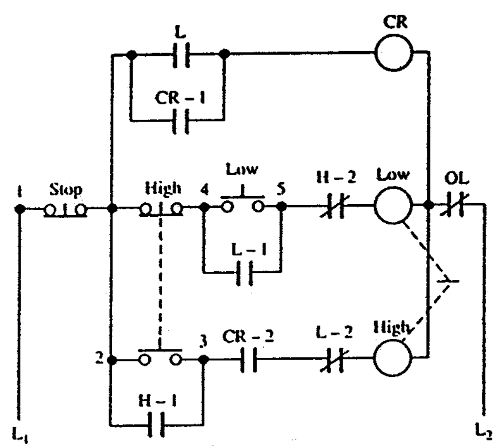


Fig. 41 Two-Speed control with Stop before High-to-Low.

27. Sequencing, Timing, Plugging, and Dynamic Braking (Figs.42-43)

The most common sequencing control type is making sure one output is ON before another can be turned ON. This is shown in Figs. 42-43. A milling machine must have lubrication flowing before it is turned ON. Starter M_1, the lube pump starter, is controlled by a start/stop seal system. Starter M_2, the milling machine starter, is controlled by a separate start/stop seal system. Note that M_2 cannot be started unless M_1 is started first, because of the M_1-2 contact. Furthermore, if M_1 goes OFF, M_2 is started first, because of the M_1-2 contact. Furthermore, if M_1 goes OFF, M_2 is turned OFF also, protecting the milling machine from lack of lubrication.

When a timed interval is needed between the energising of one starter and the energising of one or more others. The schemes shown in Fig. 12-16 are used. Both schemes use timers, in fig A, the output is to go ON a set time after the input switch is closed. When SW_1 is closed, the time is energised. After a period of time set on the timer, a timer contact closes the output's starter. In Fig. B, two outputs are involved. Contactor 1 comes ON when the start button is depressed, and it stays sealed ON. The timer coil, which is in parallel with the contactor 1 coil, comes ON at the same time. The timer runs for the set period of time. At the end of the time interval, a timer contact closure causes contactor 2 to energise

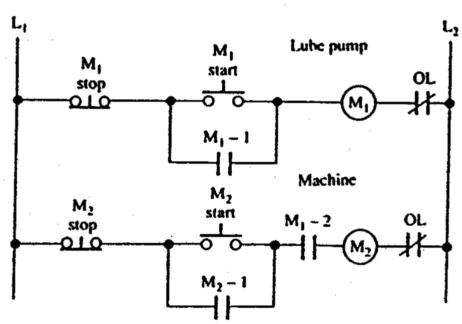


Fig.42 Interlock Sequence Control.

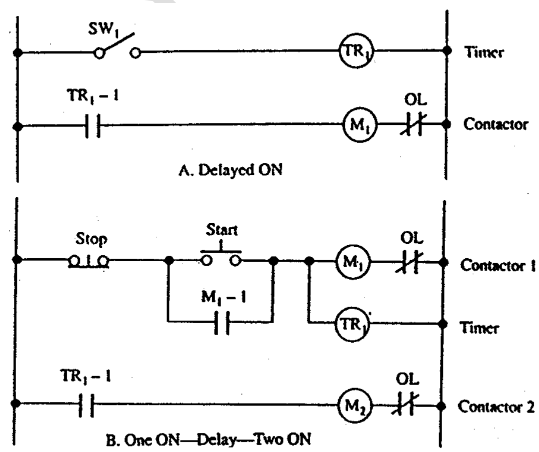


Fig.43 Timed Sequence Control.

28. Two Speed Starting (Fig.44)

Two speed starter with High-Low-Stop pushbutton station. Starting from rest at either speed or to change from low to high speed is possible. To change from high to low speed, the stop button must be operated first.

29. Two Speed Starting + Pilot light to indicate Motor Operation at Each Speed (Fig.45)

One pilot light is used to indicate low and high-speed operation.

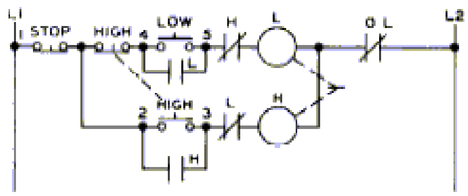


Fig.44 Two Speed Starting

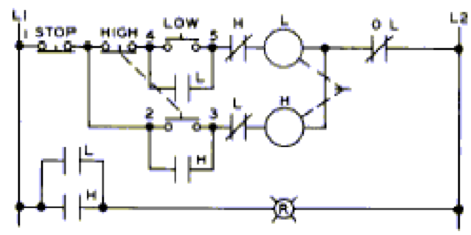


Fig.45 Two Speed Starting with pilot light indicator.

2.6 Development of Control Circuits

1. Automatic control of a water pump

A pump which pumps water from a storage tank into a pressure tank, as shown in Fig. 46. It has the following features

1. The START button is pushed whenever the water is too low in the pressure tank. (b). The pump is allowed to run until the tank is observed to be full. The operator then pushes the STOP button.
2. A float switch FS1 is installed in the pressure tank near the top so that the operator need only press the START button, thus energising the pump and starting water to flow into the tank. When the level of the water has reached float switch 1, its contacts will be opened, thus stopping the pump and the flow of water (c).
3. A float switch FS2 is installed to maintain the lower level of the tank. This version of the control circuit requires that the pump be started whenever the water reaches a predetermined low level. (d)
4. A control to prevent the pump from starting whenever the storage tank is low in water (float switch FS3 to sense the extreme low level of water in the storage tank and to open a set of contacts whenever the water in the stage tank reached the desired low level). It must prevent its starting whenever the water is low. It must also stop the pump if it is running and the water reaches this low level in the stage tank (e).

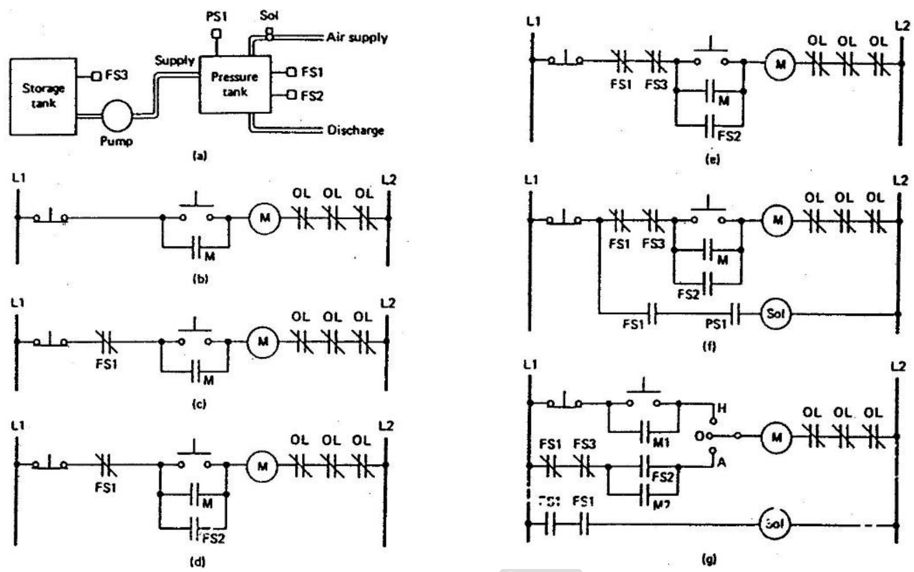
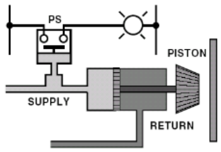


Fig.46 Automatic control of water pump.

5. A pressure is exerted on the storage tank by the addition of the proper amount of air to the top of the tank (Sol). Air must be let into the tank only when the water level is at its highest position and the pressure is under the desired discharge pressure of the tank (f). This pressure switch will perform the function of start for the solenoid valve. When the pressure is lower than the set point of the pressure switch, its contacts must close and complete the circuit through it to the solenoid. If, however, the water is below its top level when the pressure drops, we do not want the solenoid valve to open. FS1 is of the double-pole type having one NO and one NC set of contacts can be wired as fig (f). The circuit for the solenoid valve is a two-wire control circuit requiring that both FS1 and pressure switch PS1 is closed in order that wire will be placed in the tank by the energising of the solenoid valve.



CHAPTER 3

Electromechanical Relays

3.1 Overview

An electromechanical relay (Fig.1) uses a physical moving part to connect contacts within the output component of the relay. The movement of this contact is generated using electromagnetic forces from the low-power input signal, allowing the completion of the circuit that contains the high-power signal.

Definitions:

a. A solenoid is a device that produces mechanical motion from the energization of an elec-tromagnet coil. The movable portion of a solenoid is called an armature.
b. A relay is a solenoid set up to actuate switch contacts when its coil is energized.
c. Pull-in current is the minimum amount of coil current needed to actuate a solenoid or relay from its "normal" (de-energized) position.
d. Drop-out current is the maximum coil current below which an energized relay will return to its "normal" state.

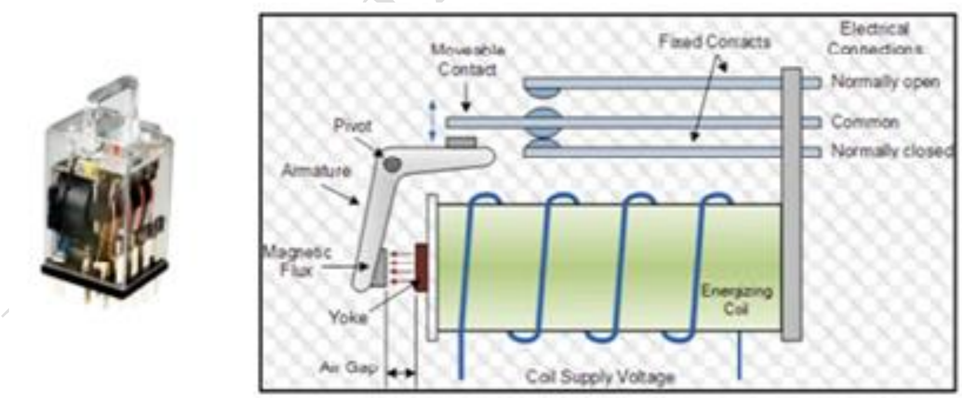


Fig.1 An electromechanicsl relay.

3.1.1 Types of Relays

Relays may be classified in several ways (Figs.2&3) but here we look at their logical performance. In other words, the fundamental type of relay is determined by its function. One functional classification system is given below:

1. Magnitude Relays.
2. Directional Relays.
3. Ratio Relays.
4. Differential Relays.
5. Pilot Relays.

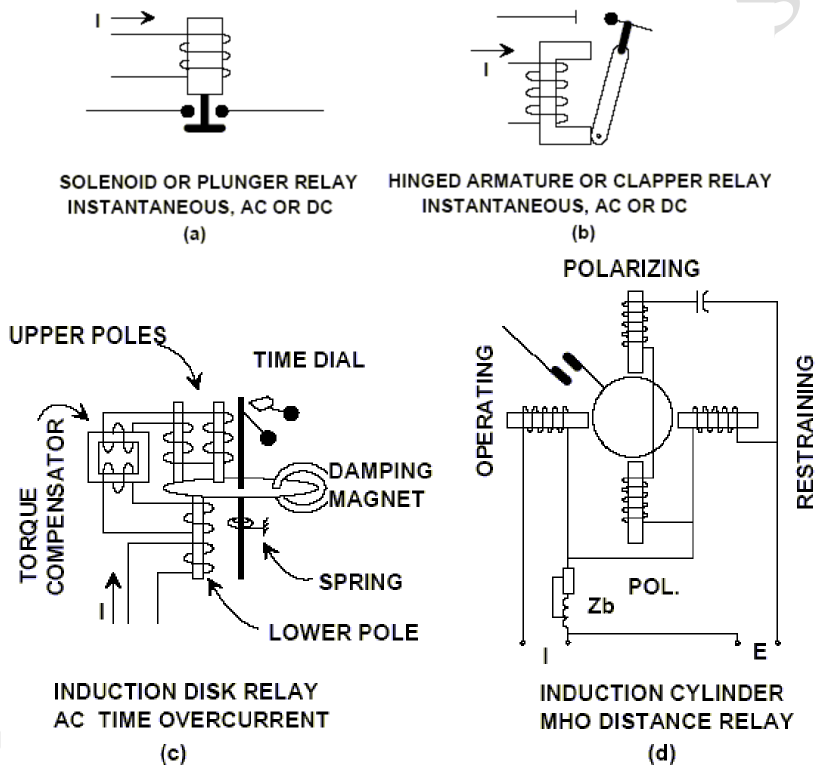


Fig.2 Several common types of electromechanical relays.
(a) Solenoid or plunger relay instantaneous, AC or DC.
(b) Hinged armature or clapper relay instantaneous, AC or Dc.
(c) Induction disk relay AC time overcurrent.
(d) Induction cylinder MHO distance relay.

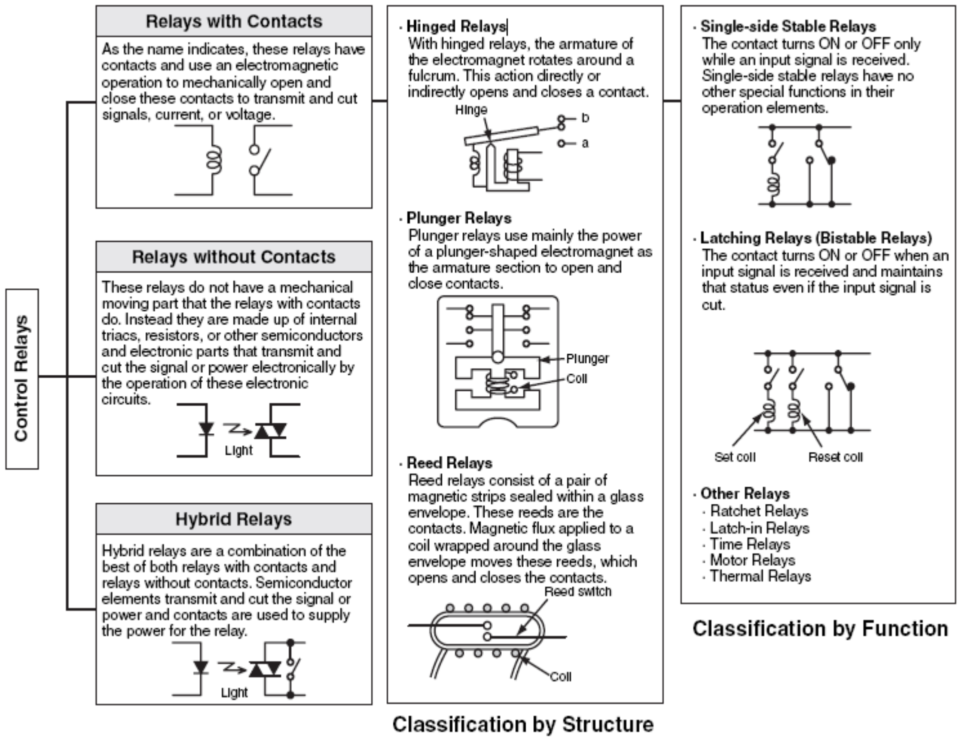


Fig.3 One way to classify relays. (Relays without contacts are not Included).

3.1.2 Linear Electromechanical & Rotary Solenoid (Actuators)

Both types of solenoid, linear and rotational (Figs.4-10) are available as either a holding (continuously energised) or as a latching type (ON-OFF pulse) with the latching types being used in either energised or power-off applications.

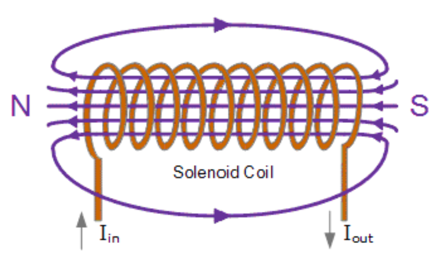


Fig.4 Magnetic Field produced by a Coil.

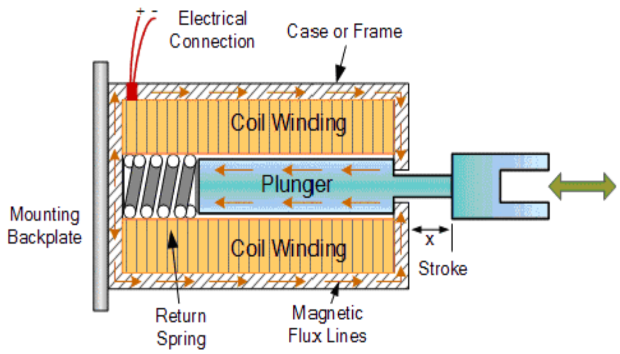


Fig.5 Pull-type Linear Solenoid Construction.

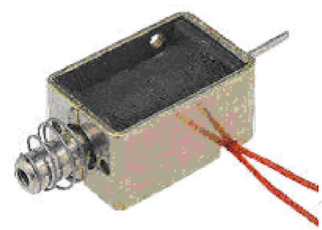


Fig.6 Linear Solenoid.

1. **Linear electromechanical Solenoid (actuator):** Linear solenoids can also be designed for proportional motion control were the plunger position is proportional to the power input. When electrical current flows through a conductor it generates a magnetic field, and the direction of this magnetic field with regards to its North and South Poles is determined by the direction of the current flow within the wire. This coil of wire becomes an “Electromagnet” with its own north and south poles exactly the same as that for a permanent type magnet. The strength of this magnetic field can be increased or decreased by either controlling the amount of current flowing through the coil or by changing the number of turns or loops that the coil has. An example of an “Electromagnet” is shown in Figs.5&6. When an electrical current is passed through the coils windings, it behaves like an electromagnet and the plunger, which is located inside the coil, is attracted towards the centre of the coil by the magnetic flux setup within the coils body, which in turn compresses a small spring attached to one end of the plunger (Figs.7-10). The force and speed of the plungers movement is determined by the strength of the magnetic flux generated within the coil. When the supply current is turned “OFF” (de-energised) the electromagnetic field generated previously by the coil collapses and the energy stored in the compressed spring forces the plunger back out to its original rest position. This back and forth movement of the plunger is known as the solenoids “Stroke”, in other words the maximum distance the plunger can travel in either an “IN” or an “OUT” direction, for example, 0 – 30mm. Linear solenoids are useful in many applications that require an open or closed (in or out) type motion such as electronically activated door locks, pneumatic or hydraulic control valves, robotics, automotive engine management, irrigation valves to water the garden and even the “Ding-Dong” door bell has one. They are available as open frame, closed frame or sealed tubular types.

2. **Rotary Solenoids:** that produce an angular or rotary motion from a neutral position in either clockwise, anti-clockwise or in both directions (bi-directional). Rotary solenoids can be used to replace small DC motors or stepper motors were the angular movement is very small with the angle of rotation being the angle moved from the start to the end position.

Commonly available rotary solenoids have movements of 25, 35, 45, 60 and 90° as well as multiple movements to and from a certain angle such as a 2-position self restoring or return to zero rotation, for example 0-to-90-to-0°, 3-position self restoring, for example 0° to +45° or 0° to -45° as well as 2-position latching. Their construction consists of an electrical coil wound around a steel frame with a magnetic disk connected to an output shaft positioned above the coil. When the coil is energised the electromagnetic field generates multiple north and south poles which repel the adjacent permanent magnetic poles of the disk causing it to rotate at an angle determined by the mechanical construction of the rotary solenoid. Rotary solenoids are used in vending or gaming machines, valve control, camera shutter with special high speed, low power or variable positioning solenoids with high force or torque are available such as those used in dot matrix printers, typewriters, automatic machines or automotive applications etc.

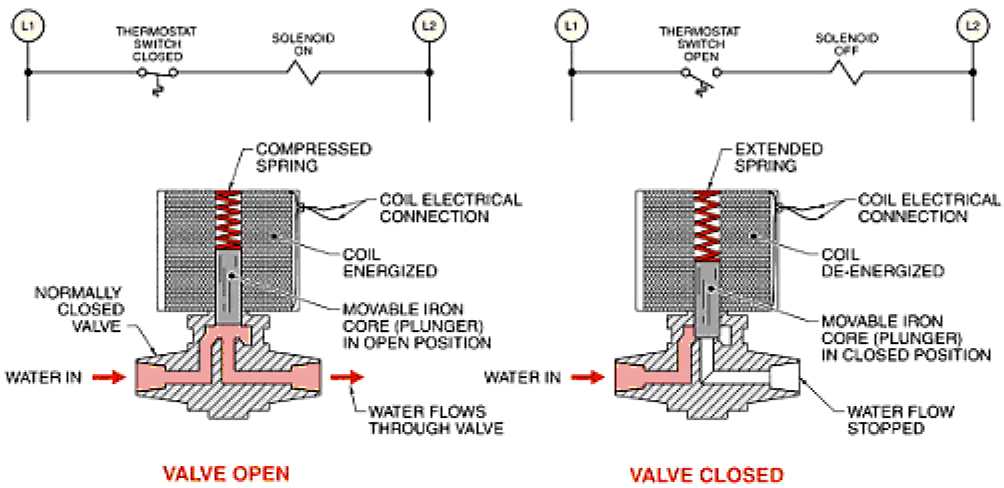


Fig.7 Solenoid valves. Solenoids activate a switch or valve using a movable iron core (plunger).

Fig.8 Rotary Solenoid.

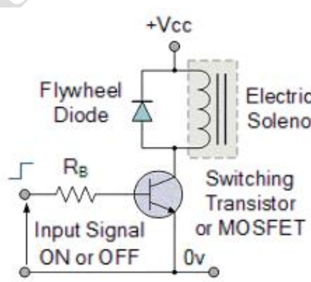


Fig.9 Switching Solenoids using a Transistor.

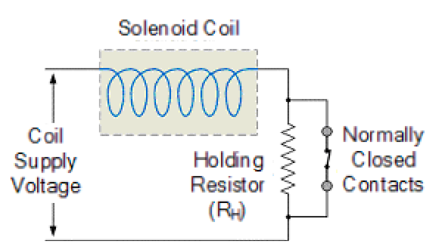


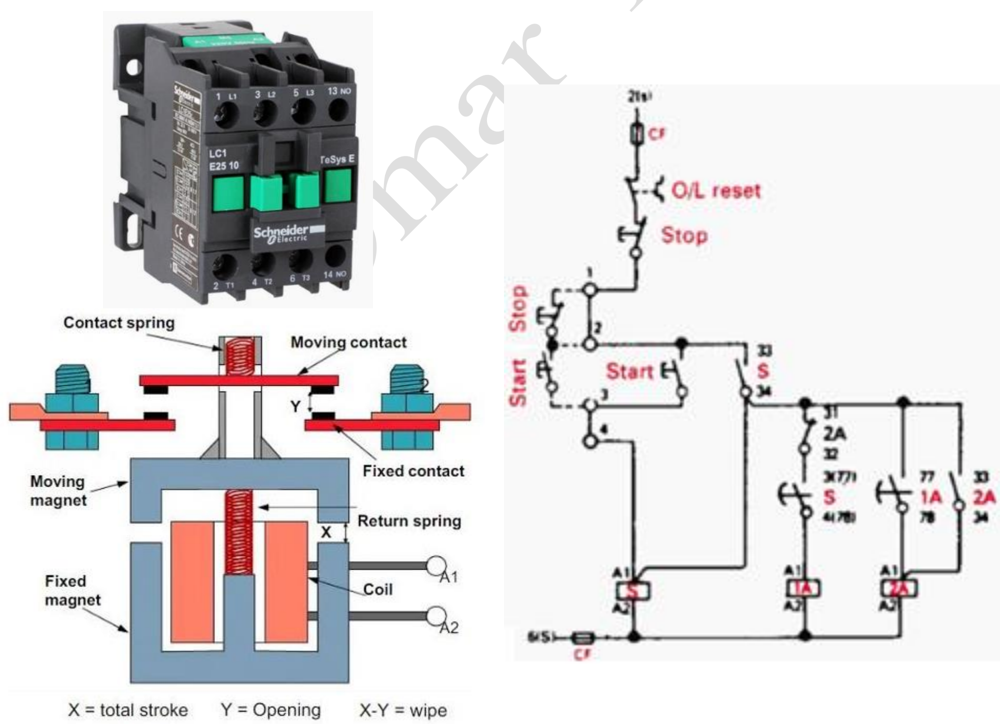
Fig.10 Reducing Solenoid Energy Consumption.

3. Contactor-The Switching Device

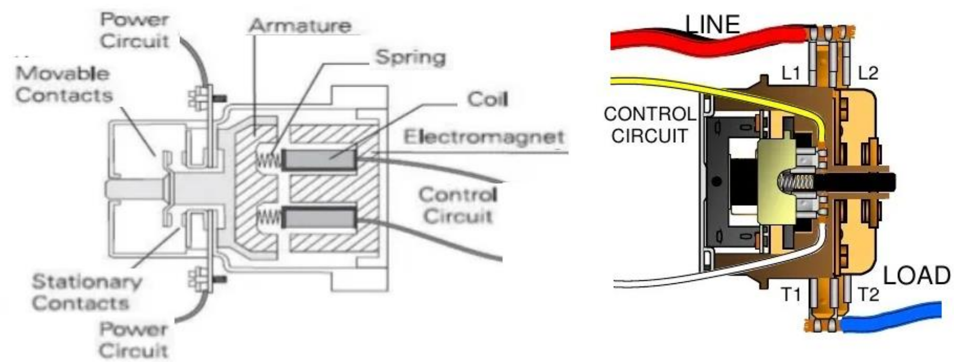
The most widespread switching device used in a starter is the a.c. air-break contactor (Figs.11a,b,c) which consists of contact assemblies actuated by electromagnetic action. An operating coil is enclosed by the magnetic yoke, and when energized attracts an armature to which is attached a set of moving contacts which make with a set of stationary contacts.

The contactor is magnetically held closed by maintaining the current flow through the coil. If the voltage to the coil fails or falls below a defined level, the contactor opens, thus disconnecting the motor from the supply. The coil must be constantly energised in order to keep the contactor closed. Alternatively, contactors can be fitted with a mechanical latch which does not require continuous energisation. Keeping in mind the following:

a. A contactor is a large relay, usually used to switch current to an electric motor or other high-power load.
b. Large electric motors can be protected from overcurrent damage through the use of over-load heaters and overload contacts. If the series-connected heaters get too hot from excessive current, the normally-closed overload contact will open, de-energizing the contactor sending power to the motor.



a. Contactor simplified construction, and typical motor starting control circuit.



b. Contactor construction and cutaway.

Utilization Category		Current as multiples of operational current			
		Normal Operation		Proving Operation	
		make	break	make	break
AC1	Non-inductive or slightly inductive loads such as furnaces and heating loads	1	1	1.5	1.5
AC2	Starting of slip ring motors. Plugging with rotor resistance in circuit	2.5	2.5	4	4
AC3	Starting of cage motors, switching of motors during running	6	1	10	8
AC4	Starting of cage motors, plugging inching	6	6	12	10

c. Contactor utilization categories.

Fig.11 Features of a typical contactor.

3.2 Time-Delay Relays

Time delay relays (Figs.12-13) are built in these four basic modes of contact operation:

1: Normally-open, timed-closed. Abbreviated ”NOTC”, these relays open immediately upon coil de-energization and close only if the coil is continuously energized for the time duration period. Also called normally-open, on-delay relays.

2: Normally-open, timed-open: Abbreviated ”NOTO”, these relays close immediately upon coil energization and open after the coil has been de-energized for the time duration period. Also called normally-open, off delay relays.

3: Normally-closed, timed-open. Abbreviated "NCTO", these relays close immediately upon coil de-energization and open only if the coil is continuously energized for the time duration period. Also called normally-closed, on-delay relays.

4: Normally-closed, timed-closed. Abbreviated "NCTC", these relays open immediately upon coil energization and close after the coil has been de-energized for the time duration period. Also called normally-closed, off delay relays.

5. One-shot timers provide a single contact pulse of specified duration for each coil energization (transition from coil off to coil on).

6. Recycle timers provide a repeating sequence of on-off contact pulses as long as the coil is maintained in an energized state.

7. Watchdog timers actuate their contacts only if the coil fails to be continuously sequenced on and off (energized and de-energized) at a minimum frequency.

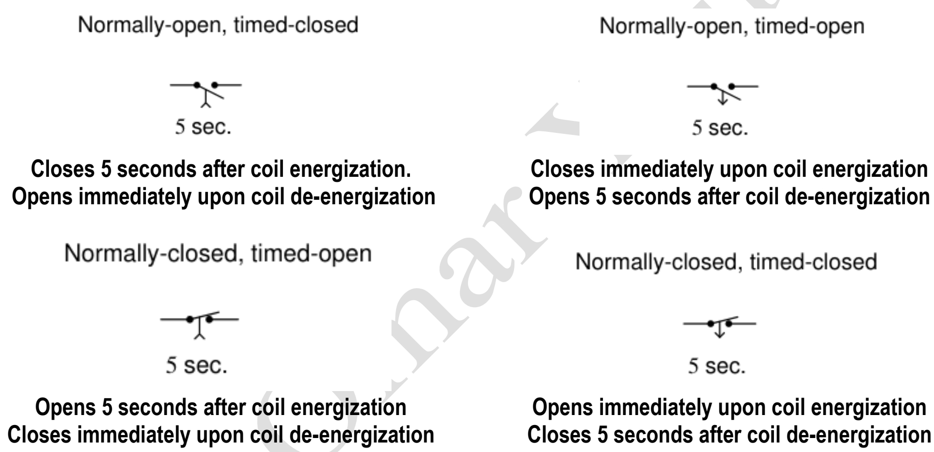
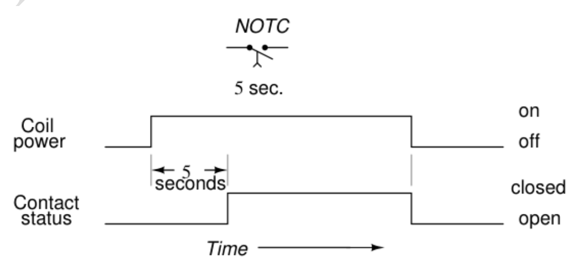


Fig.12 Time delay relay symbols.



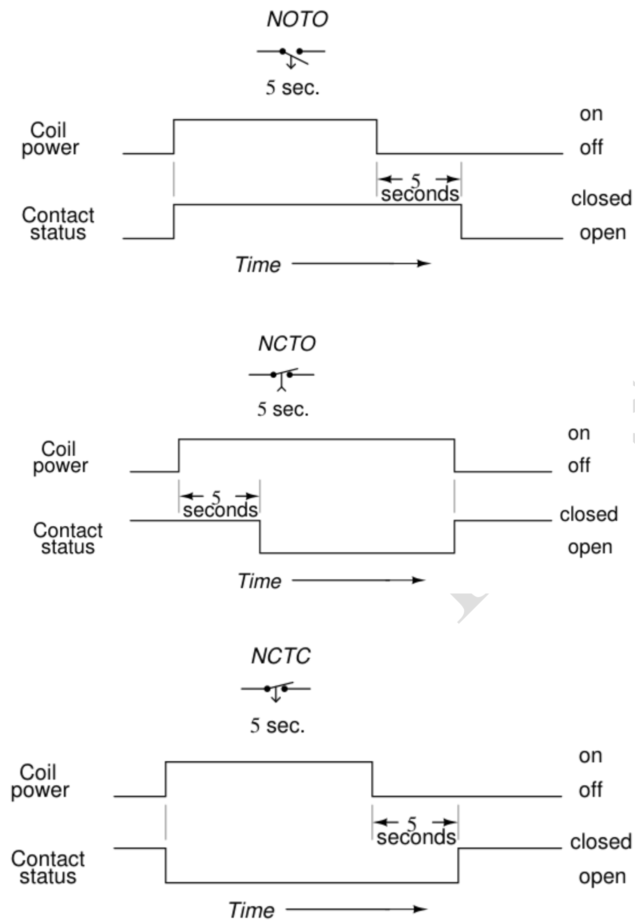


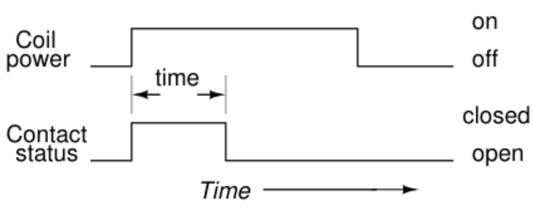
Fig.13 Timing diagrams of time-delay relays.

Time-delay relays are very important for use in industrial control logic circuits. Some examples of their use include:

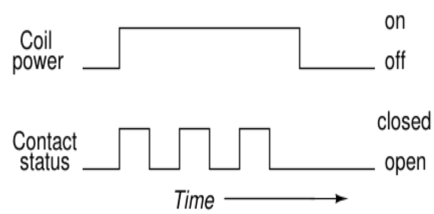
1. Flashing light control (time on, time off): two time-delay relays are used in conjunction with one another to provide a constant-frequency on/off pulsing of contacts for sending intermittent power to a lamp.
2. Engine autostart control: Engines that are used to power emergency generators are often equipped with "autostart" controls that allow for automatic start-up if the main electric power fails. To properly start a large engine, certain auxiliary devices must be started first and allowed some brief time to stabilize (fuel pumps, pre-lubrication oil pumps) before the engine's starter motor is energized. Time-delay relays help sequence these events for proper start-up of the engine.

3. Furnace safety purge control: Before a combustion-type furnace can be safely lit, the air fan must be run for a specified amount of time to ”purge” the furnace chamber of any potentially flammable or explosive vapors. A time-delay relay provides the furnace control logic with this necessary time element.
4. Motor soft-start delay control: Instead of starting large electric motors by switching full power from a dead stop condition, reduced voltage can be switched for a ”softer” start and less inrush current. After a prescribed time delay (provided by a time-delay relay), full power is applied.
5. Conveyor belt sequence delay: when multiple conveyor belts are arranged to transport material, the conveyor belts must be started in reverse sequence (the last one first and the first one last) so that material doesn't get piled on to a stopped or slow-moving conveyor. In order to get large belts up to full speed, some time may be needed (espec ially if soft-start motor controls are used). For this reason, there is usually a time-delay circuit arranged on each conveyor to give it adequate time to attain full belt speed before the next conveyor belt feeding it is started.

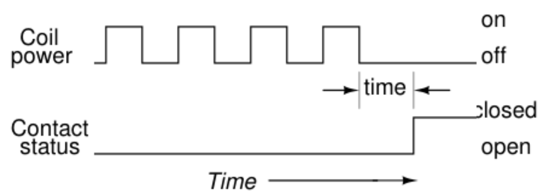
The older, mechanical time-delay relays used pneumatic dashpots or fluid-filled piston/cylinder arrangements to provide the ”shock absorbing” needed to delay the motion of the armature.Newer designs of time-delay relays use electronic circuits with resistor-capacitor (RC) networks to generate a time delay, then energize a normal (instantaneous) electromechanical relay coil with the electronic circuit's output. The electronic-timer relays are more versatile than the older, mechanical models, and less prone to failure. Many models provide advanced timer features (Fig.14) such as ”one-shot” (one measured output pulse for every transition of the input from de-energized to energized), ”recycle” (repeated on/off output cycles for as long as the input connection is energized) and ”watchdog” (changes state if the input signal does not repeatedly cycle on and off).
The ”watchdog” timer is especially useful for monitoring of computer systems. If a computer is being used to control a critical process, it is usually recommended to have an automatic alarm to detect computer ”lockup” (an abnormal halting of program execution due to any number of causes). An easy way to set up such a monitoring system is to have the computer regularly energize and de-energize the coil of a watchdog timer relay (similar to the output of the ”recycle” timer). If the computer execution halts for any reason, the signal it outputs to the watchdog relay coil will stop cycling and freeze in one or the other state. A short time thereafter, the watchdog relay will ”time out” and signal a problem.



"One-shot" normally-open relay contact



"Recycle" normally-open relay contact



"Watchdog" relay contact

Fig.14 Electronic-timer relays

3.3 Timing Relays Applications

1. Consequent Motors Starting

The elementary diagram shown in Fig.15 describes how to start motor No. 2 after motor No. 1 is started, and to trip both motors simultaneously. Pushing the start button: energises both the starter coil, 1M, and the timer coil, TR; the hold-in contacts, 1M, close and maintain the circuit after the start button is released. After the on-delay timer coil is energised, the timing begins. At the end of the timing period, the normally open contact closes, which energises the starter coil, 2M. Pushing the stop button trips both motors simultaneously.

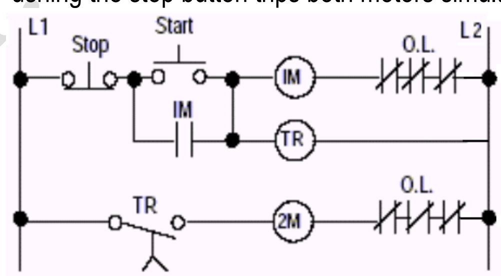


Fig.15 Consequent motors starting.

2. Consequent Motors Stopping

The circuit shown in Fig.16 indicates that coil 1M must be energised before coil 2M is able to hold itself in. Each coil is energised by its own start button and can be tripped immediately by its own stop button. Timer TR is used in an off-delay mode, which causes coil 2M to de-energise in a fixed amount of time after coil 1M is dropped out.

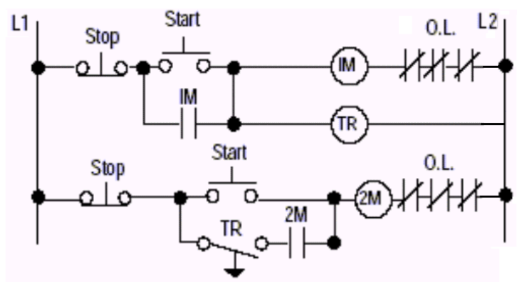


Fig.16 Consequent motors stopping.

3. Sequence Timing

Fig. 17 indicates that after starter 1M is de-energised, timer TR is used in the off-delay mode. This allows starter coil 2M to remain energised for a predetermined time.

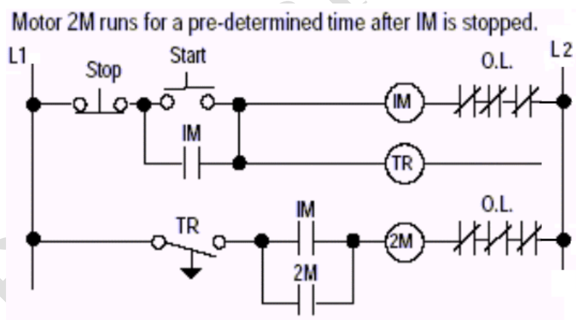


Fig.17 Sequence timing I.

4. Sequence Timing

With the N.C., instantaneous contact [TR (inst.)] on the timer TR shown in Fig.18, the starter coil 2M cannot be energised when the timer is energised. After starter coil 1M and the time coil TR are de-energised, coil 2M will be energised and will remain so until the pre-set time delay has elapsed. Timing relay TR must be pneumatic, because the off-delay must function without power.

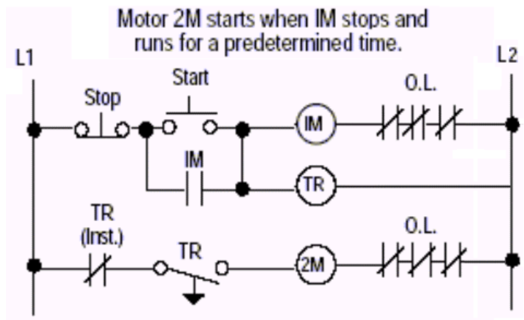


Fig.18 Sequence timing II.

5. Timed Plugged Stop

This timer shown in Fig.19 is used in the off-delay mode in conjunction with reversing starters. When the stop button is pushed, the reverse contactor is energised. The timer should be set to hold the reverse contactor in just long enough to bring the motor to a complete stop.

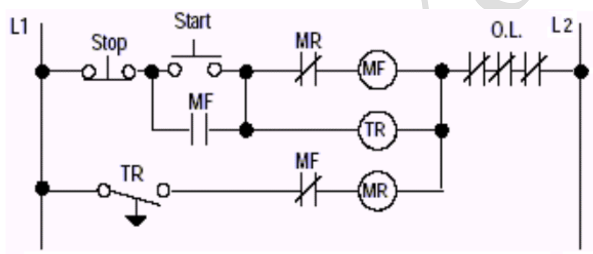


Fig.19 Timed Plugged Stop.

6. Anti-plug Protection

The circuit shown in Fig.20 employs a timer in the off-delay mode to prevent manual plugging of the motor.

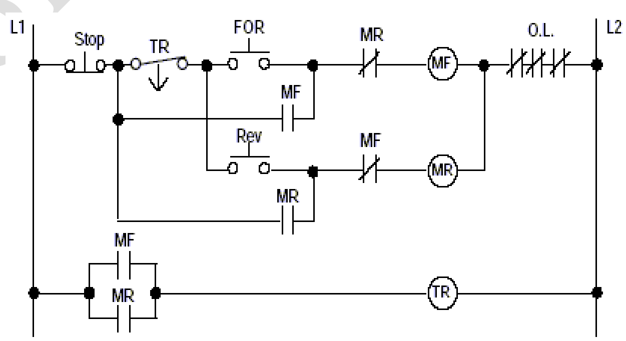


Fig.20 Anti-plug Protection.

7. Backspin Protection (2-wire control)

The timer shown in Fig.21 is used in the off-delay mode to prevent restarting the motor immediately, e.g. an impeller type pump with a stand pipe would be driven in reverse (when stopped) by the water in the stand pipe. The timer prevents restarting the pump until this reverse action on the impeller is stopped.

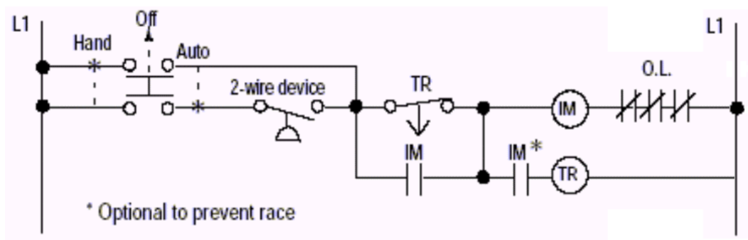


Fig.21 Backspin Protection (2-wire control).

8. Backspin Protection (3-wire control)

The circuit shown in Fig.22 demonstrates the same protection concept illustrated in Fig. 7, but by using 3-wire control.

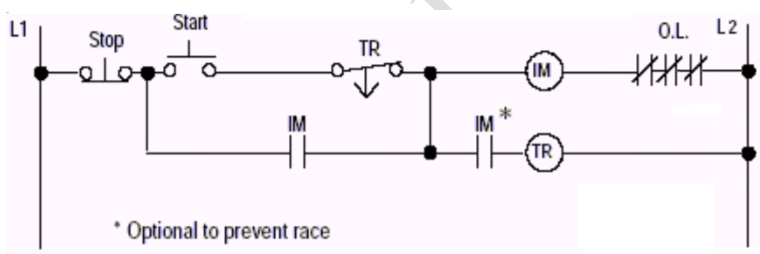


Fig.22 Backspin Protection (3-wire control).

9. Delayed Return

The circuit shown in Fig.23 can be used if the operation of a machine such as a drill press requires a dwell at the end of the down stroke before it can return to the rest position. Limit switches 1LS and 2LS control the forward and reverse functions, and the timer TR controls the length.

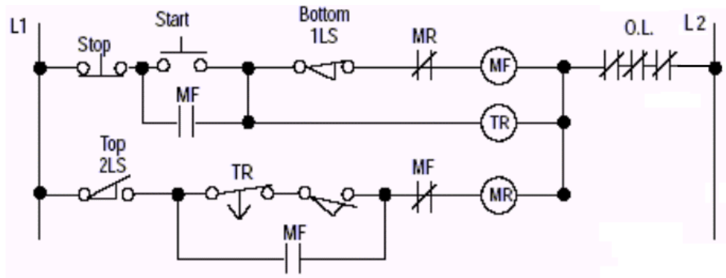


Fig.23 Delayed Return.

10. Lubrication Pump Sequence

For this application, an on- and off-delay timer is necessary. As shown in Fig.24, this timer is used to ensure that the lubricating motor 1M, is running before the main motor, 2M, starts, and that motor 1M still runs after the main motor has stopped.

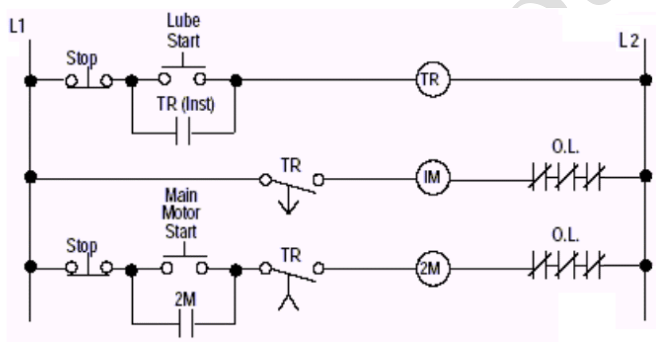


Fig.24 Lubrication Pump Sequence.

3.4 Solid-State Timers

Solid State Timers come in many shapes and sizes. The most common timers used in industry: ON-delay solid-state timers and the OFF delay solid-state timers.

a. ON Delay Timer Connection

The on-delay solid-state timer relay (Fig.25) is a two-piece device in which one part of the device is the base and the other is the time relay. The base of the on-delay timer is interchangeably used with control relays. The base has eight pin holes, see figure 1, and a keyhole to ensure proper placement. The pin layout, shown in Fig.26, of the ON delay timer, works as follows:

- Pin 7 and 2 are the coil terminals

- Pin 8 and 1 are the common terminals for the two sets of contacts
- Pin 3 is normally open contact and common to pin one.
- Pin 4 is a normally closed contact and common to pin one
- Pin 6 is a normally open contact and is common and to pin eight
- Pin 5 is a normally closed contact and common to pin eight

b. OFF Delay Timer Connection

The off delay timer (Fig.26) is much like the on delay timer relay except it has 11 pins instead of the eight pins. The base of the off delay timer has 11 terminals to connect the control wires of the control system. It also contains 11 female pin holes and a female keyhole to ensure the device is seated properly. The off delay unit has a dial to adjust and set the preset time and 11 male pins and a male key way for proper connection to the base.

The off delay relay pin layout, operates as follows:

- Pin 2 and 10 are the coil terminals.
- Pin 1 and 11 are the common terminals to the two sets of contacts
- Pin 3 is a normally open contact that is common to pin 1
- Pin 4 is a normally closed contact, and to pin 1
- Pin 9 is a normally open contact common to pin 11
- Pin 8 is a normally closed contact common to pin 11
- Pins 5 and 6 is the internal circuit used to trigger the off delay timer.
- Pin 7 is not used

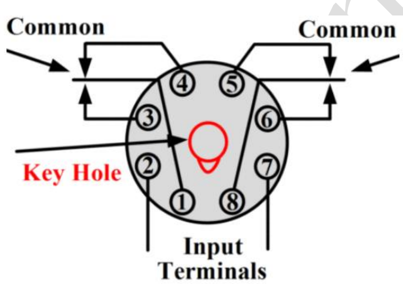


Fig.25 ON Delay Pin Layout.

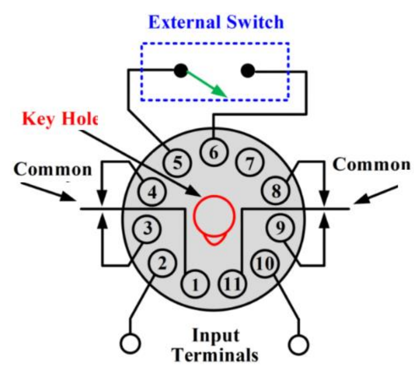


Fig.26 OFF Delay Pin Layout.

Solid state timers- also known as solid state relays or solid state timer relays—are used in numerous electrical and electronic devices to control of a wide variety of resistive and inductive loads. The performance characteristics and other numerous benefits of solid state timers over their electromechanical counterparts make them ideal for a broader range of switching applications such as:

1. Heaters
2. Lights
3. Motors
4. Motion control devices

These different types of timers allow switching operations to be performed at different times—either instantaneously or delayed—depending on the position of the voltage on the AC sine wave. Some of the most common types of solid state timers include:

1. Zero-switching relays are the most common type of timer relays used currently. These switches turn on the load when the control voltage is applied and the voltage crosses the zero point on the AC sine wave, resulting in a slight delay of the turn-on of the solid-state timer. The load is switched off when the control voltage in the relay is removed.
2. Instant-on switches, on the other hand, turn on the load immediately when the control voltage is activated. Therefore, the load is turned on at any point of the sine wave making it ideal for precise control applications.
3. Peak-switching timer relays, as their name implies, turn on the load when the control voltage is activated, and the voltage of the load is at the peak position on the sine wave. As with the other relays, the relay turns off when the control voltage is removed.

<u>1. Definitions (Figs.27-30)</u>

a. Key

T: is the set time delay

T: is a timing cycle less than the set time. (t) Can reflect that a reset signal has been applied or power has been removed prior to completion of the time delay a gate signal has been applied which momentarily interrupts the timing cycle.

Tt: is the completion of the time delay after the gated signal is removed.

X: is the duration of the gate signal

b. Contact Inputs (R, S, G):

For optimum reliability use external switches that are designed for low level switching.

c. Solid-state Signal Inputs (R, S, G):

Proximity switch, photoelectric switch, etc

<u>2. Timing Relay Terminals</u>

1. (I) Input Power (terminals 2 & 10)	- Power to terminals 2 and 10 must be applied continuously. The time delay and output contact can reset immediately upon removal of power. – For a DC power supply, the positive (+) must be connected to terminal 10.
2. (S) Start Signal (terminals 2 and 6)	-A signal must be applied across terminals 2 and 6 to start the timing interval. This signal can be either momentary or maintained.
3. (R) Reset Signal (terminals 2 and 7)	-The reset signal is not required for normal operation. Reset can be accomplished by removing power from terminals 2 and 10.

- To reset the timer without removing power, a signal must be applied across 2 and 7 which resets the timing cycle and returns the output contacts to their shelf state.
- The reset signal will override both the start signal and gate signal.
- The reset signal can be either momentary or maintained.

4. (G) Gate Signal (terminals 2 and 5) Signal Gate Pause

-The gate signal is not required for normal operation.
- The gate signal provides a pause or retentive timing function. When a signal is applied across terminals 2 and 5 the timing cycle is momentarily interrupted. When the signal is removed, the timing cycle resumes timing at the point the cycle was interrupted and will continue timing until the time delay is completed or the gate signal is re-applied.

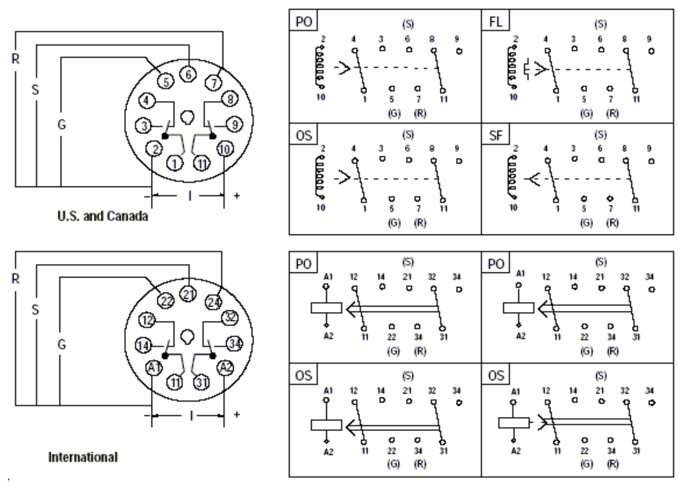


Fig.27 Timing relays symbols.
PO: Signal (On-delay) , SF: Signal (Off-delay), L: Flicker (Repeat Cycle) , OS: One Shot
Signals S, R, and G are typically contact closures

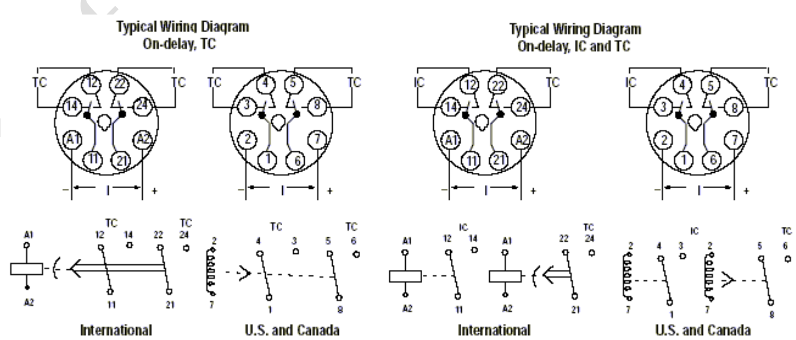


Fig. 28 Solid state timers wiring diagrams.
(I) Input Power (terminals 2 and 7). IC = Instantaneous Contacts. TC = Timed Contacts.

3. Timing Relay Construction

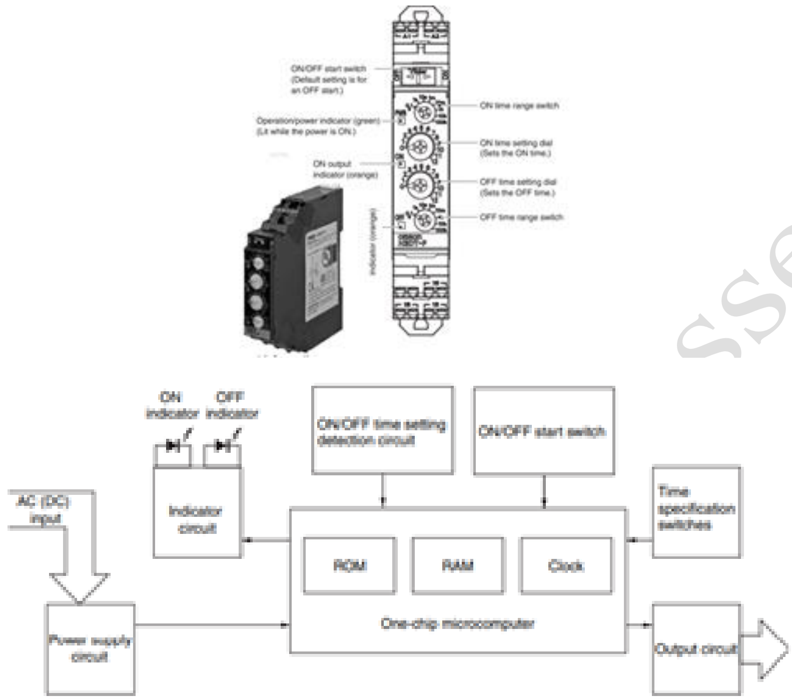
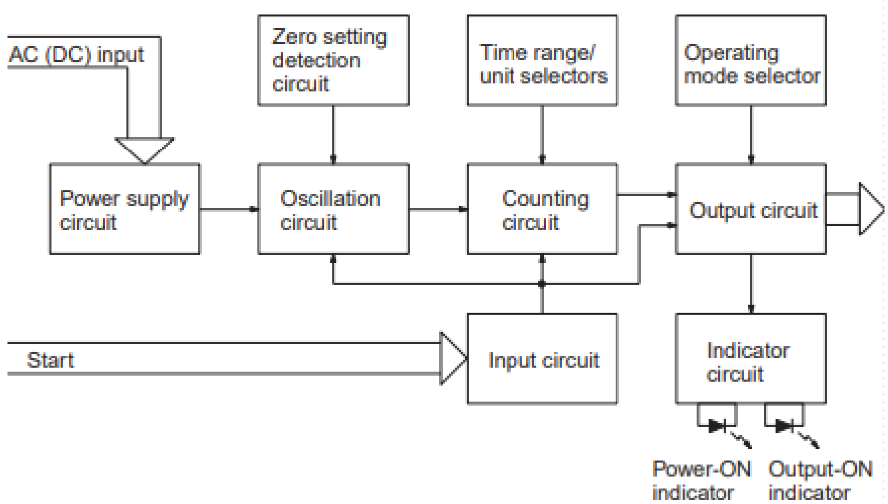


Fig.29 A typical solid state timer block diagram and front view.



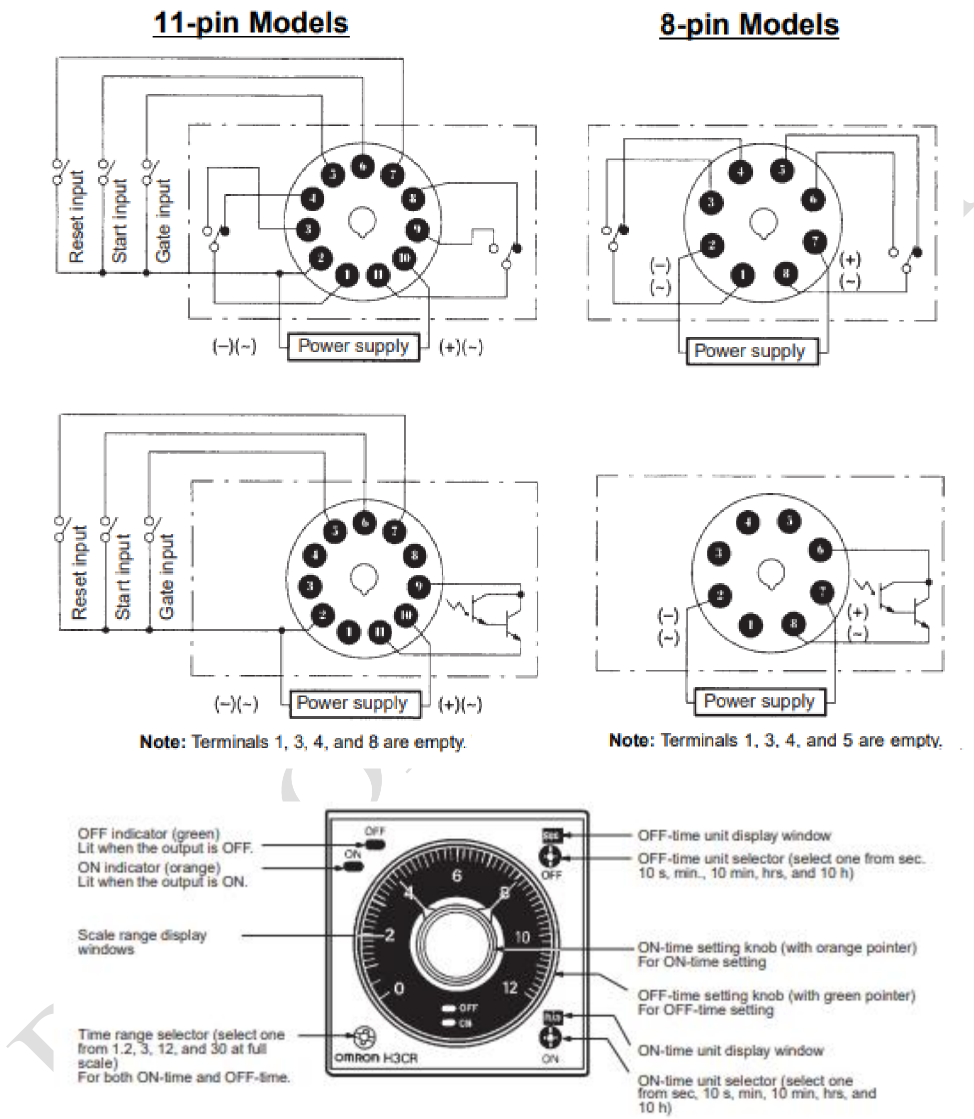


Fig30 Solid state timer feature.

3.5 Solid State Relays

Unlike electro-mechanical relays (EMR) which use coils, magnetic fields, springs and mechanical contacts to operate and switch a supply, the solid state relay, or SSR, has no moving parts but instead uses the electrical and optical properties of solid state semiconductors to perform its input to output isolation and switching functions.

Just like a normal electro-mechanical relay, SSR's provide complete electrical isolation between their input and output contacts with its output acting like a conventional electrical switch in that it has very high, almost infinite resistance when nonconducting (open), and a very low resistance when conducting (closed). Solid state relays can be designed to switch both AC or DC currents by using an SCR, TRIAC, or switching transistor output instead of the usual mechanical normally-open (NO) contacts.

While the solid state relay and electro-mechanical relay are fundamentally similar in that their low voltage input is electrically isolated from the output that switches and controls a load, electro-mechanical relays have a limited contact life cycle, can take up a lot of room and have slower switch speeds, especially large power relays and contactors. Solid state relays have no such limitations.

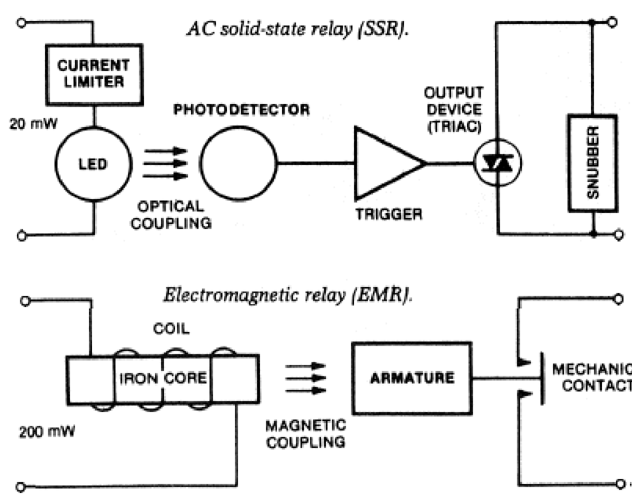


Fig.31 Solid state relay and electromagnetic configurations.

Thus the main advantages solid state relays have over conventional electro-mechanical relays is that they have no moving parts to wear out, and therefore no contact bounce issues, are able to switch both "ON" and "OFF" much faster than a mechanical relays armature can move, as well as zero voltage turn-on and zero current turn-off eliminating electrical noise and transients.

Solid state relays can be bought in standard off-the-shelf packages ranging from just a few volts or amperes to many hundreds of volts and amperes of output switching capability. However, solid state relays with very high current ratings (150A plus) are still too expensive to buy due to their power semiconductor and heat sinking requirements, and as such, cheaper electro-mechanical contactors are still used.

Similar to an electro-mechanical relay, a small input voltage, typically 3 to 32 volts DC, can be used to control a much large output voltage, or current. For example 240V, 10Amps. This makes them ideal for microcontroller, PIC and Arduino interfacing as a low-current, 5-volt signal from say a micro-controller or logic gate can be used to control a particular circuit load, and this is achieved with the use of opto-isolators.

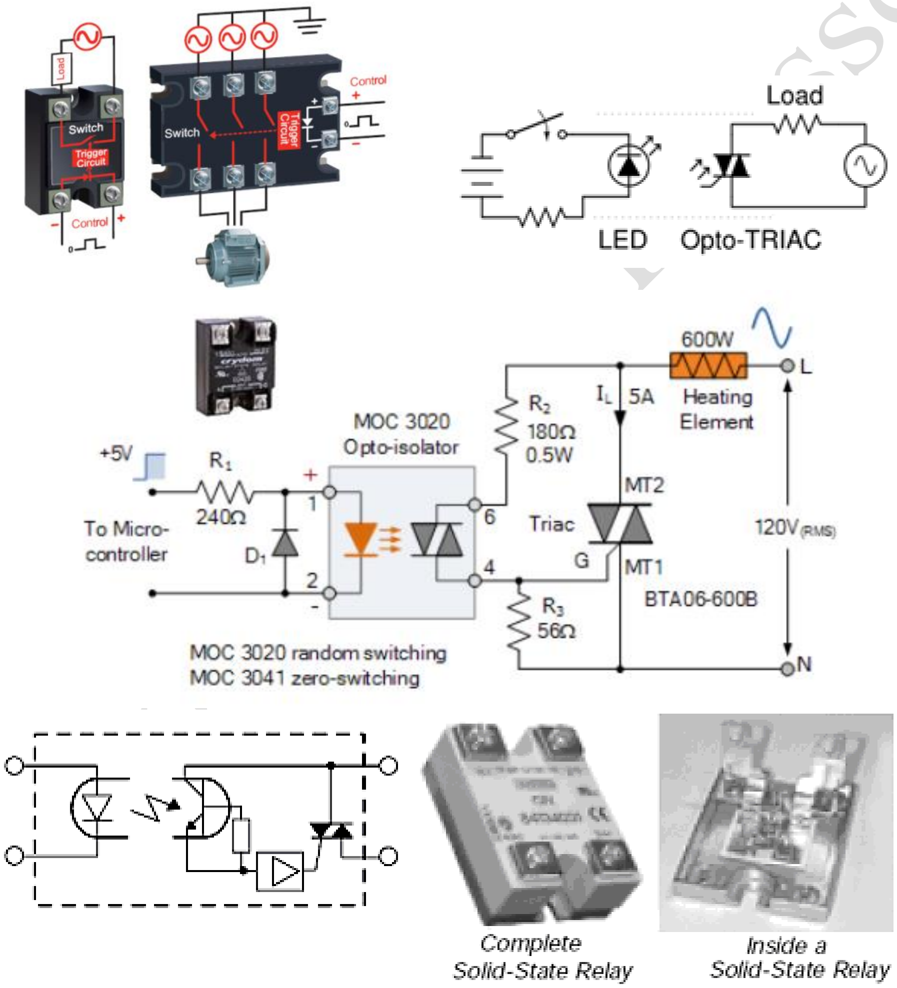


Fig.32 An AC SolidState Relay circuit.

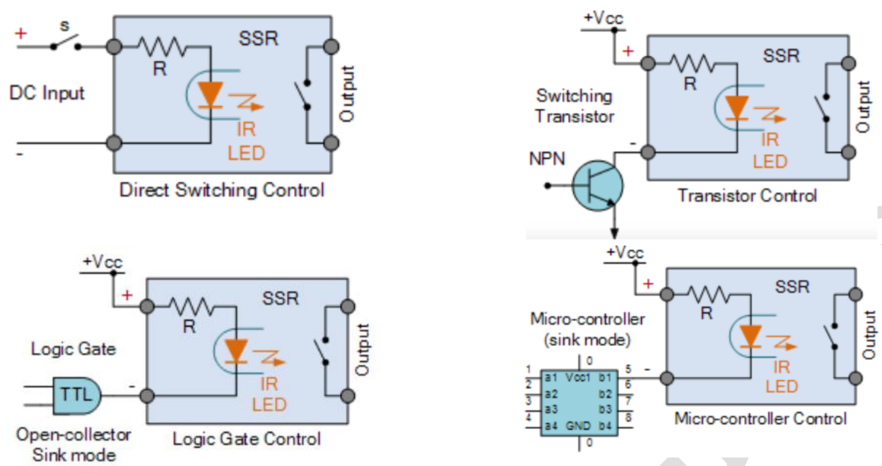


Fig.33 Solid State Relay DC Input Circuit.

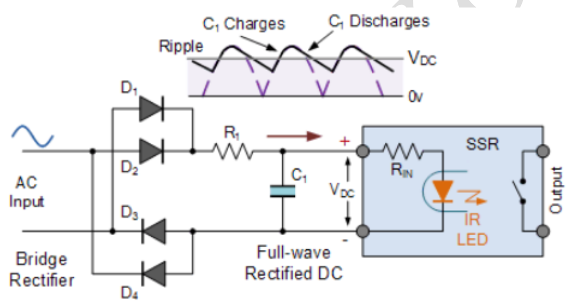


Fig.34 Solid State Relay AC Input Circuit.

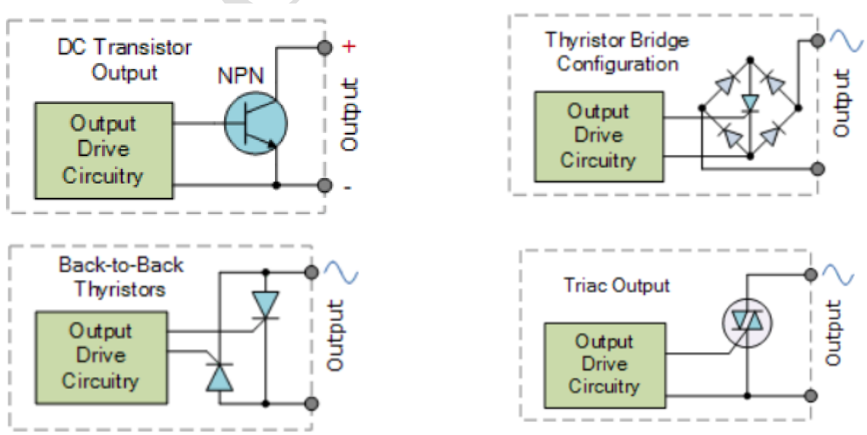


Fig.35 Solid State Relay Output Circuits.

	Solid State Rrelays	Electromechanical Relays
Electrical Noise	• Leverage zero voltage turn-on and zero current turn-offs • Generate minimal electrical disturbance	• Can generate significant signal noise as a result of mechanical system
Electromechanical - Power Consumption	• Feature low power consumption • Require little input power for switching loads • Ideal for creating more sustainable, energy-efficient solutions • High heat generation	• Power consumption is a function of the switching voltage and the internal resistance of the material being used in the switch • Require higher input power to operate
Electromechanical - Shock & Vibration	• Are highly resistant to shock and vibration • Are not susceptible to erratic or unreliable operation in demanding environments	• Mechanical system is subject to external forces that can lead to unreliable and erratic operation
Electromechanical - Switching Capabilities	• Respond to control signals in less than 100µs	• Can respond to control signals in 5 – 15 milliseconds (about 100 times slower than an SSR)
Compatibility with Control Systems	• Do not generate sparks or electric arcs and do not bounce electrically or mechanically • Have isolation levels up to 4kV • Magnetic fields have little effect on them • Are preferable to EMRs in environments where volatile combustibles are in use	• Arc when they interrupt current therefor not suitable for environments with volatile matter • Cannot operate in areas with large electromagnetic forces
Performance in Harsh Environments	• Do not generate sparks or electric arcs and do not bounce electrically or mechanically • Have isolation levels up to 4kV • Magnetic fields have little effect on them • Are preferable to EMRs in environments where volatile combustibles are in use	• Arc when they interrupt current therefor not suitable for environments with volatile matter • Cannot operate in areas with large electromagnetic forces
Positional Sensitivity	• Are positional insensitive • Are suitable for mounting in vertical or horizontal positions, "dead bug" position or adjacent mounting	• Mechanical system is subject to external forces • External forces must be perpendicular to relay action

Table 1 Comparative features of SSRs and EMRs.

3.6 Timers Timing Diagrams

A timer is an electronic relay whose output certain circuits after certain adjustable delay from the moment voltage is applied. Typical timing diagrams are:

1. Delayed ON and long-time delayed ON timers

In which the output contact connects with a certain adjustable delay from the moment voltage is applied to supply terminals A1-A2 (Fig.36). It has different timing ranges, e.g. 0.6-6s, 6-60s, 0.6-6min, 6-60 min in delayed ON version or 0.06-0.6s, 0.6-6s, 0.6-6h, 6-60h in long-time delayed ON version. Range selection is made by dipswitches located on the front of the relay.

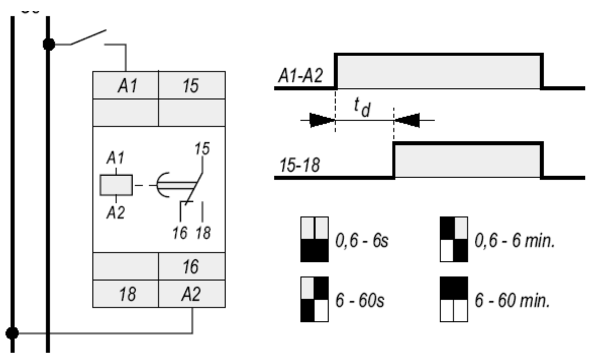


Fig.36 Delayed ON timer.

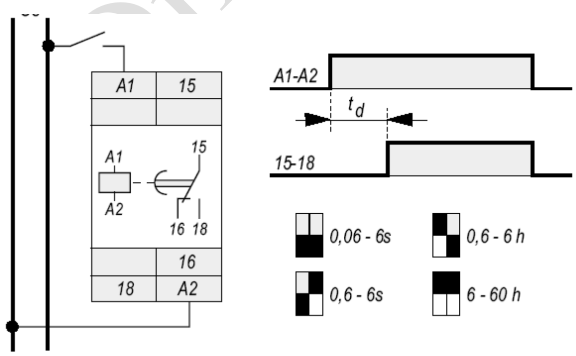


Fig.37 Long time delayed ON timer.

2. Delayed ON timer with instantaneous contact

In this type there are two output contacts (Fig.38). One contact connects instantly when voltage is applied to the supply terminals A1-A2 and the other connects with a certain adjustable delay with different timing ranges.

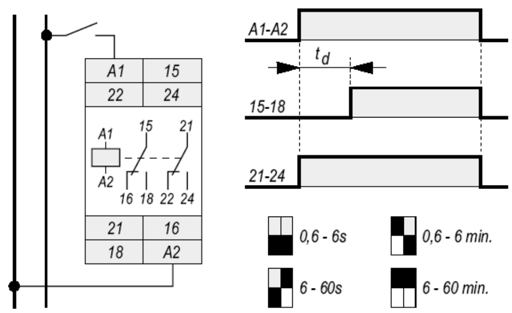


Fig.38 Delayed ON timer with instantaneous contact.

3. Impulse ON timer

In this timer when voltage is applied to terminals A1-A2, the output contact connects and goes back to stand-by after a pre-set time (Fig.39).

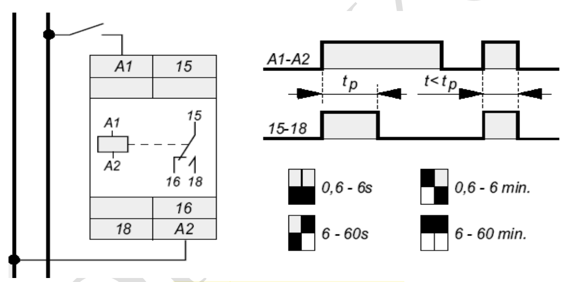


Fig.39 Impulse ON timer.

4. Delayed ON through contact timer Function

The output contact in this type connects with an adjustable delay from the moment voltage is applied to terminals Y1-Y2. This is done by a voltage free control contact and it disconnects the moment the terminals are disconnected as shown in Fig.40. The timer must be supplied with the nominal voltage between A1-A2. Immediate disconnection will occur if supply voltage is removed.

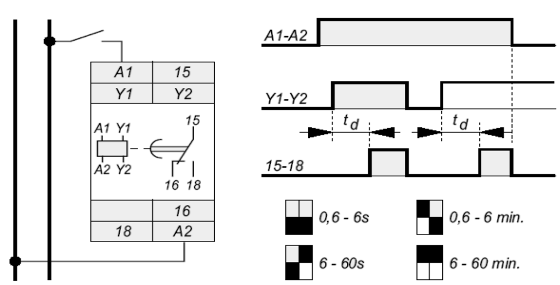


Fig.40 Delayed ON through contact timer Function.

5. Star-delta starter timer

The purpose of this timer is to control star-delta starting. As shown in Fig.41, once supply voltage is applied to A1-A2 terminals, the star contact (17-18) closes for a pre-selected time (1-10 sec. or 6-60 sec). When this time is up, it opens, there is a pause (100ms) and then the delta contact connects (17-28).

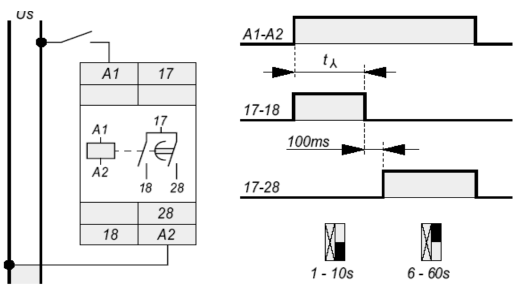


Fig. 41 Star-delta starter timer.

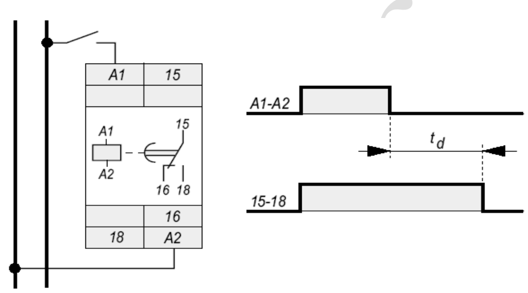


Fig. 42 Delayed OFF timer.

6. Delayed OFF timer

Electronic relay whose output contact instantly connects when supply voltage is applied to terminals A1-A2. It disconnects with an adjustable delay from the moment the relay loses supply voltage. There are several types depending on the range of timers.

7. Delayed OFF through contact timer

As shown in Fig.43, the timer must be supplied with nominal voltage between A1-A2. When connecting the Y1-Y2 terminals with a voltage-free control the output contact connects instantly. It disconnects with a pre-selected time delay when the terminals are disconnected. When the supply voltage is removed immediate disconnection will occur.

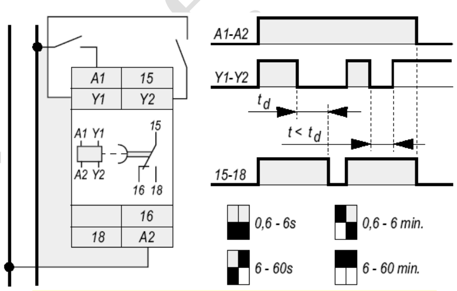


Fig.43 Delayed OFF through contact timer.

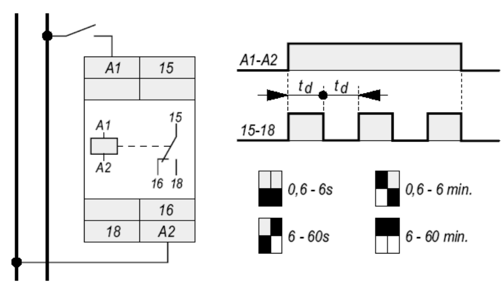


Fig.44 Symmetric on-off Technical characteristics.

8. Symmetric on-off

The output contact connects and disconnects intermittently. The connection and disconnection times are equal and pre-adjustable. This is shown in Fig. 44.

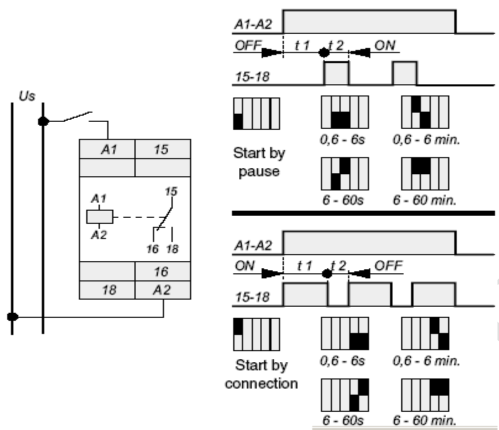


Fig. 45 Asymmetric on-off, started by connection on or off.

9. Asymmetric on-off and long-time asymmetric on-off started by connection on or off

The output contact connects and disconnects intermittently. Connection and disconnection times may be set separately as shown in Fig.45 for timing ranges: 0.6-6s; 6-60s; 0.6-6 min and 6-60min and Fig.46 for timing ranges: 0.6-6min; 6-60min; 0.6-6h and 6-60 h . The intermittent cycle begins with a connection or pause selected by dipswitch and starts the instant connection is made from supply voltage to the A1-A2 terminals. A new step is begun if voltage supply is interrupted during operation.

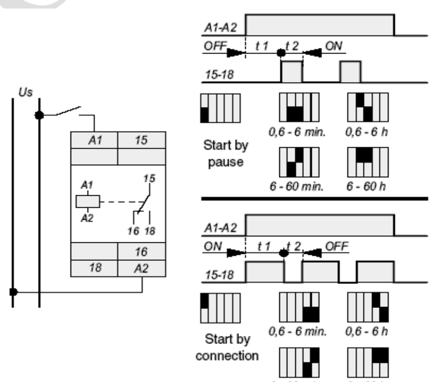


Fig. 46 Long time asymmetric on-off, started by connection on or off.

3.7 Power System Protective Relays

The power system protective devices provide the intelligence and initiate the action, which enables circuit-switching equipment to respond to abnormal or dangerous system conditions. Following is a brief description of the types and characteristics of relays and other protective devices most commonly used in industrial plant power systems along with some brief application considerations.

1. Large electric circuit breakers do not contain within themselves the necessary mechanisms to utomatically trip (open) in the event of overcurrent conditions. They must be "told" to trip by external devices.
2. Protective relays are devices built to automatically trigger the actuation coils of large electric circuit breakers under certain conditions.

3.7.1 Overcurrent Relays

The most common relay for short-circuit protection of the industrial power system is the overcurrent relay. The overcurrent relays used in the industry are mostly of the electromagnetic attraction, induction, and solid-state types. Relays with bimetallic elements used for thermal overload protection are also used intensively.

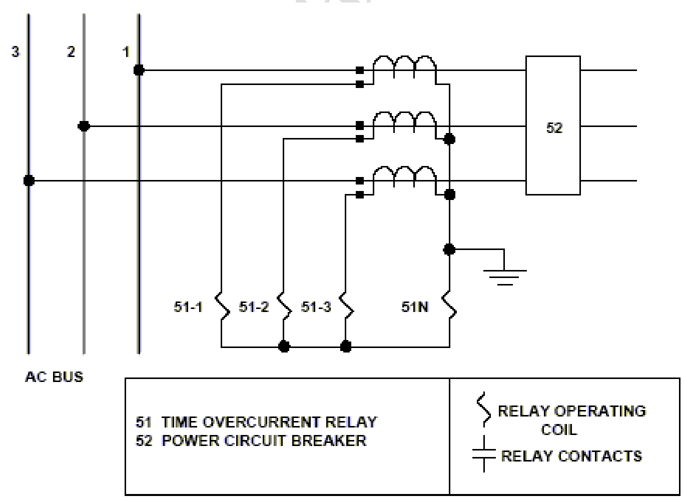


Fig. 47 External connection of an overcurrent relay.

The construction of the induction-type over-current relay is similar to a watt-hour meter since it consists of an electromagnet and a movable armature, which is usually a metal disk on a vertical shaft restrained by a coiled spring. The relay contacts are operated by the moveable armature.

The pick up or operating current for all overcurrent relays is adjustable. When the current through the relay coil exceeds a given setting, the relay contacts close and initiate the circuit breaker tripping operation. The relay usually operates on current from the secondary of a current transformer

Typical protective relay practice is to use ground relays to protect against single phase to ground short circuits and phase relays to protect against phase to phase short circuits and three phase short circuits. Figs.47 and 48 show three phase relays and one ground relay connected to current transformers (CT's). Three current transformers feeding over-current relays. Note that the ground relay is device 51N and the phase relays are 51-1 for phase 1, 51-2 for phases 2, and 51-3 for phase 3. Three-phase and phase to phase short circuits will be detected by the phase relays, and phase to ground short circuits will be detected by the ground relay.

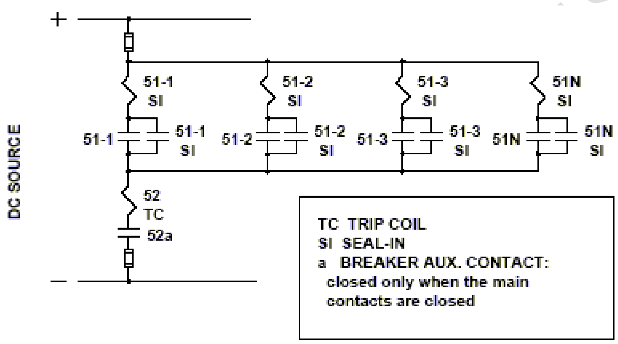


Fig.48 Schematic diagram of an overcurrent relay for phase and ground OC protection on a three-phase system.

3.7.2 Time-Overcurrent Relay with Voltage Control

A short circuit on an electric system is always accompanied by a corresponding voltage dip, whereas an overload will cause only a moderate voltage drop. Therefore a voltage-restrained or voltage-controlled overcurrent relay is able to distinguish between overload and fault conditions. A voltage-restrained overcurrent relay is subjected to two opposing torques, an operating torque due to current and a restraining torque due to voltage. As such the overcurrent required to operate the relay is higher at normal voltage than it is at reduced voltage. A voltage-controlled overcurrent relay operates by virtue of current torque only; the application of which is controlled by another relay element set to operate at some predetermined value of voltage. Such relay characteristics are useful where it is necessary to set the relay close to or below load current, while retaining certainty that it will not operate improperly on normal load current. This is shown in Fig.49.

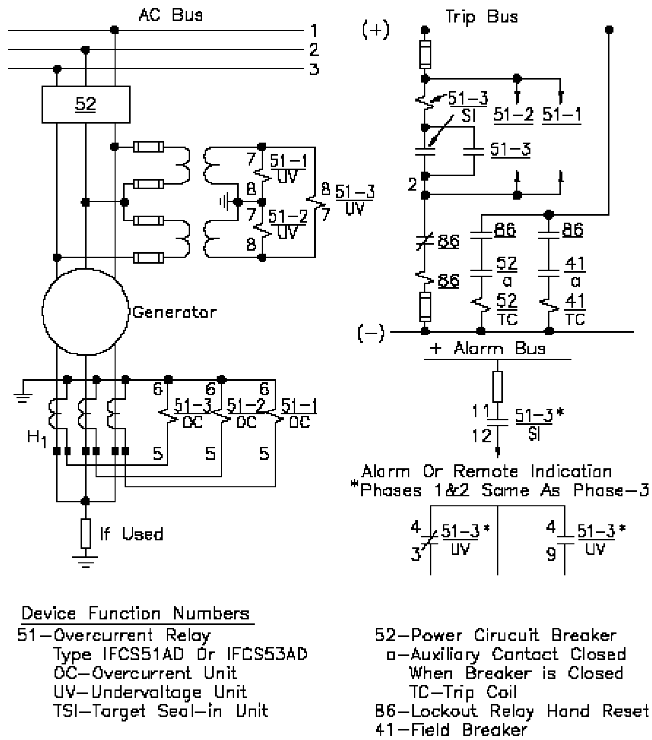


Fig.49 Schematic diagram of an overcurrent relay with voltage control on a generator.

3.7.3 Directional Overcurrent Relays

Directional overcurrent relays may be either ground or phase relays, meaning that the relay is supposed to protect against either ground faults (single-phase-to-ground or double phase-to-ground short circuit) or phase faults (any short circuits involving phase-phase such as three-phase, phase-to-phase, or double phase-to-ground). Directional overcurrent relays may be either directionally controlled or directionally supervised. Directional control means that there is no torque produced by the overcurrent element unless the directional unit operates. Directional supervision means that the directional unit and the overcurrent unit have contacts in series in the trip circuit.

For a fault in the non-trip direction, the directionally supervised relay will start its timing, but the directionally controlled relay will not. Thus, directional control is preferred, since faults in the non-trip direction should not interfere with timing for subsequent faults in the trip direction. Directional overcurrent relays for phase protection use line current for an operating quantity along with a polarising voltage (to determine the direction of the fault relative to the relay). Fig.50 is an AC elementary diagram showing a phase directional overcurrent relay. V_{23} is used for polarising the I_1 overcurrent unit. Note that the phasor diagrams are shown for unity power factor, but that similar results would apply if the power factor were lagging (as expected during a fault). Load currents will not pick up the overcurrent unit, and the directional action will be correct for short circuits.

Ground directional overcurrent relays use the residual current and a polarising quantity that can be (a) zero-sequence voltage, (b) neutral current from a delta-Wye (grounded) transformer (or other grounding transformer), or (c) negative-sequence voltage and negative-sequence current. Fig.51 shows a ground directional overcurrent relay with a broken-delta connection of PT's to obtain zero-sequence voltage (actually 3 V_o). Since V_o is zero for balanced loads, three-phase faults, and phase-phase faults, and since any fault involving ground will produce a zero-sequence voltage that is always in the same polarity, then the zero-sequence voltage is useful as a polarising quantity for ground relays.

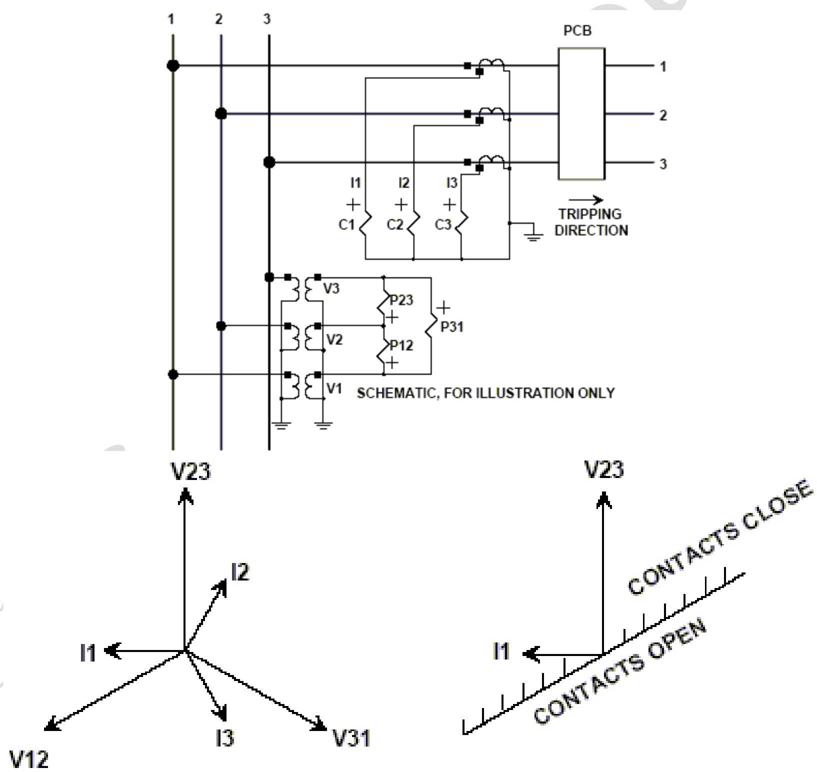


Fig. 50 AC elementary diagram for a phase directional overcurrent relay.
Phase sequence is 1-2-3.

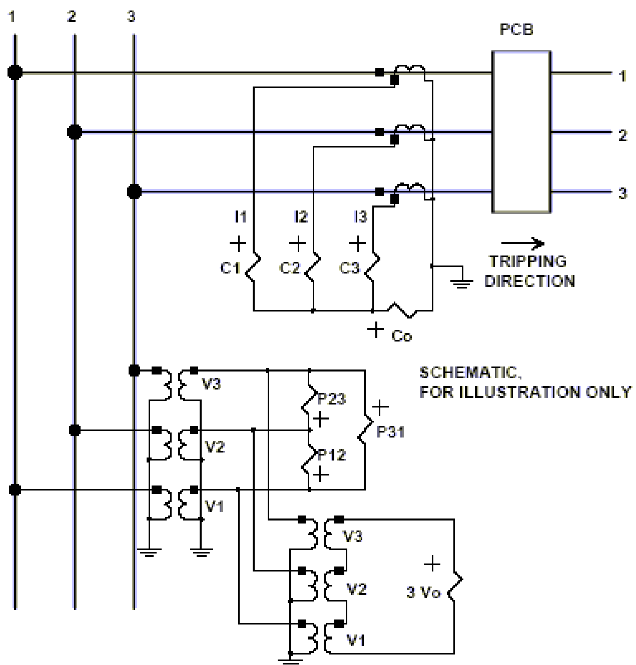


Fig. 51 Elementary diagram of a ground directional overcurrent relay. Potential polarisation is obtained from zero-sequence voltage from Wye to broken-delta PT.

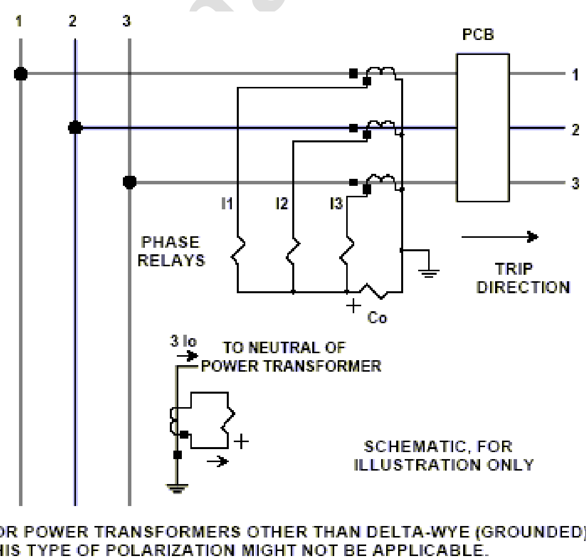


Fig. 52 Elementary diagram of a ground directional overcurrent relay. Current polarisation is obtained from zero-sequence current from neutral of delta-Wye (Grounded) power transformer.

For faults near a delta-Wye (solidly grounded) transformer bank, the zero-sequence voltage will be quite small, and neutral current polarisation is preferable. Fig.52 shows this current polarisation. For Wye-Wye banks, the neutral current cannot be used to polarise ground relays, since the ground current is simply passed through from one side to the other. For Wye-Wye-delta banks and Wye grounded autotransformers with delta tertiaries, the neutral may sometimes be used.

3.7.4 Directional OC Protection of Feeders and TLs Lines–1

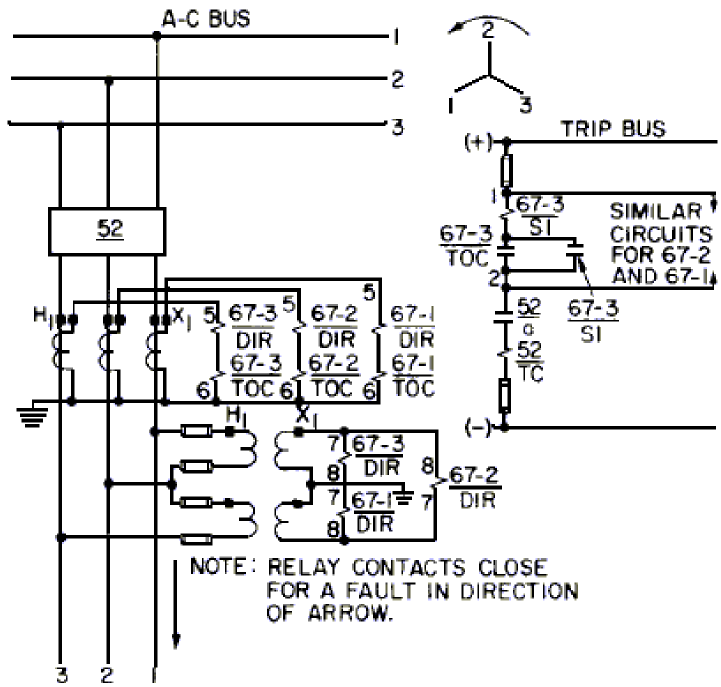


Fig. 53 Typical 90-degree connection of three relays used for directional overcurrent protection of a single line.
TOC: Time-Overcurrent unit. DIR: Directional unit.
SI: Seal-In (Indicating Contactor Switch).

The directional overcurrent relays are employed primarily for the protection of feeders and transmission lines in applications where single-phase relays are desired or required. They consist of two units, an instantaneous power-directional unit (bottom) of the induction-cup type, and a time overcurrent unit (top) of the induction-disk type. The directional-unit contacts control the operation of the overcurrent unit (directional control). Typical external connections of current and potential transformers are shown in Fig.53. With this connection, the current (at unity-power-factor load) leads the polarising potential by 90 degrees.

3.7.5 Directional OC Protection of Feeders and TLs-II

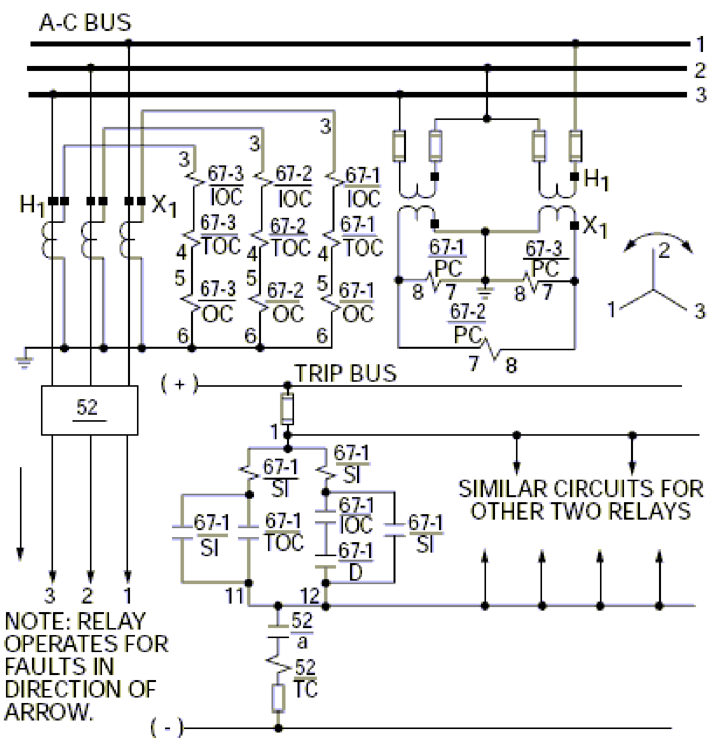
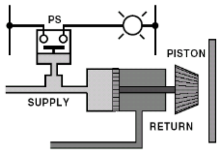


Fig. 54 Typical external connections for three single-phase relays for directional phase-fault protection of a single line.

These relays consist of three units, an instantaneous power-directional unit of the induction-cup type, a time overcurrent unit of the induction-disk type, and an instantaneous-overcurrent unit of the induction-cup type. The directional- unit contacts control the operation of both the instantaneous and the time- overcurrent units (directional control). In this application, the instantaneous unit provides high-speed protection for close-in high-current faults. The relays are frequently applied for phase-fault protection of a single line. Typical external connections of current and potential transformers are shown in Fig.54. With this connection, the current (at unity-power-factor load) leads the polarising potential by 90 degrees. Since the directional unit has a 45 degrees characteristic, its maximum torque will occur when the fault current (balanced 3-phase fault) lags its unity-power-factor position by 45 degrees.



CHAPTER 4

Sensor Basics

4.1 Overview

Sensors convert a physical phenomenon into a measurable electrical signal. But some sensors do not naturally respond to changing physical phenomena and require signal conditioning. Before the sensor output can be digitized, the signal may need additional components and circuitry to produce a signal that can take advantage of the full capabilities of the measurement hardware and reduce the effects of noise from external interference.

Essential to any data acquisition application is a transducer sensor that converts real-world phenomena, such as temperature and pressure, into measurable currents andvoltages. Let's explore the types of things you want to measure and map them to the types of sensors you need to get there.

4.2 Types of Sensors

"Sensors" have now become crucial to improve productivity. There is a wide variety of sensors, each has its strengths and weaknesses.

1. Photoelectric sensors "Detection based on "light""
   a. Photoelectric sensors
   b. Fiberoptic sensors
   c. Laser sensors: "Received light" recognition type - "Position" recognition type - iii. Camera with built-in laser sensor
   d. Color sensors
2. Inductive Proximity Sensors "Detection based on "eddy current" :
   a. Proximity sensors, b. Inductive displacement sensors
3. Contact Sensors "Detection based on "contact"": Contact-type displacement sensors
4. Ultrasonic Sensors "Detection based on "ultrasonic"": Ultrasonic sensors
5. Vision sensors "Detection based on "images"": Vision sensors
6. Sound: Sound waves are created by pressure variations in the air. Microphones transform sound pressure into capacitive variations, which are then converted into an electrical voltage.
7. Strain: Strain gauges are used to measure the deformation of a material due to an applied force. The resistance of a strain gauge changes with small bends and pulls on the material.

8. Pressure: Pressure is defined as force per unit area that a fluid exerts on its surroundings. The three most universal types of pressure transducers are the bridge (strain-gage based), variable capacitance, and piezoelectric.
9. Load and Torque: Load is a term frequently used to refer to the force exerted on a structure or body measured in Newtons (N). Torque is the tendency of a force to rotate an object about an axis.
10. Temperature: Thermocouples produce small changes in voltage in relation to temperature while resistance temperature sensors have resistance changes in relation to temperature. Learn more about the difference between thermocouples, RTDs, and thermistors and the environments that best suit them.
11. Vibration: Accelerometers are commonly used to measure vibration and contain piezoelectric crystals that generate an electric charge proportional to force from oscillations.

4.3 Detection Based on "Light" Photoelectric Sensors

1. Outline

a. A photoelectric sensor emits a light beam (visible or infrared) from its light-emitting element.
b. A reflective-type photoelectric sensor is used to detect the light beam reflected from the target.
c. A thrubeam type sensor is used to measure the change in light quantity caused by the target crossing the optical axis.

The light source (Fig.1) used for each of the three modes comes from a light emitting diode (a solid-state semi-conductor which emits light when the current through the diode is forward biased). Light emitting diodes (LEDs) are manufactured to emit a visible coloured light (red, green, and yellow) or invisible (infrared) light. Visible LEDs are used for switch status indication, and in retroreflective applications, they provide easy reflector alignment to the sensor. The light intensity of infrared LEDs is inherently greater than the visible ones. These "higher powered" LEDs are better suited for thru-beam and diffused style sensors. Switching the LED off and on at a predetermined frequency (modulating) increases the light intensity and lifetime of the LED while reducing the average power consumed. The pulsed LED provides a stronger signal when compared to a continuously illuminated LED; therefore, a larger sensing range can be obtained. Another key advantage to modulating the sensor is to provide protection against external light interference. The receiving circuit, typically phototransistor based, is modulated at the same frequency as the emitter's. Since the receiving circuit is only powered during the emitters "on cycles," there is very little time for erroneous light to provide a false signal. Photoelectric sensors (Fig.2) are comprised of the following components:

1. Light Source (LED),	2. Receiver (phototransistor),
3. Signal Converter,	4. Amplifier.

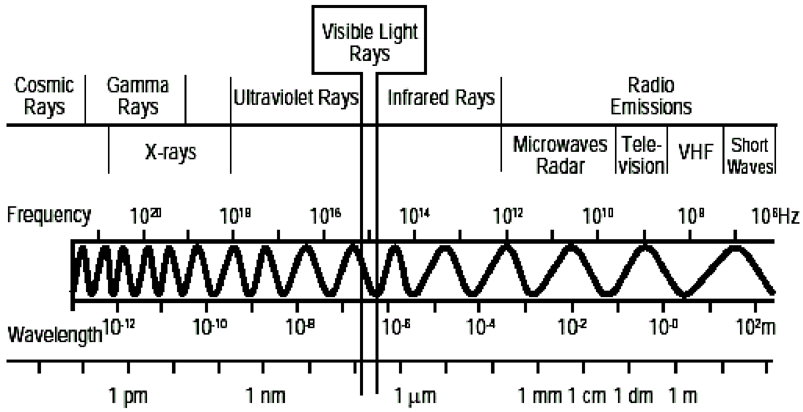


Fig.1 Wavelength spectrum.

The generated light pulses that are received by the phototransistor are converted into electrical signals. These signals are analysed in order to determine if they are the result of the actual transmitted light. Upon verification, the output of the sensor is switched accordingly. With the appropriate conditioning, light or dark sensing is achieved.

2. Principle and major types (Fig.3)

A beam of light is emitted from the light emitting element and is received by the light receiving element.

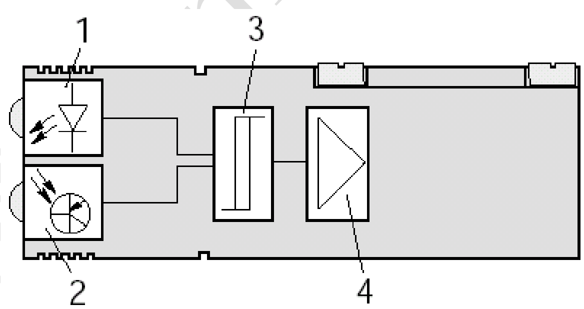


Fig.2 Photoelectric sensor main components.

1. Light Source (LED). **2. Receiver (phototransistor).**
3. Signal Converter. **4. Amplifier.**

3. Features

1. Non-contact detection

   Since detection is possible without contact, there will be no damage to targets. The sensor itself will not be damaged either, ensuring long service life and maintenance-free operation.

2. Almost all materials detectable.

Since the sensor either detects targets based on the reflectivity or the quantity of interrupted light, almost all kinds of materials are detectable. This includes glass, metal, plastic, wood, and liquid.

3. Long detecting distance

Photoelectric sensors are generally high power and allow long-range detection.

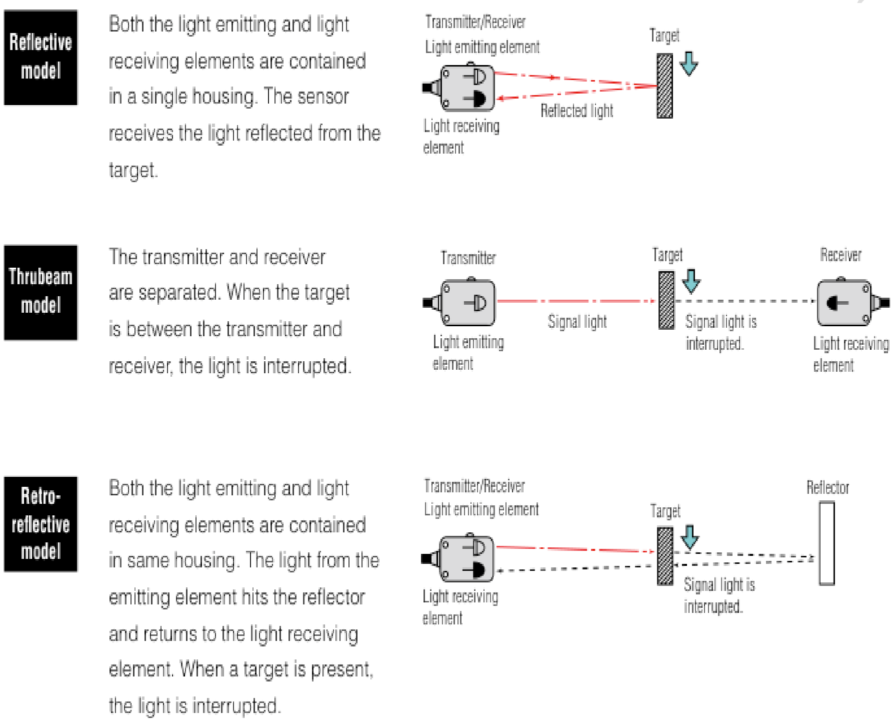


Fig.3 Major types of photoelectric sensors.

4. Classification (Fig.4)

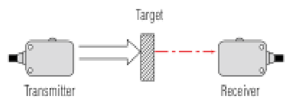
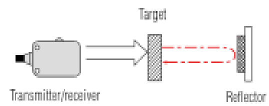
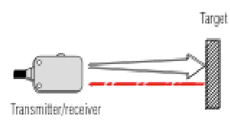
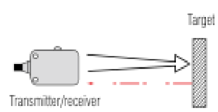
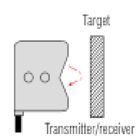
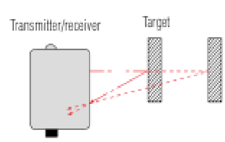
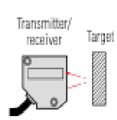
Type	Detection configuration	Features
Thrubeam		Detection occurs when the target crosses the optical axis between transmitter and receiver. • Long-detecting distance • Stable detecting position • Opaque objects detectable regardless of shape, color or material • Powerful beam
Retro-reflective		Detection occurs when the target crosses the optical axis between sensor head and reflector. • Reflector allows installation in a limited space • Simple wiring • Longer detecting distance than the diffuse-reflective sensor type • Easily-adjustable optical axis • Opaque objects detectable regardless of shape, color, or material
Diffuse-reflective		Detection occurs when the light beam, emitted to the target, is reflected by the target and received. • Space-saving (requires installation of sensor unit only) • Adjustment of optical axis not required • Reflective transparent objects detectable • Color differentiation possible
Focused-beam reflective		Detection occurs when the beam spot, emitted to the target, is reflected by the target and received. • Minute objects detectable • Target markings detectable • Detection possible through narrow openings between machines • Visible beam spot
Small-spot definite reflective		The transmitting and receiving portions are constructed at an angle, allowing detection within the limited area where the optical axes intersect. • Effect of target background is minimal • Low hysteresis • Slight height differences are detectable • Visible beam spot
Fixed-distance		Detects the target at a specific distance according to the angle of the reflected light beam. • Unaffected by highly reflective targets or backgrounds • Stable detection of materials with varying reflectance and color • Highly accurate detection of minute objects • Visible beam spot
Luster recognition		When the light beam hits a target, the beam reflects differently according to the luster of the target. The sensor detects the difference in luster based on how the beam reflects (specular or diffusive). • On-line detection is possible. • Detection is not affected by target color. • Transparent targets can be detected.

Fig.4 Classification of photoelectric sensors.

4.4 Detection Based on "Light" Fiberoptic sensors

1. Properties of Light

a. Rectilinear Propagation: When light travels through air or water, it always travels in a straight line.

b. Refraction: Refraction is the phenomenon of light being deflected as it passes obliquely through the boundary between two mediawith different refractive indices.

c. Reflection (Regular Reflection, Retroreflection, Diffuse Reflection):

i. regular reflection: A flat surface, such as glass or a mirror, reflects light at an angle equal to the incident angle of the light

ii. Retroreflection: A corner cube takes advantage of this principle by arranging three flat surfaces perpendicular to each other. Light emitted toward a corner cube repeatedly propagates regular reflections and the reflected light ultimately moves straight back toward the emitted light.

iii. Diffuse Reflection: Matte surfaces, such as white paper, reflect light in all directions.

2. Optical Fibers

are made from either glass or plastic. Most are roughly the diameter of a human hair, and they may be many miles long. Light is transmitted along the center of the fiber from one end to the other, and a signal may be imposed. Fiber optic systems are superior to metallic conductors in many applications. Their greatest advantage is bandwidth. Because of the wavelength of light, it is possible to transmit a signal that contains considerably more information than is possible with a metallic conductor — even a coaxial conductor. Other advantages include

a. Electrical Isolation — Fiber optics do not need a grounding connection. Both the transmitter and the receiver are isolated from each other and are therefore free of ground loop problems. Also, there is no danger of sparks or electrical shock.

b. Freedom from EMI — Fiber optics are immune to electromagnetic interference (EMI), and they emit no radiation themselves to cause other interference.

c. Low Power Loss — This permits longer cable runs and fewer repeater amplifiers.

d. Lighter and Smaller — Fiber weighs less and needs less space than metallic conductors with equivalent signal-carrying capacity. Copper wire is about 13 times heavier. Fiber also is easier to install and requires less duct space.

3. Light Sources (Light Generation-Fig.5):

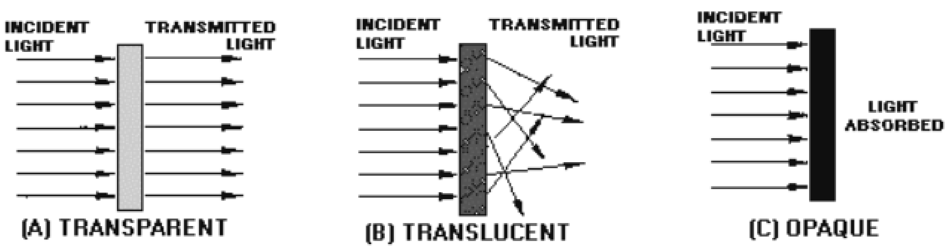
a. Pulse Modulated light: The majority of Photoelectric Sensors use pulse modulated light that basically emits light repeatedly at fixed intervals.

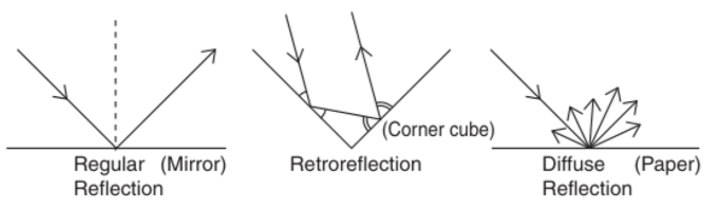
b. Light Source Color and Type:

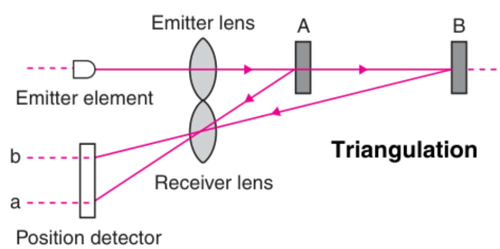
c. Triangulation: Distance-settable Sensors generally operate on the principle of triangulation. Light from the Emitter strikes the sensing object and reflects diffused light. The Receiver lens concentrates the reflected light on the position detector (a semiconductor that outputs a signal according to where the light strikes it). When the sensing object is located at A near the optical system, then the light is concentrated at point a on the position detector. When the sensing object is located at B away from the optical system, then the light is concentrated at point b on the position detector.

3. Detection Principles (Figs.6-8)

Optical fiber is comprised of a central core with a high refractive index surrounded by cladding with a low refractive index. When light enters the core, repetitive total internal reflection at the boundary of the less refractive cladding guides the light down the optical fiber. The angle of the light traveling through the optical fiber increases to about 60° by the time the light exits the fiber and strikes a sensing object.







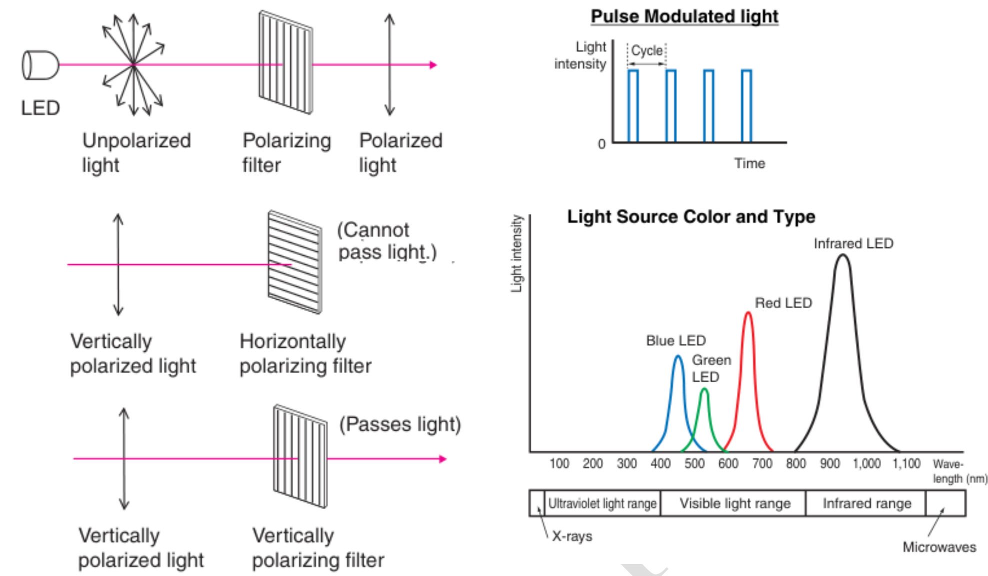


Fig.5 Light Sources (Light Generation).

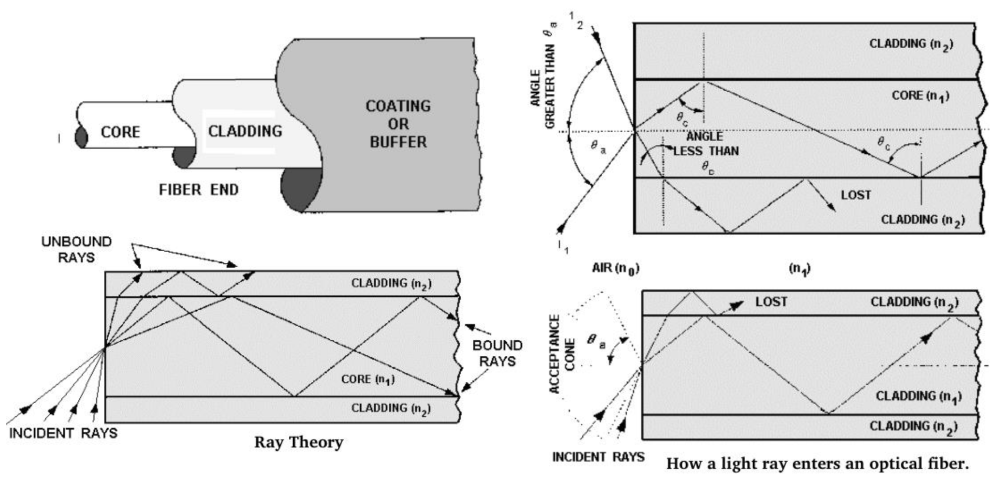


Fig.6 Basic structure of an optical fiber.

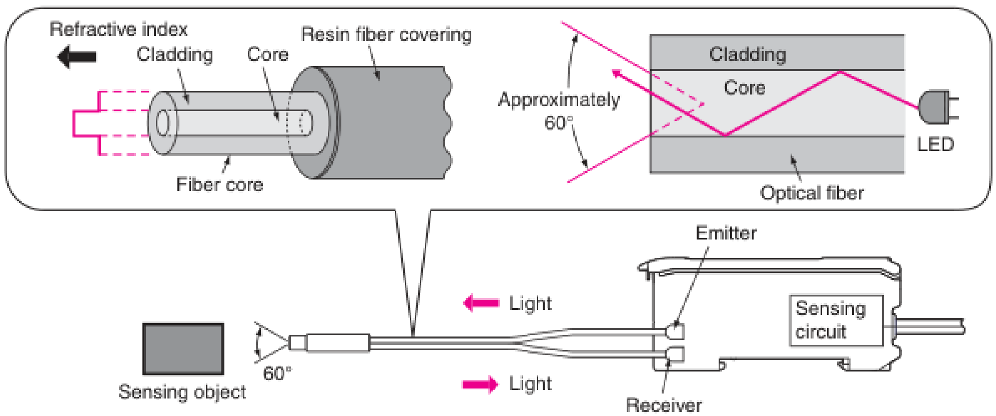


Fig.7 Detection Principles.

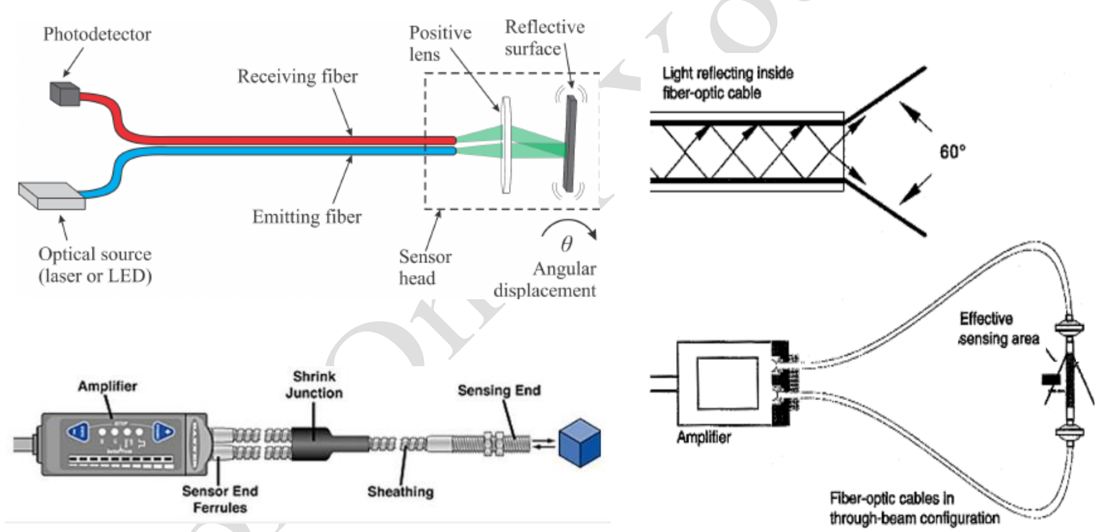


Fig.8 Upper Left: Fiber optic angular displacement sensor. Lower Left: Fiber optic sensing system. Right: In a fiber-optic sensing system, the emitter and the receiver share a single housing. The fiber-optic cable that is connected to the amplifier allows the sensor to reach areas inaccessible to standard photoelectric sensors.

4. Classification (Fig.9)

a. Classification by Sensing Method

i. Through-beam Sensors: The emitter and receiver fibers are installed facing each other so that the light from the emitter enters the receiver. When a sensing object passing between the emitter and receiver fibers interrupts the emitted light, it reduces the amount of light that enters the receiver. This reduction in light intensity is used to detect an object.

ii. Reflective Sensors: The emitter and receiver fibers are installed in the same housing and light normally does not return to the receiver. When light from the emitter strikes the sensing object, the object reflects the light and it enters the receiver where the intensity of light is increased. This increase in light intensity is used to detect the object.

iii. Retro-reflective Sensors: The emitter and receiver fibers are installed in the same housing and light from the emitter is normally reflected back to the receiver by a Reflector installed on the opposite side. When the sensing object interrupts the light, it reduces the amount of light received. This reduction in light intensity is used to detect the object.

iv. Limited-reflective Sensors: Sensors receive light reflected from the sensing object to detect it. The emitter and receiver are installed to receive only regular-reflection light, so only objects that are at specific distance (area where light emission and reception overlap) from the Sensor can be detected. In Fig.9 the sensing object at (A) can be detected while the object at (B) cannot.

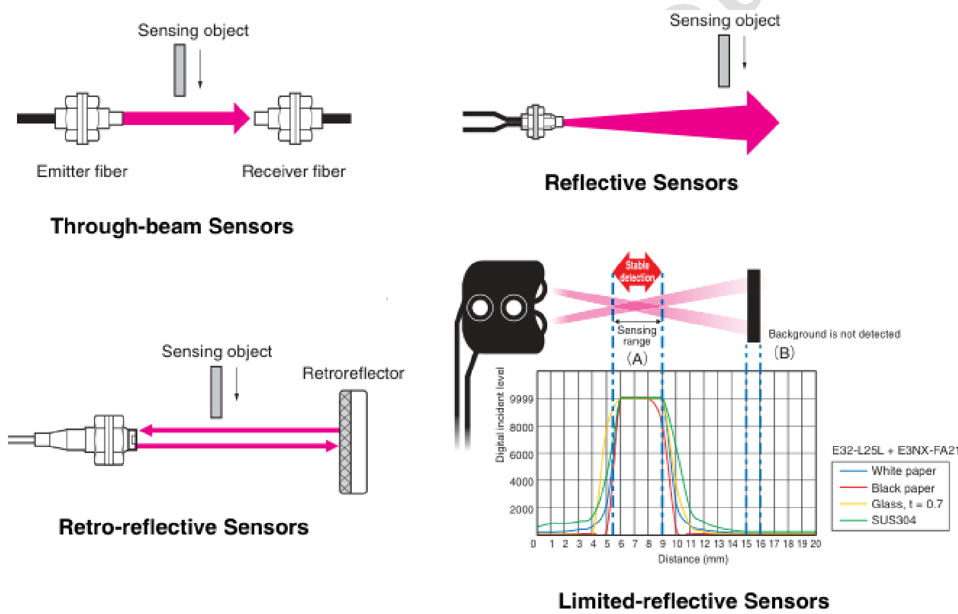


Fig.9 Optical fiber classification.

b. Types of Fiber Cables (Figs.10-11)

i. Flexible Fibers: The flexible fiber has a small bending radius for easy routing without easily breaking. It is easy to use because the cable can be bent without significantly reducing light intensity.

ii. Standard Fibers: This fiber have a large bending radius compared with bend- resistant or flexible fiber. Use this fiber where the bending radius is large, or on non- moving parts.

iii. Break-resistant Fibers: This fiber is resistant to repeated bends for use on moving parts.

v. Standard Reflective Fiber Units: This structure is standard for most Reflective Fiber Units. The receiver fiber is located next to the emitter fiber.

vi. Coaxial Reflective Fiber Units: These Fiber Units offer better detection of small objects at close distances (of 2 mm or less) than Standard Reflective Fiber Units. They also detect glossy surfaces more reliably than Standard Reflective Fiber Units, even if the surface is tilted. The receiver fibers are arranged around the emitter fiber.

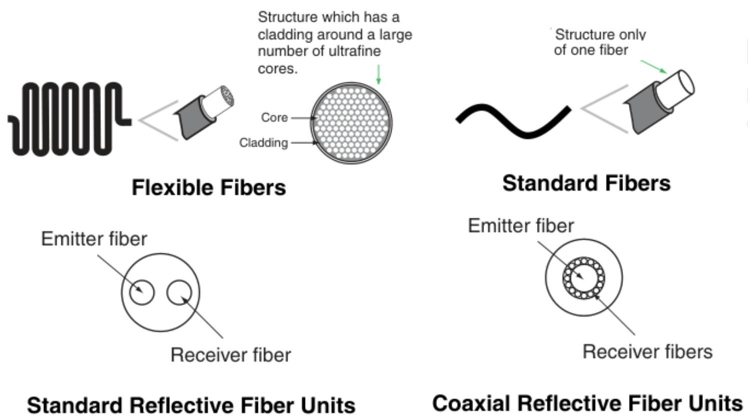


Fig.10 Types of Fiber Cables.

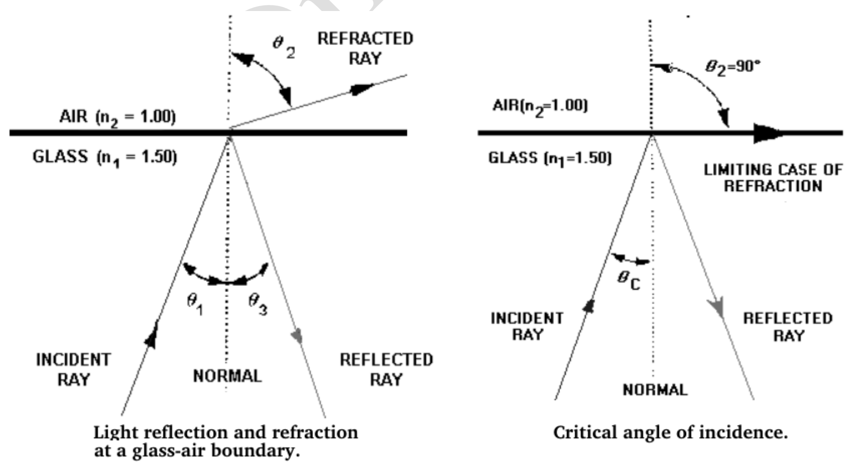


Fig.11 Light reflection and refraction at a glass-air boundary.

5. Fiber Optic sensor principles.
Fiber optic sensors consist of an optical source (LEDs, Lasers, Laser diodes etc.) optical fiber, sensing element (transducer), optical detector and electronic processing unit (Optical spectrum analyzer, wave analyzer, oscilloscope etc). A block diagram of fiber optic sensor system is shown in Fig12.

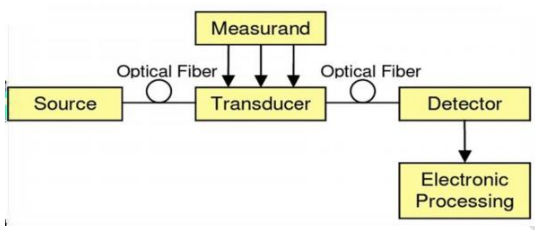


Fig.12 A block diagram of fiber optic sensor system.

6. Classification of fiber optics sensors
Fiber optic sensors can be classified under three categories.
These three classes are further sub divided as following;

1) On the basis of sensing location-
   (a) Intrinsic
   (b) Extrinsic

2) On the basis operating principle-
   (a) Based on intensity
   (b) Based on phase
   (c) Based on wavelength
   (d) Based on polarisation

3) On the basis of their application –
   (a) Physical sensor s
   (b) Chemical sensors
   (c) Bio-medical sensors

4) On the basis of response to the measurement point-
   (a) Point to point sensors
   (b) Multiplex sensors 5

1-a-INTRINSIC FIBER OPTIC SENSORS: In such type of sensors (Fig.13), sensing takes place within the fiber itself. These type of sensors have their dependency on the optical fiber properties itself to convert an environmental action into a modulation of the light beam passing through it. Virtually, any environmental effect can be converted to an optical signal to be interpreted .Each environmental effect may be measured by dozens of different fiber optic sensors approaches. It has been designed in such a way that it sensed only the environmental effects. • The most important characteristics of intrinsic fiber optic sensors is that it provides distributed sensing over long distances.

1-b-EXTRINSIC FIBER OPTIC SENSORS: In such type of sensors (Fig.14), sensing takes place in a region outside of the fiber and essentially fiber serves as a conduit for the to and from transmission of light to the sensing region efficiently and in a desired form. These sensors may be used strictly as information carriers that lead up to a black box to impress information on a light beam that propagates to a remote receiver. The black box may contain mirrors, a gas or liquid cell ,a cantilevered arm or dozens of other mechanisms that may generate ,modulate or transform a light beam. The most important advantage of using these sensors is that their ability to reach places which seems to be unreachable.

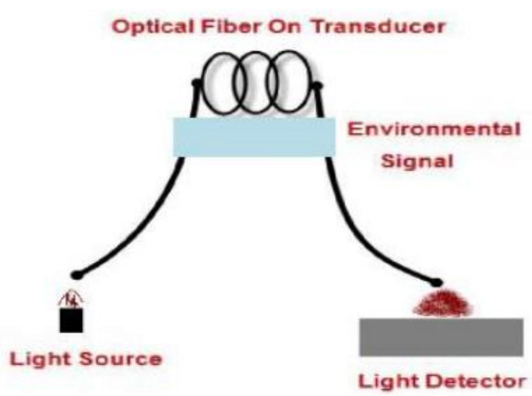


Fig.13 interinsic-type fiber-optic sensor.

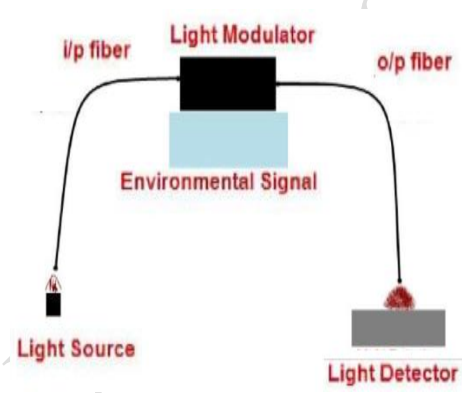


Fig.14 Extrinsic-type fiber-optic sensor.

7. Applications (Fig.15)

A number of differing methods are used to gather the data by using the transmission, reflection & scattering properties of fibre as it reacts to local forces. (eg: Rayleigh, Raman & Brillouin scattering). Each method is chosen to best serve an application based on the distance, accuracy/resolution, and speed of measurement required. The light is often required to travel long distances, or is very weak upon its return so many systems also require special stages of amplifiers. Other enabling developments have been the advances in the actual cable and attachment technology to ensure when the fibre is being laid, attached or embedded it only senses the required element it is looking for. This also leads to high reliability and low maintenance of the sensing system.

a. Application for Acoustic sensing:

Acoustic sensing is a technology used to monitor all sort of sensitive locations, from oil & gas pipelines to railway tracks, military bases and international borders. Recently we have also seen that this technology serves for fracking. This system deploys fibre optic underground and uses sharp pulses of laser light, usually of a narrow band and low phase noise. When sounds from above are transmitted through the ground, they cause minuscule vibrations in the cable, and so can be sensed. This is also used for detecting leaks in off shore pipelines, as fibres sense the changing of acoustic pitch of the surrounding water. Acoustic sensing can also be used to determine the presence of gas bubbles in oil pipes, which in turn can be interpolated into flow data.

b. Application for Temperature sensing:

Measuring temperature; this is a similar idea to the acoustic sensing. A system pulses laser light through a fibre optic cable and **detects** the amount and type of light reflected back to the unit. By using sophisticated algorithms, this light backscatter is translated into temperature data. Systems can detect change in temperature of less than 0.01°C and pinpoint the location of a thermal event to within one metre. This system is widely used in oil & gas industries to monitor in real time down hole temperatures, long pipelines for leaks. The very low power and optical nature of the sensing makes this ideal for use with hazardous flammable materials or harsh environments such as deserts or arctic conditions.

c. Application for Strain & Pressure sensing:

A distributed strain system can accurately locate ground movements near pipelines such as landslides, erosion or seismic activity with a resolution of 20 microstrain at 1metre intervals over many kilometres. Strain sensing is also used to monitor underground tunnels or in cities to monitor local structures while major close-by excavations might be undertaken. Monitoring can be done continuously with one interrogator looking at many channels by using a combination of **circulators** & **switches** or routinely as part of regular inspections.

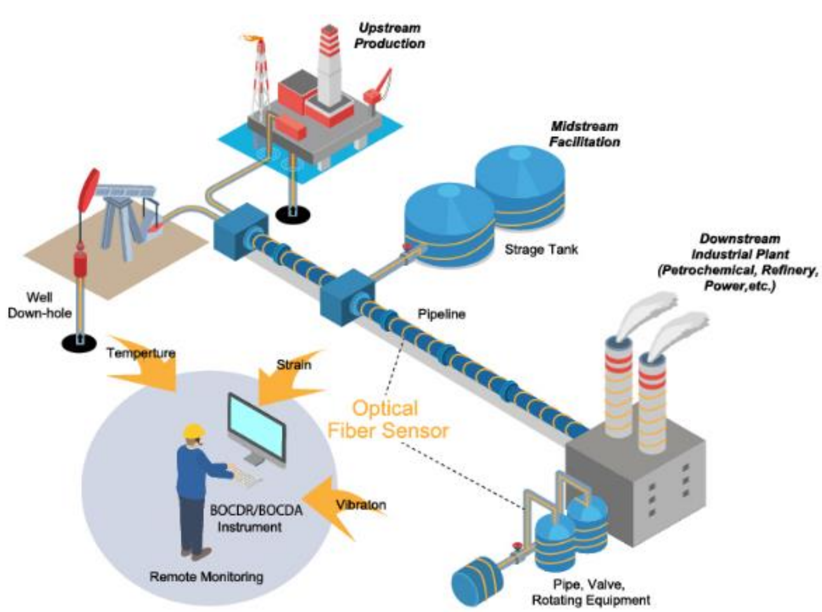
d. Application for Intruder detection:

Fibre sensing systems can pick up tiny vibrations and combine some of the sensing methods described above. They can be constructed into a range of intruder detection applications. A fibre can be imbedded into a fence, pipeline or trench and linked to a system which can detect and identify locations of disturbances.

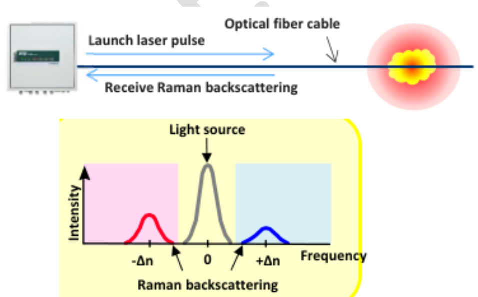
e. Typical applications:

1. Tunnel safety monitoring: Using pulses of laser light transmitted through an optical fiber cable, the DTSX can determine temperature by intensity variations of Raman-scattering that phenomenon occurs along the entire length of the optical fiber cable, and it also can determine the locations of those temperature readings using light that is bounced back (backscattering) to the source.
2. Pipeline L eak Detection: By capturing changes in the surface temperature of the pipeline in 1-meter units at least every 10 seconds. That means it can immediately detect leaks of any size, and even makes it easy to find the location of a leak.

a. Applications for social infrastructure.

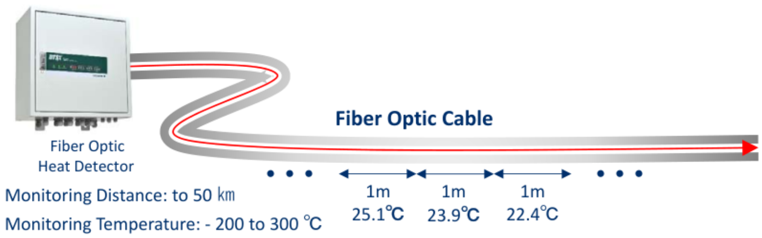


b. Applications for plants

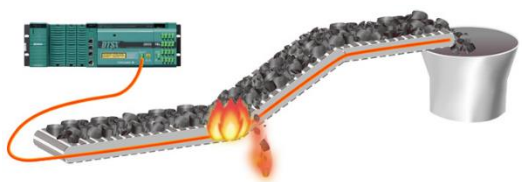


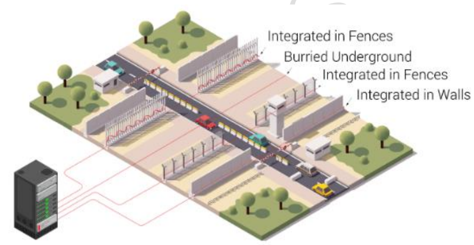
c. Tunnel safety monitoring.

d. Pipeline L eak Detection.



e. The Fiber Optic Cable Is the Temperature Sensor.





f. Conveyor Belt Fire Detection **g. Perimeter security.**

Fig.15 Typical applications of fiber optic sensors.

4.5 No-Touch Sensors

There are four types of no-touch sensors: inductive, capacitive, ultrasonic, and photoelectric (Table 1). Inductive proximity sensors use an electromagnetic field to detect the presence of metal objects. Capacitive proximity sensors use an electrostatic field to detect the presence of any object. Ultrasonic proximity sensors use sound waves to detect the presence of objects. Photoelectric sensors react on changes in the received quantity of light. Some photoelectric sensors can even detect a specific colour.

Sensor	Objects Detected	Technology
Inductive	Metal	Electromagnetic Field
Capacitive	Any	Electrostatic Field
Ultrasonic	Any	Sound Waves
Photoelectric	Any	Light

Table 1 Comparison of sensors.

4.6 Detection Based on "Eddy Current" Proximity Sensors

1. Operating Principles of Proximity Sensors (Figs.16-17)

a. Detection Principle of Inductive Proximity Sensors Inductive Proximity Sensors detect magnetic loss due to eddy currents that are generated on a conductive surface by an external magnetic field. An AC magnetic field is generated on the detection coil, and changes in the impedance due to eddy currents generated on a metallic object are detected. Other methods include Aluminum-detecting Sensors, which detect the phase component of the frequency, and All-metal Sensors, which use a working coil to detect only the changed component of the impedance. There are also Pulse-response Sensors, which generate an eddy current in pulses and detect the time change in the eddy current with the voltage induced in the coil. The sensing object and Sensor form what appears to be a transformer-like relationship.

b. Detection Principle of Capacitive Proximity Sensors: Capacitive Proximity Sensors detect changes in the capacitance between the sensing object and the Sensor. The amount of capacitance varies depending on the size and distance of the sensing object. An ordinary Capacitive Proximity Sensor is similar to a capacitor with two parallel plates, where the capacity of the two plates is detected. One of the plates is the object being measured (with an imaginary ground), and the other is the Sensor's sensing surface. The changes in the capacity generated between these two poles are detected. The objects that can be detected depend on their dielectric constant, but they include resin and water in addition to metals.

c. Detection Principle of Magnetic Proximity Sensors: The reed end of the switch is operated by a magnet. When the reed switch is turned ON, the Sensor is turned ON.

1. Outline of eddy-current proximity sensors (Fig.18)

A proximity sensor can detect metal targets approaching the sensor, without physical contact with the target. Proximity sensors are roughly classified into the following three types according to the operating principle: the high-frequency oscillation type using electromagnetic induction, the magnetic type using a magnet, and the capacitance type using the change in capacitance.

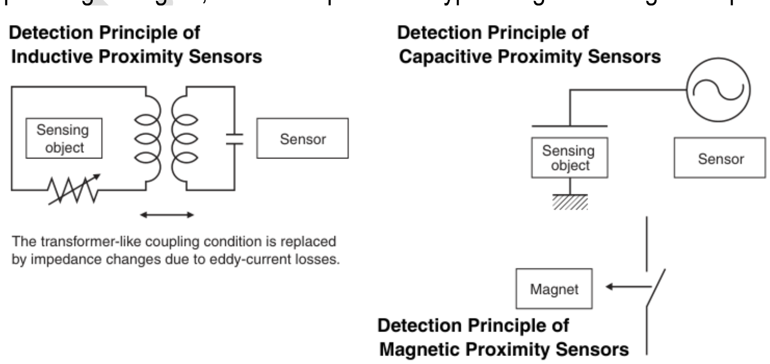


Fig.16 Operating principles of proximity sensors.

Items requiring confirmation	Inductive Proximity Sensors	Capacitive Proximity Sensors	Magnetic Proximity Sensors
Sensing object	Metallic objects (iron, aluminum, brass, copper, etc.)	Metallic objects, resins, liquids, powders, etc.	Magnets
Electrical noise	Affected by positional relationship of power lines and signal lines, grounding of cabinet, etc. CE Marking (EC Directive compliance) Sensor covering material (metal, resin). Easily affected by noise when the cable is long.		Almost no effect.
Power supply	DC, AC, AC/DC, DC with no polarity, etc. Connection method, power supply voltage.		
Current consumption	Depends on the power supply, i.e., DC 2-wire models, DC 3-wire models, AC, etc. DC 2-wire models are effective for suppressing current consumption.		
Sensing distance	The sensing distance must be selected by considering the effects of factors such as the temperature, the sensing object, surrounding objects, and the mounting distance between Sensors. Refer to the set distance in the catalog specifications to determine the proper distance. When high precision sensing is required, use a Separate Amplifier model.		
Ambient environment	Temperature or humidity, or existence of water, oils, chemicals etc. Confirm that the degree of protection (refer to the *Degree of Protection*) matches the ambient environment.		
Physical vibration, shock	An extra margin must be provided in the sensing distance when selecting Sensors for use in environments subject to vibration and shock. To prevent Sensors from vibrating loose, refer to the catalog values for tightening torque during assembly.		
Assembly	Effects of tightening torque, Sensor size, number of wiring steps, cable length, distance between Sensors, surrounding objects. Check the effects of surrounding metallic and other objects, and the specifications for the mutual interference between Sensors.		

Fig.17 Selection by Detection Method.

2. Principle and major types of eddy-current proximity sensors (Fig.19)

a. General sensor

A high-frequency magnetic field is generated by coil L in the oscillation circuit. When a target approaches the magnetic field, an induction current (eddy current) flows in the target due to electromagnetic induction. As the target approaches the sensor, the induction current flow increases, which causes the load on the oscillation circuit to increase. Then, oscillation attenuates or stops. The sensor detects this change in the oscillation status with the amplitude detecting circuit, and outputs a detection signal.

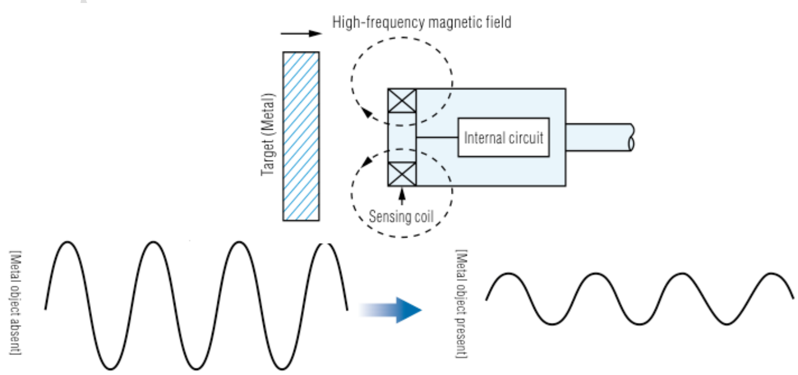
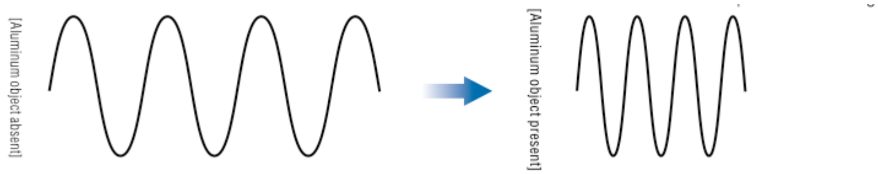


Fig.18 Eddy-current proximity sensors.



Magnetism	Strong ←		Weak
Detecting distance of general-purpose model	Long ←		Short
Detecting distance of aluminum detection model	Short		→ Long
Typical metal	Iron/SUS440	SUS304*	Aluminum/brass/copper

Fig.19 Magnetic objects and non-magnetic objects. Remember that magnetic objects are easily attracted by a magnet, whereas non-magnetic objects are not.

b. Nonferrous-metal type (Figs.20-21)

The nonferrous-metal type is included in the high-frequency oscillation type. The nonferrous-metal type incorporates an oscillation circuit in which energy loss caused by the induction current flowing in the target affects the change of the oscillation frequency. When a nonferrous-metal target such as aluminum or copper approaches the sensor, the oscillation frequency increases. On the other hand, when a ferrous-metal target such as iron approaches the sensor, the oscillation frequency decreases. When the oscillation frequency becomes higher than the reference frequency, the sensor outputs a detection signal.

3. Features

a. Detecting metal only

Inductive proximity sensors can only detect metal targets. They do not detect non-metal targets such as plastic, wood, paper, and ceramic. Unlike photoelectric sensors, this allows a proximity sensor to detect a metal object throughopaque plastic.

b. Excellent environmental resistance

Proximity sensors are durable. For example, most of all sensor head models satisfy the IP67 requirements by sealing the inside with filling material or other measures. Since these sensors only detect metal objects, the detection is not affected by accumulated dust or oil splash on the sensor head.

“Inductive displacement sensors” not only detect the presence of a target but also measure the distance to a target .

a. Type 1:

As the target approaches the sensor head, the eddy current loss increases and oscillation amplitude becomes smaller accordingly. This oscillation amplitude is rectified to obtain DC voltage variations. The rectified signal and distance have an approximate proportional relationship. The linearization circuit corrects the linearity to obtain a linear output that is proportional to the distance.

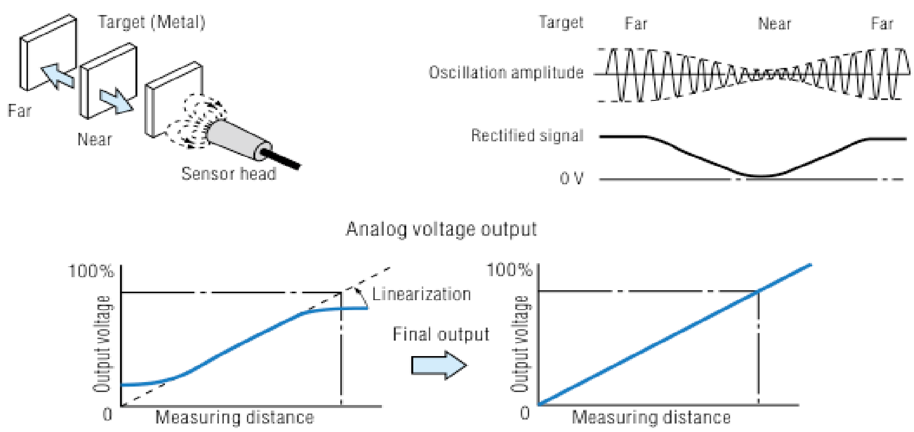


Fig.20 "Inductive displacement sensors" not only detect the presence of a target but also measurethe distance to a target.

b. Type 2:

As a target approaches the sensor head, the oscillation amplitude becomes smaller and the phase difference from the reference waveform becomes larger. By detecting changes in the amplitude and phase, the sensor can obtain a value approximately proportional to the distance. Then, a high-accuracy linearization processing corrects the value digitally based on the target material, to obtain a linear output that is proportional to the distance.

One type detects both amplitude and phase difference to enable detection of nonferrous metals such as copper and aluminum so that it can be an all metal supporting sensor. When only the magnitude of the amplitude is detected, it is hard to determine whether it is changing due to the change in the material or due to the distance to the target. Therefore, the sensor detects the change in the phase as well to verify the change in the material.

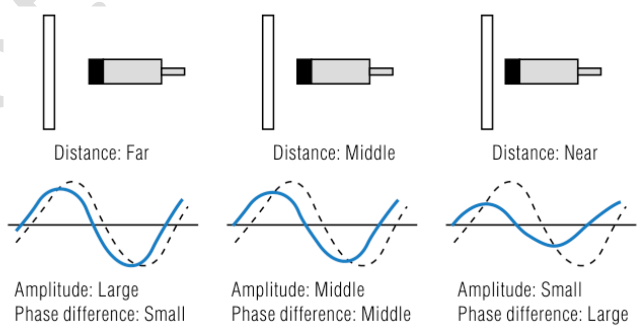


Fig.21 "Inductive displacement sensors" not only detect the presence of a target but also measurethe distance to a target. ------- Reference waveform.

4. Inductive Proximity Sensors- Principle of Operation

Most of inductive proximity sensors are of the Eddy Current Killed Oscillator (ECKO) type. This type of sensor contains four basic elements as shown in Figs.22-23.

The oscillator creates a radio frequency that is emitted from the coil away from the face of the sensor. If a metal plate enters this radiated field, eddy currents circulate within the metal.

The oscillator requires energy to maintain the eddy currents in the metal plate. As the plate approaches the sensor, the eddy currents increase and cause a greater load on the oscillator. The oscillator stops when the load becomes too great. The trigger circuit senses when the oscillator stops, then changes the state of the switching device (a transistor in DC sensors, a thyristor in AC sensors) to control the load.

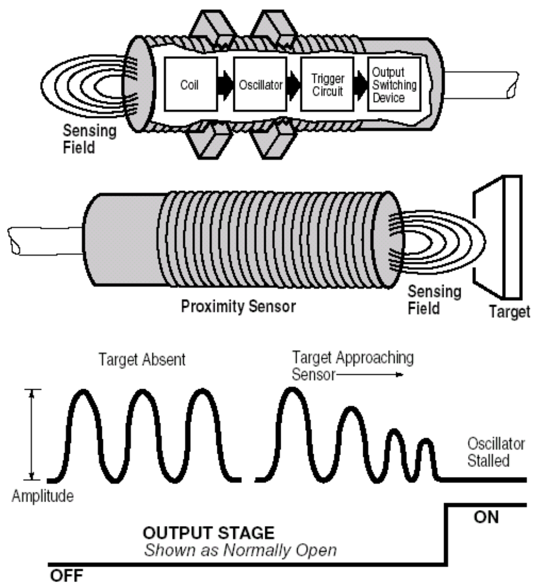


Fig.22 Inductive proximity sensor.

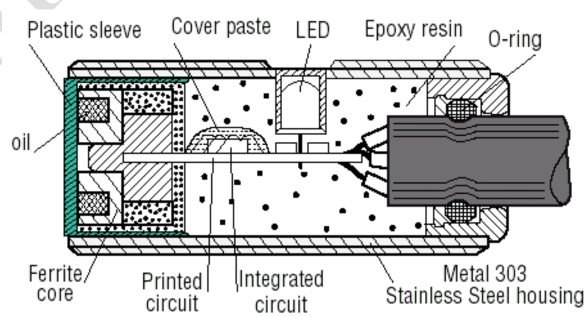


Fig.23 Typical housing of inductive proximity sensors.

5. Cpacitive Proximity Sensors- Principle of Operation

Capacitive sensors act similar to a simple capacitor. As shown in Fig.24, a metal plate, in the end of the sensor, is electrically connected to the oscillator. The object to be sensed acts as a second plate. When power is applied to the sensor, the oscillator senses the external capacitance between the target and the internal sensor plate. This forms a part of the feedback capacitance in the oscillator circuit. Capacitive sensors detect targets in the opposite manner as inductive sensors. As a target approaches a capacitive sensor, the oscillations increase until they reach a threshold level and activate a switching device.

The majority of proximity sensor housings are manufactured from 303 stainless steel, nickel-plated brass or crastin. Crastin housings are made with a semicrystalline polyenterephthalate material reinforced with short glass fibres. This combination of material is ideal for producing superior precision moulded parts with exceptionally low conductance. Crastin will retain dimensional stability and its electrical and dielectric properties are virtually unaffected by temperature changes or by wet environments.

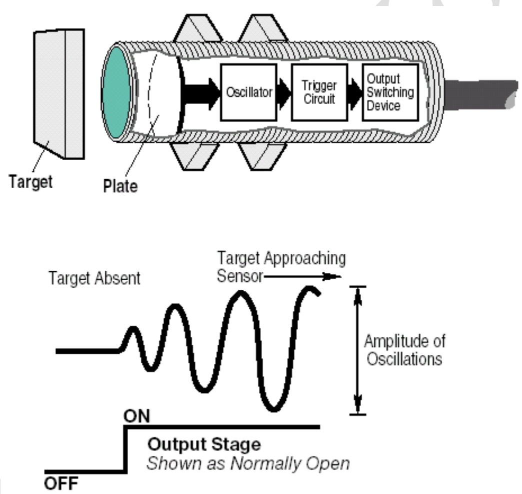


Fig.24 Capacitive proximity sensors.

6. Explanation of terms related to proximity sensors (Fig.25)

a. Standard Sensing Object: A sensing object that serves as a reference
b. Sensing Distance: The distance from the reference position (reference surface) to the measured operation (reset) when the standard sensing object is moved by the specified method.
c. Set Distance: The distance from the reference surface that allows stable use, including the effects of temperature and voltage, to the (standard) sensing object transit position. This is approximately 70% to 80% of the normal (rated) sensing distance.

d. Response Time:
   - t1: The interval from the point when the standard sensing object moves into the sensing area and the Sensor activates, to the point when the output turns ON.
   - t2: The interval from the point when the standard sensing object moves out of the Sensor sensing area to the point when the Sensor output turns OFF.

e. Response Frequency: The number of detection repetitions that can be output per second when the standard sensing object is repeatedly brought into proximity.

f. Hysteresis (Differential Travel): With respect to the distance between the standard sensing object and the Sensor, the difference between the distance at which the Sensor operates and the distance at which the Sensor resets.

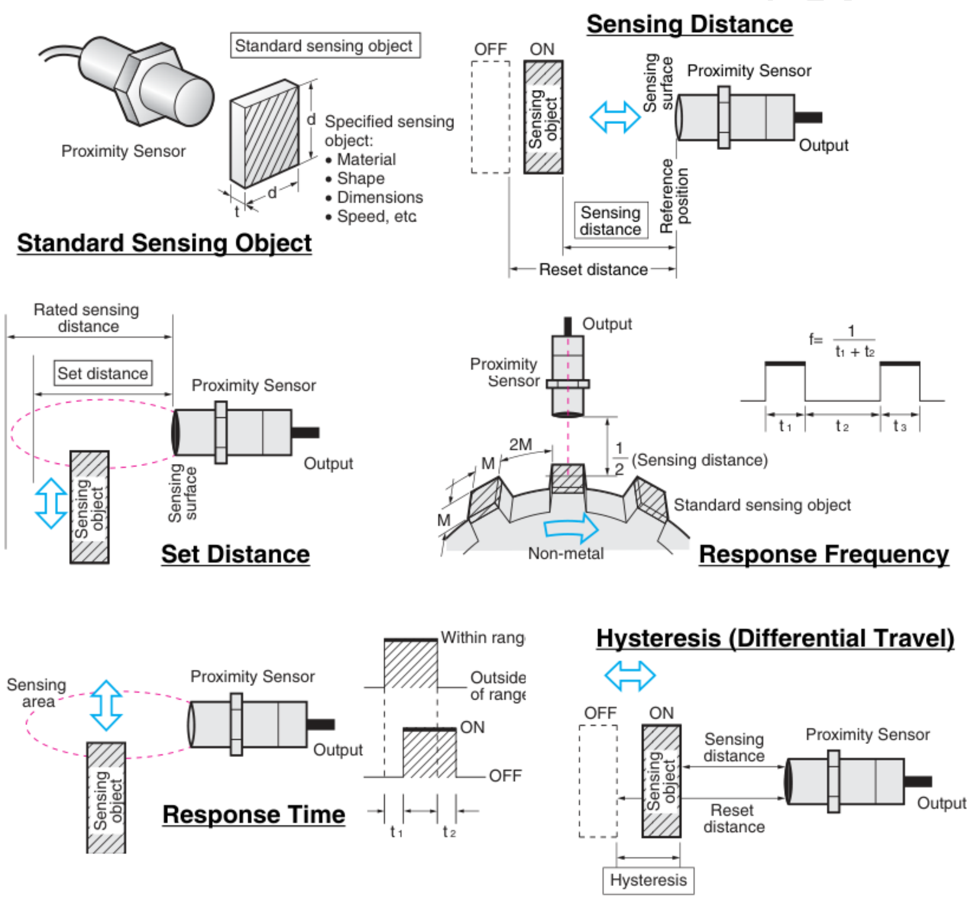


Fig.25 Explanation of terms related to proximity sensors.

4.7 Detection Based on "Ultrasonic" Ultrasonic sensors

1. What is ultrasonic?

"Ultrasonic" generally refers to a "high pitch sound that is inaudible to humans."

Sound is expressed by a unit called frequency (Hz). The greater the frequency, the higher the pitch of sound becomes. The unit Hz (hertz) means the number of oscillations per second. For example, a wave that oscillates 100 times in a second is expressed as 100 Hz. The audible range for humans is said to be between about 20 Hz and 20 kHz. In other words, ultrasonic waves have a frequency of 20 kHz or greater.

Comparison between optical sensors (reflective model) and ultrasonic sensors

Typical sensors used for distance measurement are optical sensors.

The following table shows the advantages and disadvantages when optical sensors and ultrasonic sensors are compared. Typical sensors used for distance measurement are optical sensors.

Familiar examples of devices using ultrasonic waves.In our ordinary life, the following ultrasonic sensors are used:

1. Fish detector (used for fishery or bass fishing)
2. Active sonar in a submarine (used for finding enemy submarines or battle ships)
3. Back sonar for cars (for detecting obstacles during backing a car to prevent single-car accident)

Item	Optical (reflective model) *	Ultrasonic
Detectable target	Detection is affected by target materials/colors	Detection is unaffected by target materials/colors
Detecting distance	1000 mm 3.94' max.	10 m 32.8' max.
Accuracy	High	Low
Response speed	Fast	Slow
Dust/water	Affected	Unaffected
Measuring range	Small	Large

Table 3 Excluding the Time of Flight (TOF) type.

2. Operating principle "Piezoelectric Ceramics-Figs.26-28"

Piezoelectric ceramics generate electromotive force between the electrodes in proportion to the amount of mechanical force applied to the element. The reverse is also true. If voltage is applied between the electrodes, mechanical displacement is generated proportional to that voltage. From the magnitude of the electromotive force, the presence of an object is detected and the distance from the Sensor to the object is measured.

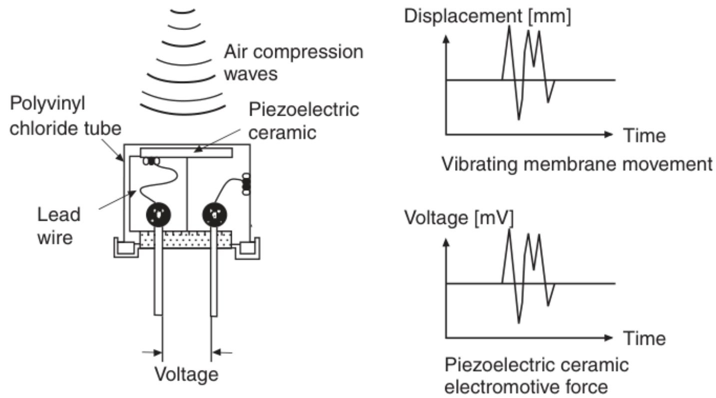


Fig.26 Operating principle "Piezoelectric Ceramics".

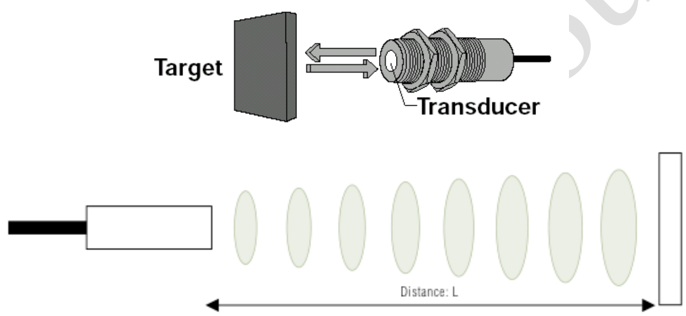


Fig.27 Theory of ultrasonic sensors.

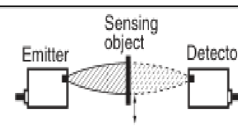
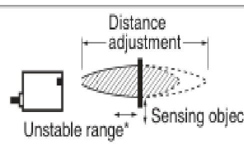
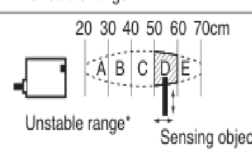
Through-beam		Detects the attenuation or interrupted condition of the ultrasonic beam caused by the object passing between the Emitter and Detector.	
Reflective	**Convergent reflective (Distance adjustable)**	Detects only the beam reflected from the object existing within the sensing distance range set with the distance adjuster.	
	Convergent reflective (Zone setting)	Detects only the beam reflected from the object existing in the sensing range set with the distance selector.	

Fig.28 Classification by sensing method.

As the name indicates, ultrasonic sensors measure distance by using ultrasonic waves. The sensor head emits an ultrasonic wave and receives the wave reflected back from the target. Ultrasonic sensors measure the distance to the target by measuring the time between the emission and reception. An optical sensor has a transmitter and receiver, whereas an ultrasonic sensor uses a single ultrasonic element for both emission and reception. In a reflective model ultrasonic sensor, a single oscillator emits and receives ultrasonic waves alternately. This enables miniaturization of the sensor head.

3. Distance calculation

The distance can be calculated with the following formula:

Distance $L = 1/2 \times T \times C$, where

L is the distance,

T is the time between the emission and reception, and C is the sonic speed. (The value is multiplied by 1/2 because T is the time for go-and-return distance.)

4. Features

The following list shows typical characteristics enabled by the detection system. As the name indicates, ultrasonic sensors measure distance by using ultrasonic waves. The sensor head emits an ultrasonic wave and receives the wave reflected back from the target. Ultrasonic sensors measure the distance to the target by measuring the time between the emission and reception.

1. [Transparent object detectable]: Since ultrasonic waves can reflect off a glass or liquid surface and return to the sensor head, even transparent targets can be detected.
2. [Resistant to mist and dirt]: Detection is not affected by accumulation of dust or dirt.
3. [Complex shaped objects detectable]: Presence detection is stable even for targets such as mesh trays or springs.

5. Terminology

a. Beam Angle: The beam angle is the angle formed by sound waves as they emanate from an ultrasonic sensor. The beam angle defines the usable area in which target detection is possible.

b. Limit zone (reflective models-Fig.29): Not only the maximum detection distance but also the minimum detection distance can be adjusted, in connection with or independently of the maximum distance. This detection range is called the limit zone (zone limit).

c. Non-sensitive zone and uncertainty zone (reflective models-Fig.29): The non-sensitive zone is the interval between the surface of the sensor head and the minimum detection distance resulting from detection distance adjustment. The uncertainty zone is the area close to the sensor where detection is not possible due to the sensor head configuratin and reverberations. Detection may occur in the uncertainty zone due to multi-reflection between the sensor and the object.

d. Directional characteristics (Fig.30): The ratio of the sound output (needed to transmit the specified sound energy to the target object) of the non-directivity emitter to the sound output of the directivity emitter is called the directivity gain. As the frequency and vibration area increase, the directivity grows sharper and sound waves are emitted with greater efficiency. The directivity of a sensor unit used as an ultrasound switch is 8° to 30° (sound pressure half-angle). The directivity is also strongly affected by the shape of the sensor horn and the vibration mode of the transducer, and thus the sensor unit shape, operation frequency, and transducer type are selected to provide the desired operation range.

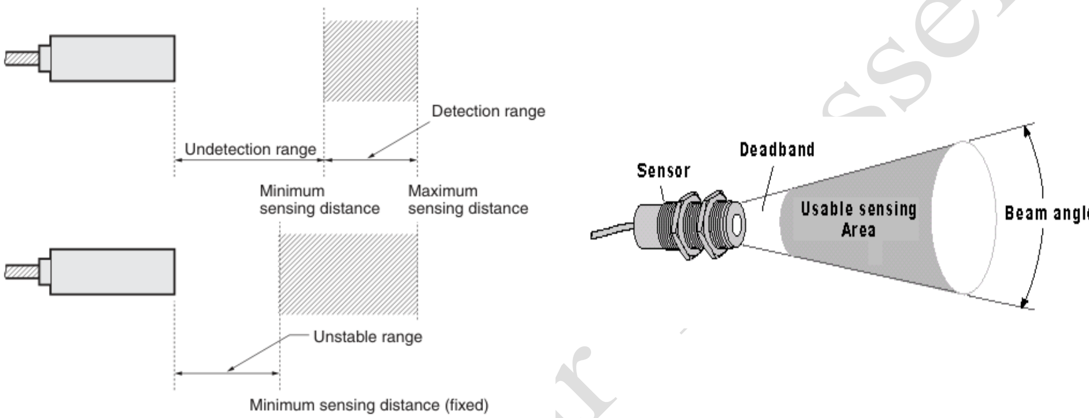


Fig.29 Limit zone and non-sensitive zone.

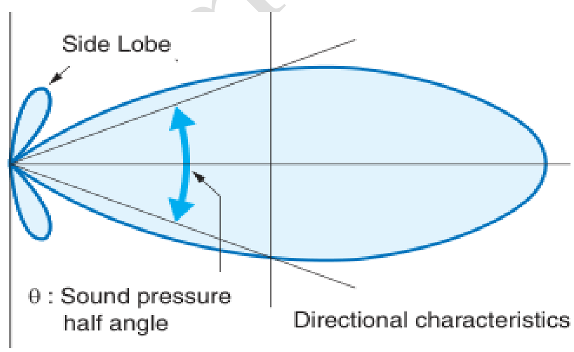


Fig.30 Directional characteristics.

6. Types and shapes of detection objects (reflective type-Fig.31): Detected objects can be classified as follows:

a. Flat-surface objects such as fluids, boxes, plastic sheets, paper, and glass.
b. Cylindrical objects such as cans, bottles, and human bodies.
c. Powders and chunk-like objects such as minerals, rocks, coal, coke, and plastic.

7. Target Response Curves

The surface area, shape and density of a target determine where it can be detected. The diagram shown in Fig.32 illustrates a target and its corresponding area of detection certain type of sensor. The target must lie completely in its specified sensing envelope to ensure accurate detection.

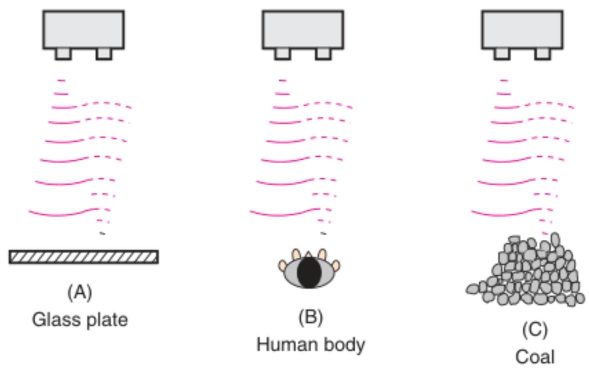


Fig.31 Types and shapes of detection objects.

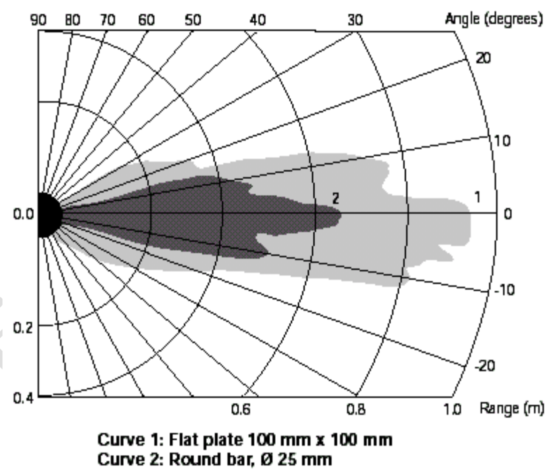


Fig.32 Response curves.

8. Environmental Influences

1. Rain or Snowfall: Rain or snow in moderate amounts will not effect the operation of ultrasonic sensors. However, the sensor should be mounted at an angle, which does not permit such media to rest on the transducer. Deposits/residue left from “standing” media can damage the transducer.) *Heavy* rain, heavy snowfall or freezing rain conditions will denigrate an ultrasonic sensor’s performance.

2. Wind: Moderate ambient air currents have little effect on ultrasonic sensor operation. (A wind speed of 30 mph will deflect a sound wave from its standard path by only ±3% max.)
3. Ambient Noise: Ultrasonic sensors are typically unaffected by audible noise produced by metal coils, compressed air, etc.
4. Ambient Temperature: Variations in the target area air temperature directly affect sensor sound wave propagation rates, and subsequent sensor accuracy. A. 17% change in propagation speed per degree Celsius is typical. For example, an ambient temperature change from 20°C to 40°C increases the sound wave travel speed by approximately 3.5%, making a stationary target appear slightly closer as the temperature rises. Several sensors have temperature compensated outputs.
5. Atmospheric Pressure: Daily changes in atmospheric pressure have a negligible effect on sound propagation.
6. Pressurised Atmospheres: Ultrasonic sensors are not designed for use in pressurised enclosures, as damage to the transducer is possible.
7. Steam: Applications which place an ultrasonic sensor in a steamy environment should be avoided. Steam can eventually penetrate the sensor housing, and damage the unit.
8. Washdown Environments: Ultrasonic Sensors are suitable for application in low-pressure "rinse" environments. In such applications, the transducer should be mounted at a slight angle to deter "standing water." Ultrasonics are not designed to withstand high-pressure washdowns.
9. Mutual interference: Sound waves produced by ultrasonic units mounted in close proximity to one another can cause unwanted sensor crosstalk. Fig.33 illustrates the recommended separation distances for multiple sensor installations:

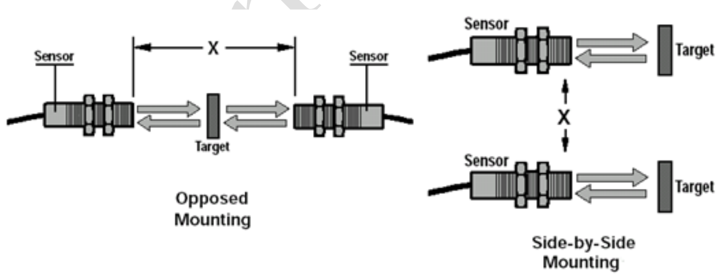


Fig.33 Mutual interference in ultrasonic sensors.

4.8 Measuring Strain with Strain Gages

1. Overview

The strain gauge (Figs.34-36) has been in use for many years and is the fundamental sensing element for many types of sensors, including pressure sensors, load cells, torque sensors, position sensors, etc. The majority of strain gauges are foil types, available in a wide choice of shapes and sizes to suit a variety of applications. They consist of a pattern of resistive foil which is mounted on a backing material. They operate on the principle that as the foil is subjected to stress, the resistance of the foil changes in a defined way.
The strain gauge is connected into a Wheatstone Bridge circuit with a combination of four active gauges (full bridge), two gauges (half bridge), or, less commonly, a single gauge (quarter bridge). In the half and quarter circuits, the bridge is completed with precision resistors.

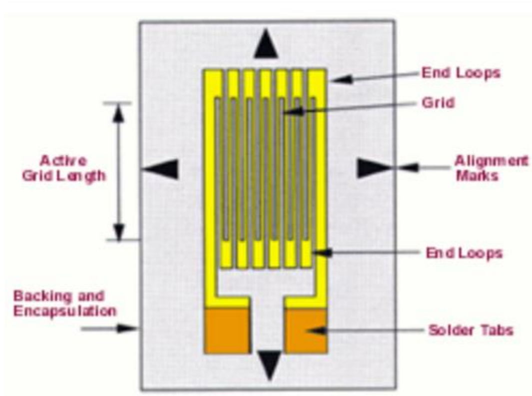


Fig.34 Strain gauge construction.

The complete Wheatstone Bridge (Fig.35) is excited with a stabilised DC supply and with additional conditioning electronics, can be zeroed at the null point of measurement. As stress is applied to the bonded strain gauge, a resistive changes takes place and unbalances the Wheatstone Bridge. This results in a signal output, related to the stress value. As the signal value is small, (typically a few millivolts) the signal conditioning electronics provides amplification to increase the signal level to 5 to 10 volts, a suitable level for application to external data collection systems such as recorders or PC Data Acquistion and Analysis Systems.
Most manufacturers of strain gauges offer extensive ranges of differing patterns to suit a wide variety of applications in research and industrialprojects.They also supply all the necessary accessories including preparation materials, bonding adhesives, connections tags, cable, etc. The bonding of strain gauges is a skill and training courses are offered by some suppliers. There are also companies which offer bonding and calibration services, either as an in-house or on-site service.

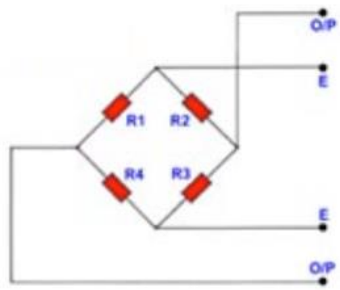


Fig.35 Wheatstone Bridge circuit.

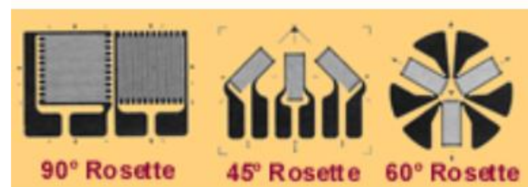


Fig.36 Some of the many Gauge Patterns available.

2. Principle of operation (Figs.36-39)

If a strip of conductive metal is stretched, it will become skinnier and longer, both changes resulting in an increase of electrical resistance end-to-end. Conversely, if a strip of conductive metal is placed under compressive force (without buckling), it will broaden and shorten. If these stresses are kept within the elastic limit of the metal strip (so that the strip does not permanently deform), the strip can be used as a measuring element for physical force, the amount of applied force inferred from measuring its resistance.

Such a device is called a strain gauge. Strain gauges are frequently used in mechanical engineering research and development to measure the stresses generated by machinery. Aircraft component testing is one area of application, tiny strain-gauge strips glued to structural members, linkages, and any other critical component of an airframe to measure stress. Most strain gauges are smaller than a postage stamp, and they look something like this:

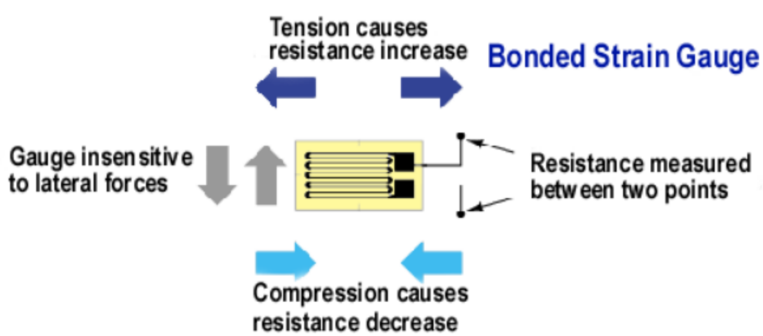


Fig.37 Principle of operation.

A strain gauge's conductors are very thin: if made of round wire, about 1/1000 inch in diameter. Alternatively, strain gauge conductors may be thin strips of metallic film deposited on a nonconducting substrate material called the carrier. The latter form of strain gauge is represented in the previous illustration. The name "bonded gauge" is given to strain gauges that are glued to a larger structure under stress (called the test specimen). The task of bonding strain gauges to test specimens may appear to be very simple, but it is not. "Gauging" is a craft in its own right, absolutely essential for obtaining accurate, stable strain measurements. It is also possible to use an unmounted gauge wire stretched between two mechanical points to measure tension, but this technique has its limitations.

Typical strain gauge resistances range from 30 Ohms to 3 kOhms (unstressed). This resistance may change only a fraction of a percent for the full force range of the gauge, given the limitations imposed by the elastic limits of the gauge material and of the test specimen. Forces great enough to induce greater resistance changes would permanently deform the test specimen and/or the gauge conductors themselves, thus ruining the gauge as a measurement device. Thus, in order to use the train gauge as a practical instrument, we must measure extremely small changes in resistance with high accuracy.

Such demanding precision calls for a bridge measurement circuit. Unlike the Wheatstone bridge shown in the last chapter using a null-balance detector and a human operator to maintain a state of balance, a strain gauge bridge circuit indicates measured strain by the degree of imbalance, and uses a precision voltmeter in the center of the bridge to provide an accurate measurement of that imbalance:

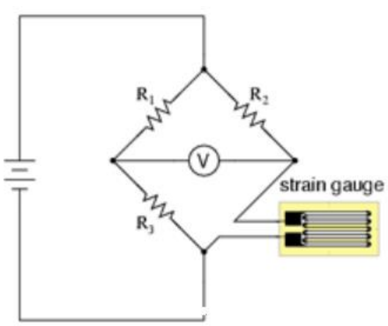


Fig.38 Quarter-Bridge strain gauge circuit.

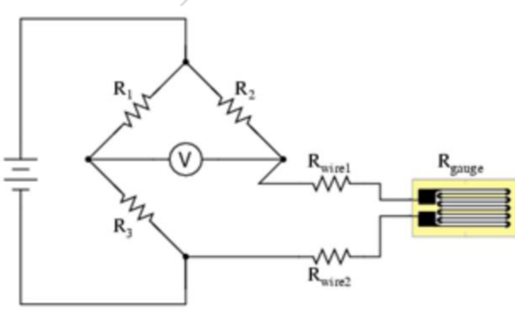


Fig.39 Two--wire Quarter-Bridge strain gauge circuit.

Typically, the rheostat arm of the bridge (R_2 in the diagram) is set at a value equal to the strain gauge resistance with no force applied. The two ratio arms of the bridge (R_1 and R_3) are set equal to each other. Thus, with no force applied to the strain gauge, the bridge will be symmetrically balanced and the voltmeter will indicate zero volts, representing zero force on the strain gauge. As the strain gauge is either compressed or tensed, its resistance will decrease or increase, respectively, thus unbalancing the bridge and producing an indication at the voltmeter. This arrangement, with a single element of the bridge changing resistance in response to the measured variable (mechanical force), is known as a quarter-bridge circuit (Figs.39-41).

As the distance between the strain gauge and the three other resistances in the bridge circuit may be substantial, wire resistance has a significant impact on the operation of the circuit. To

illustrate the effects of wire resistance, I'll show the same schematic diagram, but add two resistor symbols in series with the strain gauge to represent the wires:
The strain gauge's resistance (R_{gauge}) is not the only resistance being measured: the wire resistances Rwire1 and Rwire2, being in series with Rgauge, also contribute to the resistance of the lower half of the rheostat arm of the bridge, and consequently contribute to the voltmeter's indication. This, of course, will be falsely interpreted by the meter as physical strain on the gauge.
While this effect cannot be completely eliminated in this configuration, it can be minimized with the addition of a third wire, connecting the right side of the voltmeter directly to the upper wire of the strain gauge:

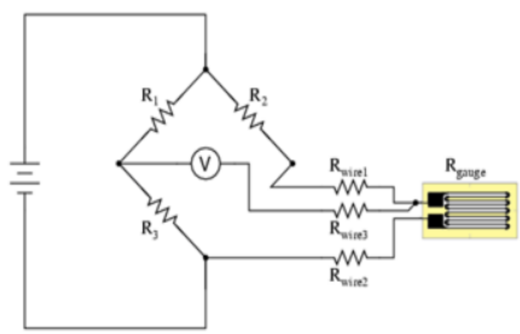


Fig.40 Three-wire Quarter-Bridge strain gauge circuit.

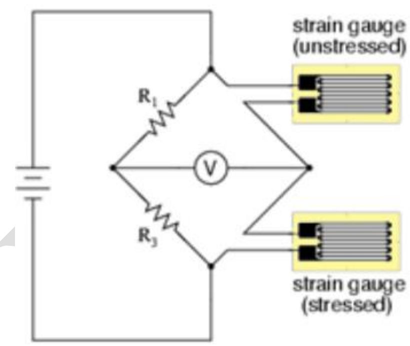


Fig.41 Quarter-Bridge strain gauge circuit with temperature compensation.

Because the third wire carries practically no current (due to the voltmeter's extremely high internal resistance), its resistance will not drop any substantial amount of voltage. Notice how the resistance of the top wire (R_{wire1}) has been "bypassed" now that the voltmeter connects directly to the top terminal of the strain gauge, leaving only the lower wire's resistance (R_{wire2}) to contribute any stray resistance in series with the gauge. Not a perfect solution, of course, but twice as good as the last circuit!
There is a way, however, to reduce wire resistance error far beyond the method just described, and also help mitigate another kind of measurement error due to temperature. An unfortunate characteristic of strain gauges is that of resistance change with changes in temperature. This is a property common to all conductors, some more than others. Thus, our quarter-bridge circuit as shown (either with two or with three wires connecting the gauge to the bridge) works as a thermometer just as well as it does a strain indicator.
If all we want to do is measure strain, this is not good. We can transcend this problem, however, by using a "dummy" strain gauge in place of R_2, so that both elements of the rheostat arm will change resistance in the same proportion when temperature changes, thus canceling the effects of temperature change:
Resistors R_1 and R_3 are of equal resistance value, and the strain gauges are identical to one another. With no applied force, the bridge should be in a perfectly balanced condition and the

voltmeter should register 0 volts. Both gauges are bonded to the same test specimen, but only one is placed in a position and orientation so as to be exposed to physical strain (the active gauge). The other gauge is isolated from all mechanical stress, and acts merely as a temperature compensation device (the "dummy" gauge).

If the temperature changes, both gauge resistances will change by the same percentage, and the bridge's state of balance will remain unaffected. Only a differential resistance (difference of resistance between the two strain gauges) produced by physical force on the test specimen can alter the balance of the bridge. Wire resistance doesn't impact the accuracy of the circuit as much as before, because the wires connecting both strain gauges to the bridge are approximately equal length. Therefore, the upper and lower sections of the bridge's rheostat arm contain approximately the same amount of stray resistance, and their effects tend to cancel.

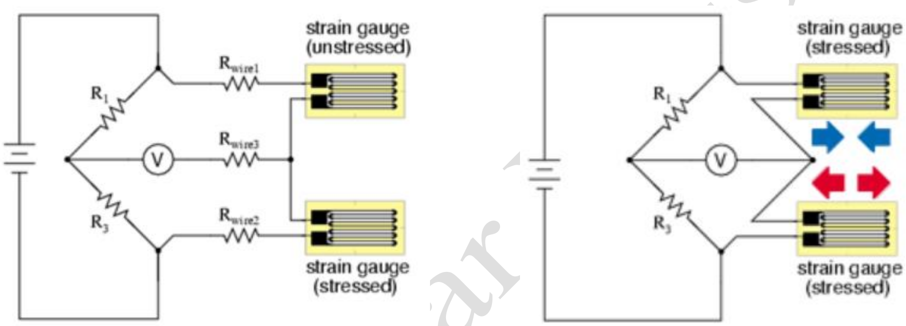


Fig.42 Half-Bridge strain gauge ciruit.

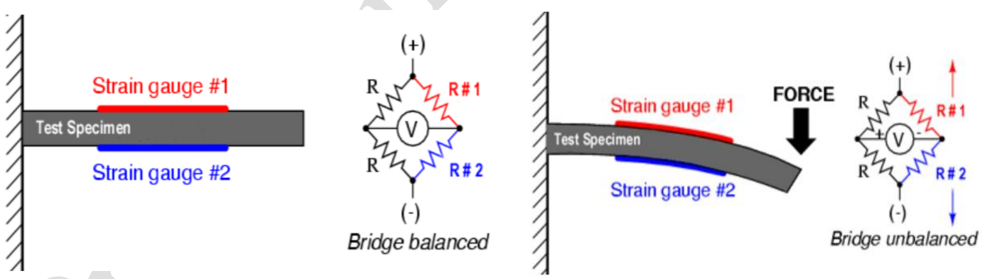


Fig.43 A pair of strain gauges may be bonded to a test specimen

An example of how a pair of strain gauges may be bonded to a test specimen so as to yield this effect is illustrated in Fig.43.

With no force applied to the test specimen, both strain gauges have equal resistance and the bridge circuit is balanced. However, when a downward force is applied to the free end of the specimen, it will bend downward, stretching gauge #1 and compressing gauge #2 at the same time:

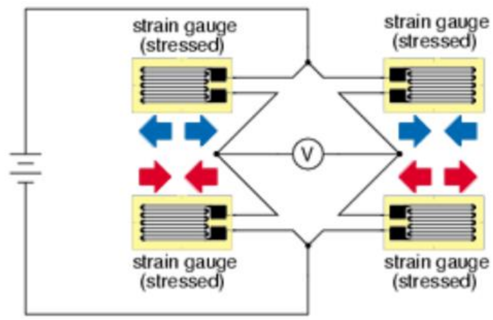


Fig.44 Full-Bridge strain gauge circuit.

In applications where such complementary pairs of strain gauges can be bonded to the test specimen, it may be advantageous to make all four elements of the bridge "active" for even greater sensitivity. This is called a full-bridge circuit (Fig.44).

Both half-bridge (Fig41) and full-bridge (Fig.44) configurations grant greater sensitivity over the quarter-bridge circuit, but often it is not possible to bond complementary pairs of strain gauges to the test specimen. Thus, the quarter-bridge circuit is frequently used in strain measurement systems.

When possible, the full-bridge configuration is the best to use. This is true not only because it is more sensitive than the others, but because it is linear while the others are not. Quarter-bridge and half-bridge circuits provide an output (imbalance) signal that is only approximately proportional to applied strain gauge force.

Linearity, or proportionality, of these bridge circuits is best when the amount of resistance change due to applied force is very small compared to the nominal resistance of the gauge(s). With a full-bridge, however, the output voltage is directly proportional to applied force, with no approximation (provided that the change in resistance caused by the applied force is equal for all four strain gauges!).

Unlike the Wheatstone and Kelvin bridges, which provide measurement at a condition of perfect balance and therefore function irrespective of source voltage, the amount of source (or "excitation") voltage matters in an unbalanced bridge like this. Therefore, strain gauge bridges are rated in millivolts of imbalance produced per volt of excitation, per unit measure of force. A typical example for a strain gauge of the type used for measuring force in industrial environments is 15 mV/V at 1000 pounds. That is, at exactly 1000 pounds applied force (either compressive or tensile), the bridge will be unbalanced by 15 millivolts for every volt of excitation voltage. Again, such a figure is precise if the bridge circuit is full-active (four active strain gauges, one in each arm of the bridge), but only approximate for half-bridge and quarter -bridge arrangements.

Strain gauges may be purchased as complete units, with both strain gauge elements and bridge resistors in one housing, sealed and encapsulated for protection from the elements, and equipped with mechanical fastening points for attachment to a machine or structure. Such a package is typically called a load cell.

4.9 Pressure Measurement Overview

1. Overview

A pressure sensor (Fig.45) is a device equipped with a pressure-sensitive element that measures the pressure of a gas or a liquid against a diaphragm made of stainless steel, silicon, etc., and converts the measured value into an electrical signal as an output.

2. Features

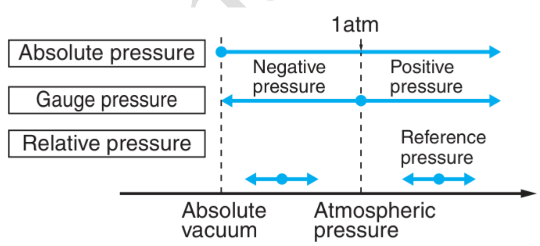
a. Different sensors are used for different measurement targets, such as liquids, gases, flammable substances, and corrosive substances.

b. There are sensors that measure the absolute pressure and those that measure the pressure relative to atmospheric pressure or a specified pressure. For sensors that use atmospheric pressure as a reference, there are sensors that measure negative pressures and positive pressures.

i. Gauge Pressure: The amount of pressure is expressed in terms of atmospheric pressure. It is referred to as "positive pressure" when it is greater than one atmosphere, and "negative pressure" when it is less than one atmosphere.

ii. Absolute Pressure: This is the amount of pressure expressed in relation to an absolute vacuum.

iii. Pressure Difference (Relative Pressure): This is the amount of pressure compared to any particular pressure (the reference pressure).



	kgf/cm²	mmHg	mmH₂O	Pa
1kgf/cm²	1	735.559	1.000028×10^4	0.0980665M
1mmHg	1.3595×10^{-3}	1	1.3595×10	0.133322k
1mmH₂O	0.99997×10^{-4}	7.356×10^{-2}	1	0.00980665k
1Pa(N/m²)	1.0197×10^{-5}	7.5006×10^{-3}	0.10197	1

Fig.45 Pressure Unit Conversion Table.

3. Operating Principles (Figs.46-48)

a. A semiconductor piezo-resistance dispersion pressure sensor has a semiconductor distortion gauge formed on the surface of the diaphragm, and it converts changes in electrical resistance into an electrical signal by means of the piezo-resistance effect that occurs when the diaphragm is distorted due to an external force (pressure).

b. A static capacitance pressure sensor has a capacitor that is formed by a static glass electrode and an opposing movable silicon electrode, and it converts changes in static capacitance that occur when the movable electrode is distorted due to an external force (pressure) into an electrical signal.

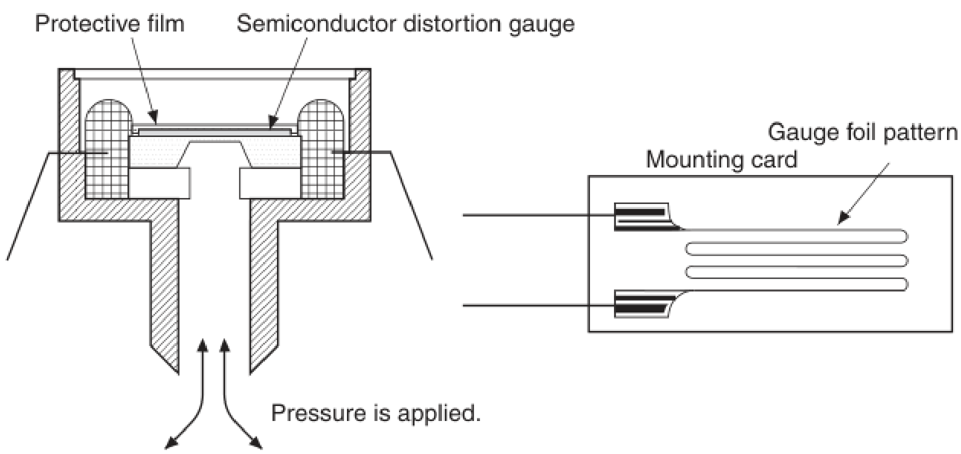


Fig.46 Semiconductor Distortion Gauge Construction.

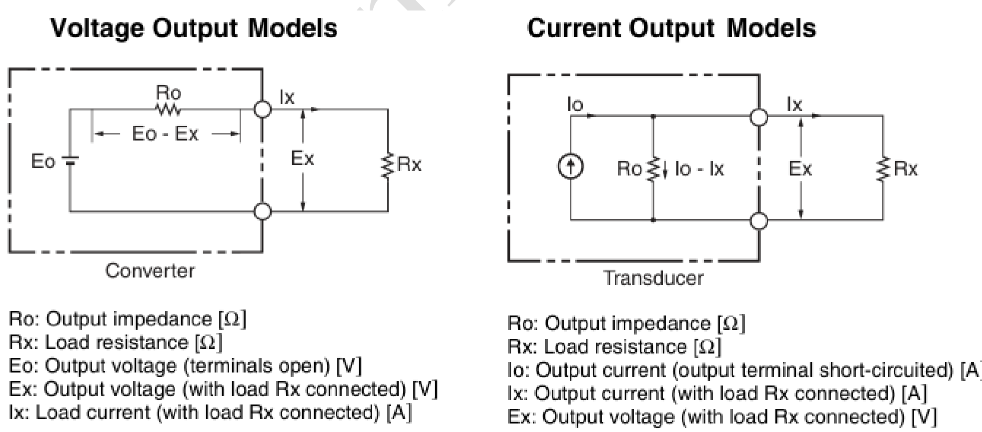
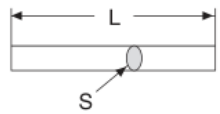


Fig.47 Measuring the output impedence.

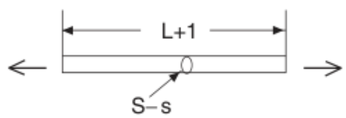


The electrical resistance of the above conductor is expressed by the following formula:

$R = \rho \times L/S$.

$\left(\begin{array}{ll} \rho: & \text{Electrical resistivity} \\ L: & \text{Conductor length} \\ S: & \text{Conductor cross-sectional area} \end{array}\right)$

When this conductor is pulled to the right or left as shown below, the length increases and the cross-sectional area decreases.



The electrical resistance of the above conductor is expressed by the following formula:

$R' = \rho \times (L+1)/(S-s)$.

Accordingly,

$R' > R$.

This shows how the application of a mechanical force changes the electrical resistance.

Fig.48 Piezo-resistance Effect.

4.10 Measuring Load and Torque with Bridge-Based Sensors

1. Overview

This section provides information to help you understand fundamentals of load and torque measurements and how different sensor specifications impact load cell or torque sensor performance in your application. In addition to the sensor characteristics, you must consider the required hardware to properly condition and acquire load and torque measurements. For example, nonconditoned sensors require voltage excitation, which is only available in certain measurement hardware.

2. What are force, load, and torque?

Force is the measure of interaction between bodies: for every action there is an equal and opposite reaction. Force is also described as a push or pull on an object. It is a vector quantity with both magnitude and direction. Load is a term frequently used to refer to the force exerted on a structure or body. The SI-recognized unit for force or load is the Newton (N). Load cells (Fig.49)

directly measure force or weight. These transducers convert mechanical force into electrical signals by measuring deformations produced by the force or weight. A common application of these devices is measuring dry or liquid materials in a hopper. A measure of the weight through a load cell yields a measure of the quantity of the material in the hopper.
Torque is the tendency of a force to rotate an object about an axis. Similar to force being described as push or pull, torque can be described as a twist to an object. The recognized SI unit of measure for torque is Newton-meters (Nm). Using a simple definition, torque is equivalent to force times distance, where a clockwise torque or twist is usually positive and a counter-clockwise torque is usually negative. Torque sensors are composed of strain gages that are affixed to a torsion bar. As the bar turns, the gages respond to the bar's sheer stress, which is proportional to the torque.

Fig.49 Load cells are used to measure force or weight.

Fig.50 Rotary slip ring torque sensors can be used to measure startup, running, and stall torque levels

3. How do load cells work?
The many different types of load cells operate in different ways (Figs.49-51, but the most commonly used load cell is the strain gage load cell. In general, you use a beam or yoke assembly that has several strain gages mounted in a Wheatstone bridge configuration so that the application of a force causes a strain in the assembly the strain gages are measuring. Generally, these devices are calibrated so that the force is directly related to the resistance change. Less commonly used pneumatic and hydraulic load cells translate force into pressure measurements. When force is applied to one side of the piston or diaphragm, the amount of pressure (pneumatic or hydraulic) applied to the other side to balance that force is measured. The most critical mechanical component of a load cell or strain gage transducer is the structure (spring element). The structure reacts to the applied load and focuses that load into an isolated, uniform strain field where strain gages can be placed for load measurement. The three common load cell structure designs—multiple-bending beam, multiple column, and shear web-form the basic building blocks for all possible load cell profiles and/or configurations.

a. Multiple-bending beam load cells

Are low capacity (20 to 22K N) and feature a wheel-shaped spring element that is adaptable to low-profile transducers. It contains four active gages or sets of gages per bridge arm, with pairs subjected to equal and opposite strains (tension and compression).

b. Multiple-column load cells

Consist of multiple columns for higher capacity (110K to 9M N). In this arrangement, each bridge arm contains four active strain gages, with two aligned along the principal axis of strain and the other two in the traverse direction to compensate for Poisson's effect.

c. Shear-web load cells

Have a medium capacity (2K to 1M N) and use a wheel form with radial webs subject to direct shear. The four active strain gages per bridge arm are bonded to the sides of the web, 45 deg to the axis of the beam.

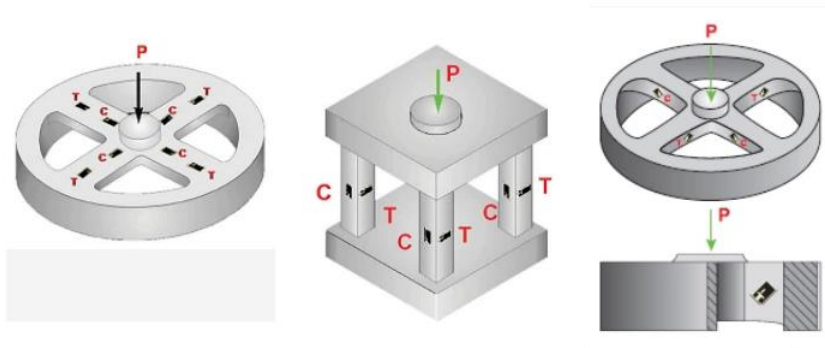


Fig.51 Load cell structure designs mount strain gages to measure compression and tension in different ways.

4. How to choose the right load cell?

Load cells operate in two basic modes: the compression mode, during which the weighing vessel sits on one or more load cells, or the tension mode, during which the weighing vessel hangs from one or more load cells. You can design the different load cell structure configurations discussed in the previous section using any of these configurations for compression-only forces, or you can design them to measure both a tension and compression force. Beyond the principal measurement, you select a load cell primarily based on capacity, accuracy, and physical mounting constraints or environmental protection. You cannot determine expected performance by any one factor. You must pinpoint it through a combination of different sensor parameters and the way you designed the load cell into your system. Refer to the table Table 4 to compare the range, accuracy, sensitivity, and price of different load cell types.

a. Capacity.

Define your minimum and maximum capacity requirements. Be sure to select the capacity over the maximum operating load and determine all extraneous load and moments before selecting a load cell. The load capacity must be capable of supporting the following:

1. Weight of the weighing structure (dead load).
2. Maximum live load that can be applied (including any static overload).
3. Additional overload arising from external factors such as wind loading or seismic activity.

b. Measurement frequency.

Load cells are designed for general-purpose use or are fatigue-rated to withstand millions of load cycles with no effect on performance. General-purpose load cells are designed for static or low-cycling frequency load.applications. They typically survive up to 1 million cycles depending on the load level and transducer material. Fatigue-rated load cells are typically designed to achieve 50 million to 100 million fully reversed load cycles, depending on the load level and amplitude.

c. Physical and environmental constraints.

One of the key characteristics to consider is how you are integrating the load cell into your system. Identify any physical restrictions that limit size (width, height, length, and so on) or the way the load cell can be mounted. Most tension and compression load cells feature center female threads on top and bottom for fixturing, but they also may have male threads or a mixture of both. Consider how the system will operate and what the worst-case operating conditions may be—the widest temperature range, the smallest weight change required to be measured, the worst environmental conditions (flood, tempest, seismic activity), and the maximum overload conditions.

5. How do torque sensors work?

a. Reaction Torque Sensors

Reaction torque is the turning force, or moment, imposed on the stationary portion of a device by the rotating portion as power is delivered or absorbed. If the load source is held rigid while the drive source is trying to rotate, the torque is sensed. Reaction torque sensors are restrained so they cannot rotate 360 deg without the cable wrapping up because the housing or cover is fixed to the sensor element. These sensors are commonly used to measure torque of a back-and-forth agitating type motion. Because these sensors do not use bearings, slip rings, or any other rotating elements, their installation and use can be very cost-effective.

b. Rotary Torque Sensors

Rotating torque sensors are similar in design and application to reaction torque sensors except that the torque sensor is installed in line with the device under test. Since the shaft of a torque sensor is rotating 360 deg, these sensors must have a way to transfer the signals from the rotational element to a stationary surface. You can accomplish this by using slip rings, rotary transformers, or telemetry.

c. Slip Ring Method (Fig.52)

For the slip ring method, the strain gage bridge is connected to four silver slip rings mounted on the rotating shaft. Silvergraphite brushes rub on these slip rings and provide an electrical path for the incoming bridge excitation and the outgoing signal. You can use either AC or DC to excite the strain gage bridge.

Load Cell Sensors	Price	Weight Range	Accuracy	Sensitivity	Comparison
Beam style	Low	10 – 5k lb	High	Medium	▪ Used with tanks, platform scales ▪ Best for linear forces ▪ Strain gages are exposed and require protection
S Beam	Low	10 – 5k lb	High	Medium	▪ Used with tank, platform scales ▪ High side load rejection ▪ Loads can be uncentered ▪ Better sealing and protection than bending beam
Canister	Medium	Up to 500k lb	Medium	High	▪ Used for truck, tank, and hopper scales ▪ Handles load movements ▪ No horizontal load protection
Pancake/Low Profile	Low	5 – 500k lb	Medium	Medium	▪ All stainless steel ▪ Used with tanks, bins, scales ▪ No load movement allowed
Button and Washer	Low	Either 0 – 50k lb or 0 – 200k lb	Low	Medium	▪ Loads must be centered ▪ No load movement allowed

Table 4 Features of load cell sensors.

d. Rotary Transformer (Fig.53)

For the transformer method, the rotating transformers differ from conventional transformers only in that either the primary or secondary winding is rotating. One transformer is used to transmit the AC excitation voltage to the strain gage bridge and a second transformer is used to transfer the signal output to the nonrotating part of the transducer. Thus, two transformers replace four slip rings, and no direct contact is required between the rotating and stationary elements of the transducer.

e. Digital Telemetry

The digital telemetry method has no contact points. The system consists of a receiver-transmitter module, coupling module, and signal processing module. The transmitter module is integrated in the torque sensor. It amplifies, digitizes, and modulates the sensor signal onto a radio frequency carrier wave that is picked up by the caliper coupling module (receiver). The digital measurement data is then recovered by the signal processing module.

6. How to choose the right torque sensor?

Similar to your load cell selections, your torque sensor selections primarily depend on your capacity needs and physical or environmental requirements.

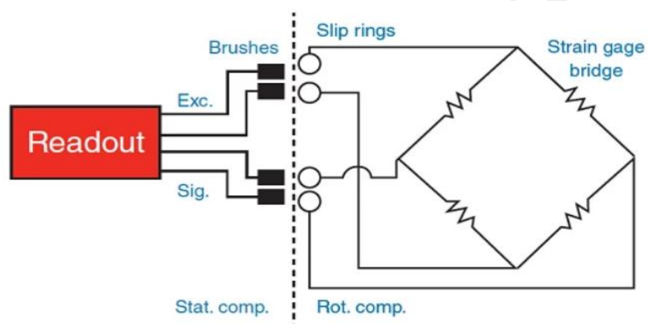


Fig.52 Slip rings provide an electrical path for excitation and the bridge measurement signal. [1]

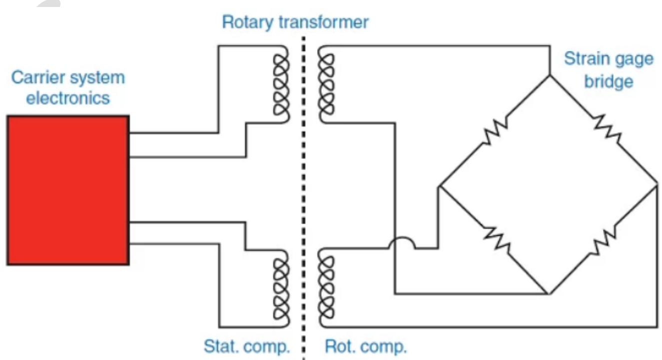


Fig.53 Two transformers are used - one to transmit the excitation signal and the other to transfer the bridge output signal.

a. Capacity.
To select the correct capacity, determine the minimum and maximum torque you expect. Extraneous torque and moments can increase the combined stress, which accelerates fatigue and affects sensor accuracy and performance. Any load other than torque, such as axial, radial, or bending, is considered extraneous and should be determined beforehand. If you cannot arrange your installation to minimize the effects of these loads, consult the sensor documentation to verify that the extraneous loads are within the sensor's ratings.

b. Physical and environmental requirements.
Evaluate any physical constraints (length, diameter, and so on) and the way the torque sensor can be mounted in your system. Consider what type of environment the sensor will be operating in to ensure proper performance across wide temperature ranges, humidity, or contaminants (oil, dirt, dust).

c. Revolutions per minute (rpm).
For rotary torque sensors, you need to understand how long the torque sensor will be rotating and at what speed to determine the RPM.

7. Signal conditioning for load and torque sensors
Load and torque sensors can be either conditioned or nonconditioned. You can connect conditioned sensors directly to a DAQ device because they contain the required components for filtering, signal amplification, and excitation leads along with the regular circuitry for measurement. If you are working with nonconditioned sensors, you must consider several signal conditioning elements to create an effective bridge-based load and torque measurement system. You many need one or more of the following:
1. Excitation to power the Wheatstone bridge circuitry
2. Remote sensing to compensate for errors in excitation voltage from long lead wires
3. Amplification to increase measurement resolution and improve signal-to-noise ratio
4. Filtering to remove external, high-frequency noise
5. Offset nulling to balance the bridge to output 0 V when no strain is applied
6. Shunt calibration to verify the output of the bridge to a known, expected value

4.11 Temperature Sensors

1. Overview
You can choose from a variety of sensors to translate temperature phenomena into a measurable signal. Three common sensor varieties are the thermocouple, RTD, and thermistor (Tables 5-6). Each has its own operating principles, benefits, considerations, and drawbacks.

In addition to the characteristics of the sensors themselves—operating range, sensitivity, linearity, response time, and so on—you must consider the requirements each sensor type imposes on the measurement hardware. For example, thermocouples require no current excitation (unlike thermistors) but do need cold-junction compensation, which is available only in certain measurement hardware systems. Table 5 provides a high-level comparison of these temperature sensor types:

2. Steps for selecting a temperature sensor

1. Thoroughly understand the measurement application and requirements.
   a. How quickly will the temperature change? Determine an appropriate response time.
   b. What is the length of deployment/how serviceable will the sensors be? Select a sensor type durable enough to reduce maintenance.
   c. How much accuracy is required? Consider the impact of sensor accuracy on overall measurement accuracy.
2. Determine the temperature ranges that you must measure.
   a. Select a sensor type that operates beyond the full range of possible temperatures.
   b. Consider the linearity of each type that meets your range requirements; select the type with the most linear response over your range of interest to improve voltage- or resistance-to-temperature conversion accuracy.
3. Consider the environment in which you are deploying the sensors.
   a. Pick a suitable sheathing material to resist any chemical exposure.
   b. Determine if you need isolation to prevent ground loops/noise.
   c. Make sure your sensors are rated to withstand vibration or abrasion if you are exposing them to those.
4. Consider how you are mounting your sensors and select an appropriate mounting style to maximize the thermal connection.
5. Select the necessary measurement hardware to condition, acquire, analyze, and display/save the temperature signals.

3. Temperature sensor characteristics (Fig.54)

Use the following characteristics to define your temperature sensor capabilities and performance. These apply to all types of temperature sensors but with some caveats and corner cases. When selecting a sensor, understand the impact of each characteristic on your measurements and be sure to select a sensor that aligns closely with your project requirements.

4. Temperature range

The temperature range of a sensor defines the temperatures at which the sensor is rated to operate safely and provide accurate measurements. Each type of thermocouple has a specified temperature range based on the properties of the metals used in creating that thermocouple. RTDs offer a smaller temperature range in exchange for better linearity and accuracy, and thermistors provide the lowest temperature ranges but excellent sensitivity. Understanding the full range of temperatures you can expose your sensor to can help prevent sensor damage while ensuring better measurements.

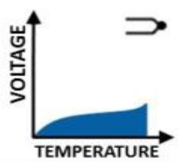
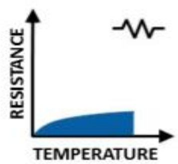
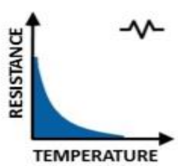
	Advantages	Disadvantages
THERMOCOUPLES 	✓ Simple ✓ Rugged ✓ Inexpensive ✓ No external power ✓ Wide temperature range ✓ Variety of styles	× Nonlinear response × Small sensitivity × Small output voltage × Requires CJC × Least stable
RTD 	✓ Most stable ✓ Good Linearity ✓ Most accurate	× Low sensitivity × Externally powered × Costly × Small output resistance × Self-heating error
THERMISTOR 	✓ Fast ✓ High output ✓ Minimal lead resistance error	× Limited temperature range × Externally powered × Nonlinear × More fragile × Self-heating error

Table 5 Advantages and Disadvantages of Temperature Sensor Types.

5. Linearity

An ideal sensor would have a perfectly linear response: a unit change in temperature would result in a unit change in voltage output across the entire temperature range of the sensor. In reality, however, no sensor is perfectly linear. Table 6. offers an idea of the temperature-to-voltage response of the three sensors.

Characteristic	Thermocouple	RTD	Thermistor
Temperature Range	Excellent -210 °C to 1760 °C	Great -240 °C to 650 °C	Good -40 °C to 250 °C
Linearity	Fair	Good	Poor
Sensitivity	Low	Medium	Very High
Response Time	Medium to Fast	Medium	Medium to Fast
Stability	Fair	Good	Poor
Accuracy	Medium	High	Medium
Susceptible to Self-Heating?	No	Yes, Minimal	Yes, Highly
Durability	Excellent	Good	Poor
Cost	Lowest	High	Low
Signal Conditioning Requirements	Cold-Junction Compensation Amplification Open Thermocouple Detection Scaling	Excitation Lead Resistance Correction Scaling	Excitation Scaling

Table 6 Comparison of Temperature Sensor Types

6. Sensitivity

The sensitivity of a given sensor indicates the percent change in measureable output for a given change in temperature. A more sensitive sensor, like a thermistor, can more easily detect small changes in temperature than a less sensitive sensor, like a thermocouple. This sensitivity, however, comes at the expense of linearity. This can be an important factor when determining the ideal sensor choice for the temperatures you are measuring. If you intend to capture fraction-of-a-degree changes over a small temperature range, a thermistor or an RTD is more ideal. For capturing larger temperature changes over a wider range of temperatures, a thermocouple may suffice. Figure 2 gives a relative idea of the voltage.

7. Response time (Figs.55-57)

Response time is the measure of time a sensor takes to respond to a change in temperature. Many factors can cause response times to increase or decrease. A larger RTD or thermistor, for example, has a slower response time than a smaller one. In exchange for this drawback and poorer thermal shunting, a larger RTD or thermistor is less susceptible to self-heating errors.Similarly, ungrounded thermocouple junctions provide a slower response time in exchange for electrical isolation. Figure 3 shows the relative difference in response times for ungrounded and grounded thermocouples.

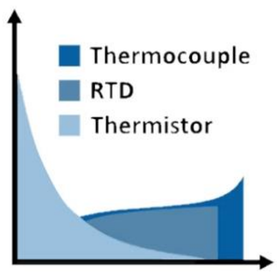


Fig.55 Temperature-to-Output Response of Sensors.

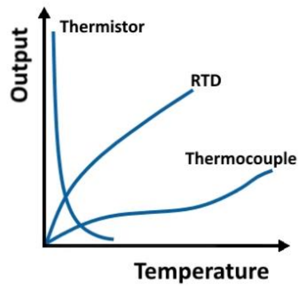


Fig.56 Sensitivity of Various Temperature Sensor Types.

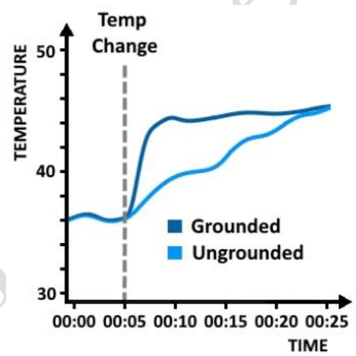


Fig.57 Response Time of Grounded Versus Ungrounded Thermocouples

8. Stability

The stability of a temperature sensor is an indication of its ability to maintain a consistent output at a given temperature. Material plays a key role in the stability of a given sensor. RTDs are often constructed of platinum for this reason as well as to ensure low reactivity. The substrate to which the platinum is bonded, however, may deform under prolonged exposure to high temperatures, which can cause additional and unexpected strain that leads to a change in measured resistance.

9. Accuracy

As with any measurement application, understanding your accuracy needs is critical in ensuring reliable results. Your sensor and measurement hardware selections play a significant role in absolute measurement accuracy, but smaller details such as cabling, relative proximity to other equipment, shielding, grounding, and so on can all affect accuracy as well. When selecting a sensor, note the specified tolerances and any factors that might impact that specification (for example, prolonged exposure to high temperatures). Also be careful to select a sensor and measurement device with similar accuracies. A tight tolerance RTD comes at a greater cost, but you may not achieve the additional accuracy if you use a low-quality measurement device.

10. Durability

To ensure your temperature sensors remain operational for the duration of your application, you need to understand theenvironment in which you are deploying them. Some sensors (thermocouples, for example) are inherently more durable because of their construction. The metals selected for a particular thermocouple, however, have different resistances to corrosion. Furthermore, a sensor encased in an isolating mineral and a protective metal sheath is more resistant to wear and corrosion over time, but it costs more and offers less sensitivity. You should also note that different sensor configurations may have special mounting requirements to ensure a solid physical and thermal connection.

11. Cost

As with any aspect of a project, cost can be a key limiting factor. In high-channel-count applications, for example, the linearity benefits of RTDs may be outweighed by the relative increase in cost versus thermocouples. You must also consider the added cost of wiring, mounting, and signal conditioning when considering total system cost.

12. Thermocouples, RTDs, and Thermistors

Thermocouples, RTDs, and thermistors all operate on the principle that certain materials respond predictably and measurably to variations in temperature. In all three cases, themeasured response is generally quite small and, as with all low-level measurements, difficult to measure accurately and reliably. Proper signal conditioning capabilities in the hardware and software components of your measurement system can greatly simplify the temperature measurement task. The following sections cover the recommended signal conditioning necessary for accurate thermocouple, RTD, and thermistor measurements.

13. Signal conditioning requirements

Each type of temperature sensor requires some level of signal conditioning to adequately acquire and digitize the measured signal for processing. The measurement hardware you select can be just as important in ensuring accurate measurements as the sensor and can mitigate or exacerbate the shortcomings of each sensor type. These signal conditioning features include the following:

1. Filtering
2. Isolation
3. Linearization
4. RTD/Thermistor-Specific Considerations
5. Thermocouple-Specific Considerations

1. Filtering

Temperature measurements often must be taken far away from the measurement equipment. This means that sensor wires carrying the analog signal to the digitizer must span a long distance. Through the length of the cable, noise from the operating environment can seep into the analog signal and lead to inaccurate measurements. You need to minimize this problem by carefully considering where you run your cabling. Avoiding AC power lines, fluorescent lighting, and computer monitors can help avoid the 50/60 Hz power line noise they often emit.You also can apply a lowpass filter to the incoming signal or incorporate one in the measurement hardware to help remove unwanted high-frequency signals.

2. Isolation

At their core, thermocouples, RTDs, and thermistors are made of electrically conductive materials. If you don't take isolation into consideration, you may inadvertently wire a measurement that is potentially dangerous to the measurement hardware or the user. Consider applying thermocouples to the casing of a large electric motor. Large motors often require very high voltages and experience even larger voltage spikes during operation. If the casing of the motor is exposed to one of these high voltages due to an internal short, a voltage spike may travel to the measurement hardware through the thermocouple wiring. You can use isolated thermocouples to prevent this, but that leads to a slower response time and added cost. Alternatively, a measurement device with channel isolation can help protect the analog-to-digital converter (ADC) circuitry as well as minimize noise from adjacent channels. You also can use an isolated measurement device to take accurate measurements when high-common-mode voltages are present by isolating the ADC circuitry from ground and allowing the measurement to float up to the signal of interest (within the limits of the device).

3. Linearization

The voltage output per unit temperature from a thermocouple, RTD, or thermistor is not a linear relationship. Because of this, you cannot simply apply a scaling coefficient to convert the measured voltage to a meaningful temperature output across the full range of thethermocouple. Fig.58, for example, shows the thermoelectric voltage output of various thermocouples across a range of temperatures. Note the nonlinear relationship.

You can choose from two options to accurately scale measurements and correct for this nonlinearity:

1. Use a lookup table and linear interpolation for measured voltages between data points in the table. This is fairly effective, but it requires coding a potentially large lookup table like the subset of one for type K thermocouples shown in Fig.86 and maintained by the National Institute of Standards and Technology (NIST).

2. Apply the voltage-to-temperature equation for the sensor type you are using to perform the measurement. For example, the high-order polynomial required for any giventhermocouple is:

$$E = \sum_{i=0}^{n}(C_i t^i), \text{ where}$$

E = Thermoelectric voltage in µV

Ci = Polynomial coefficients (provided by NIST for each temperature range)

ti = Temperature in °C

Thermistors also require a similarly complex equation to accurately convert the signals over a large range of temperatures. RTDs, on the other hand, deliver the most linear response ofthe three temperature measurement sensors. The relationship between resistance and temperature for RTDs is defined by the Callendar-Van Dusen equation as follows:

For <0 °C : RT=R0[1+AT +BT2+CT3(T −100 °C)]

For >0 °C : RT=R0[1+AT +BT2]

RT = RTD resistance at temperature T

R0 = RTD nominal resistance at 0 °C

A, B, and C = constants used to scale the RTD

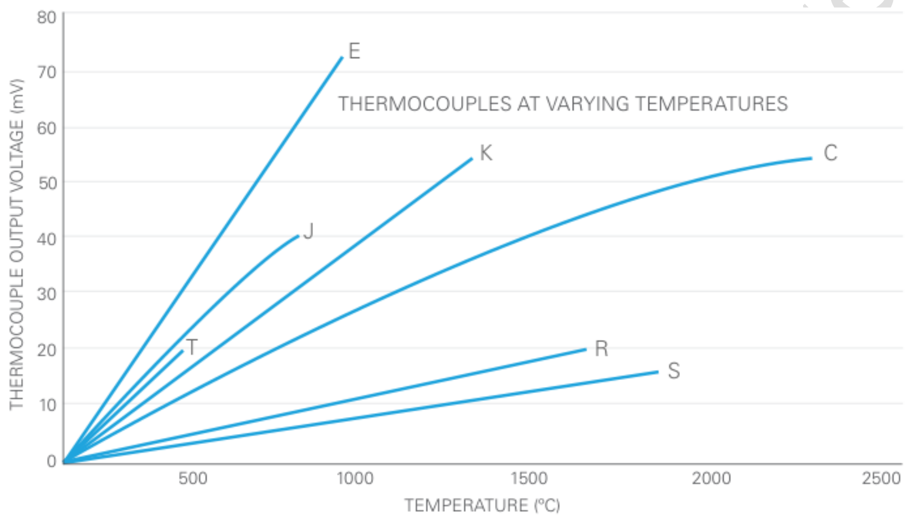


Fig.58 Thermocouple Output Voltage Versus Temperature1

4. RTD/Thermistor-Specific Considerations

a. Current Excitation

Thermistors and RTDs are resistive sensors that require a current excitation to create a measurable voltage across the device. A constant and precise current source is critical to ensuring an accurate and consistent voltage for measurement. The DAQ system you select for your RTD and thermistor measurements should provide a current excitation source that is specified to be reliable, so you can achieve the most accurate and precise measurements.

Note that performing these calculations in software may require significant computing power depending on the number of channels and sample rate as well as the temperature operating range. Having a software platform that integrates tightly with the measurement hardware can greatly simplify this scaling task by providing built-in scaling capabilities.

°C	0	1	2	3	4	5	6	7	8	9	10
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.860	8.900	8.940
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747
240	9.747	9.788	9.828	9.869	9.909	9.950	9.991	10.031	10.072	10.113	10.153
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.480	10.520	10.561
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.930	10.971
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.300	11.341	11.382
280	11.382	11.423	11.465	11.506	11.547	11.588	11.630	11.671	11.712	11.753	11.795
290	11.795	11.836	11.877	11.919	11.960	12.001	12.043	12.084	12.126	12.167	12.209
300	12.209	12.250	12.291	12.333	12.374	12.416	12.457	12.499	12.540	12.582	12.624
310	12.624	12.665	12.707	12.748	12.790	12.831	12.873	12.915	12.956	12.998	13.040
320	13.040	13.081	13.123	13.165	13.206	13.248	13.290	13.331	13.373	13.415	13.457
330	13.457	13.498	13.540	13.582	13.624	13.665	13.707	13.749	13.791	13.833	13.874
340	13.874	13.916	13.958	14.000	14.042	14.084	14.126	14.167	14.209	14.251	14.293

Fig.59 NIST Type K Thermocouple Lookup Table2
ITS-90 TABLE FOR TYPE K THERMOCOUPLE (THERMOELECTRIC VOLTAGE IN mV)

b. Connecting to Hardware Using 2-, 3-, and 4-Wire Configurations (RTDs only)

You can purchase RTDs in three wiring configurations. The differences and benefits of each are discussed in detail in the RTD sensor reference. The measurement hardware you select for your system needs to be flexible enough to incorporate the types of RTDs your application requires. Some measurement hardware allows for 2-wire RTDs only, while other hardware offers automatic detection of 3- or 4-wire RTDs. You need to select a DAQ device that is designed for your RTD's level of resistance, for example, 100 Ω or 1000 Ω RTDs.

5. Thermocouple-Specific Considerations

a.Amplification (Fig.60)

On their own, thermocouples output very small voltages for a given change in temperature that are typically on the order of millivolts and sometimes less. For example, type K thermocouples output only 40 µV per degree Celsius. Most conventional measurement hardware takes measurements within a given range, and the resolution of the device determines the smallest detectable change within that voltage range. Since the voltage you are measuring is so small in the case of a thermocouple, you may want to amplify the measured signal to take advantage of the full input range of the measurement device.

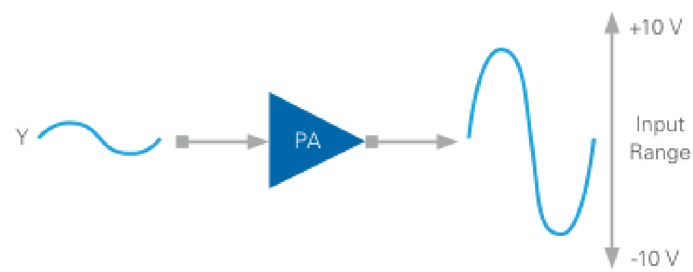


Fig.60 Amplify thermocouple outputs to detect smaller signal changes and use the full ADC input range. AMPLIFIED THERMOCOUPLE OUTPUTS

In an ideal scenario, amplification occurs as close to the primary measurement as possible.This helps to avoid amplifying any noise injected into the signal along the length of the thermocouple wires. If external amplification is not possible or if you need to simplify the measurement system, you can use a measurement device with a 24-bit ADC. This type of device can provide measurement sensitivity on the order of 0.2 °C.

b. Cold-Junction Compensation (CJC)

The nature of a thermocouple measurement, as discussed in the overview of thermocouples, relies on the voltage differential created when two dissimilar metals are joined and exposed to some relative temperature. A problem arises when you consider the connection between the thermocouple and the terminals of your measurement hardware. At this connection, another junction of dissimilar metals is created, which also generates a voltage differential, depending on the environment. If you do not account for this secondary "parasitic thermocouple," it can skew the intended temperature measurement significantly enough to produce an invalid result.
To combat this, you can incorporate a reference measurement, or "cold-junction measurement," in your measurement hardware, as shown in Fig.60. You take this reference measurement some distance away from the primary measurement and ideally adjacent to the "parasitic thermocouple" caused by connecting the actual thermocouple to the measurement device's terminals. Use a direct-measuring temperature sensor (like an RTD or thermistor) and then

subtract the resulting reference measurement from the primary measurement to remove, or compensate for, the parasitic component. This process is known as cold-junction compensation or CJC.

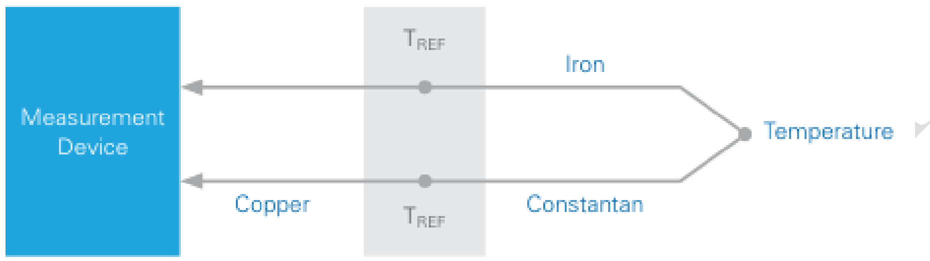


Fig.60 Cold-junction error adds more voltage to a thermocouple measurement.
COLD-JUNCTION THERMOCOUPLE MEASUREMENT

c. Removing Offset Error (Fig.61)

As discussed previously, CJC is important to correct the effect of the parasitic thermocouple created by connecting thermocouple wires to the metal terminals of your hardware. The parasitic thermocouple caused an offset in the measured voltage that led to inaccurate results. Similarly, the ambient temperature surrounding a measurement device can lead to an offset in the measured voltage from a thermocouple due to the induced voltages in the hardware itself. To correct for this, you should regularly measure the latent voltage without a thermocouple and subtract this value from each thermocouple measurement. To simplify this process, some measurement hardware provides an autozero function to regularly or semiregularly correct for any offset voltage caused by the ambient environment. This can greatly improve your overall measurement accuracy.

d. Detecting Disconnected Thermocouples (Fig.62)

Thermocouples can be susceptible to corrosion and wear over time because of their composition (dissimilar touching metals can cause corrosion in some environments) and the typical operating environment for this type of sensor. A broken or disconnected thermocouple may not be readily apparent to the user and may produce invalid data. Open thermocouple detection is a hardware feature that provides a small current to push the voltage input out of range when the hardware detects an open connection. You can easily check for this in software. When using this feature, remember that the small current can be a source of bias error in high-accuracy applications. To correct for this, you can pair open thermocouple detection with lead offset nulling, which takes the measured difference with and without the current applied and subtracts it from future measurements. This is effectively correcting for a user-induced offset error.

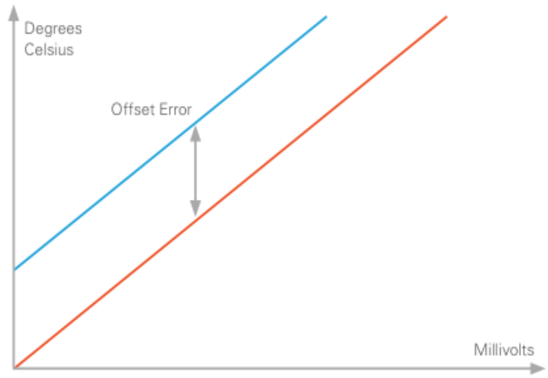


Fig.61 Autozero compensates for offset error.
AUTOZERO COMPENSATION

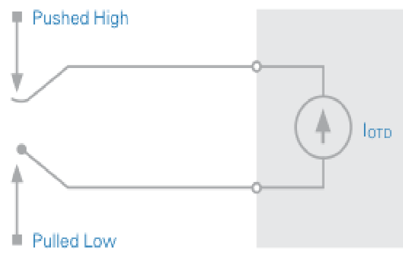


Fig.62 The open thermocouple detection circuit pushes the voltage high when the thermocouple breaks. OPEN THERMOCOUPLE DETECTION

6. Conclusion

To obtain a reliable level of accuracy in your temperature measurements, you must progress through many layers of signal conditioning, some recommended and some required. When selecting a measurement system for thermocouples, RTDs, or thermistors, you should consider built-in filtering to remove noise, isolation to prevent ground loops, and linearization for scaling voltage to temperature. If you are using thermocouples as your temperature sensor, keep in mind these additional sources of error that can impact measurement accuracy:

1. Cold-junction error—corrected by cold-junction compensation or CJC
2. Offset error—corrected by autozero and lead offset nulling
3. Open thermocouple detection for ensuring system reliability and uptime

4.12 Measuring Vibration with Accelerometers

1. Overview

This document provides information to help you understand basic vibration concepts, how accelerometers work, and how different sensor specifications impact accelerometer performance in your application. In addition to the sensor characteristics, you must consider the required hardware and software to properly condition, acquire, and visualize accelerometer measurements. For example, you need to perform signal processing on raw vibration signals to display the data in a more meaningful format, such as the frequency spectrum.

2. What is vibration?

Vibration is the movement or mechanical oscillation about an equilibrium position of a machine or component. It can be periodic, such as the motion of a pendulum, or random, such as the movement of a tire on a gravel road. Vibration can be expressed in metric units (m/s) or units of gravitational constant “g,” where 1 g = 9.81 m/s . An object can vibrate in two ways: free vibration and forced vibration.

a. Free vibration occurs when an object or structure is displaced or impacted and then allowed to oscillate naturally. For example, when you strike a tuning fork, it rings and eventually dies down. Natural frequency often refers to the frequency at which a structure “wants” to oscillate after an impact or displacement. Resonance is the tendency for a system to oscillate more violently at some frequencies than others. Forced vibration at or near an object’s natural frequency causes energy inside the structure to build. Over time the vibration can become quite large even though the input forced vibration is very small. If a structure has natural frequencies that match normal environmental vibration, then the structure vibrates more violently and prematurely fails.

b. Forced vibration occurs when a structure vibrates because an altering force is applied. Rotating or alternating motion can forcean object to vibrate at unnatural frequencies. An example of this is imbalance in a washing machine, where the machine shakes at a frequency equal to the rotation of the turnstile. In condition monitoring, vibration measurements are used to indicate the health of rotating machinery such as compressors, turbines, or pumps. These machines have a variety of parts, and each part roved safety and reduced cost.

3. How do you measure vibration?

Vibration is most commonly measured using a ceramic piezoelectric sensor or accelerometer. An accelerometer (Figs.63-64) is a sensor that measures the dynamic acceleration of a physical device as a voltage. Accelerometers are full-contact transducers typically mounted directly on high-frequency elements, such as rolling-element bearings, gearboxes, or spinning blades. These versatile sensors can also be used in shock measurements (explosions and failure tests) and slower, low-frequency vibration measurements. The benefits of an accelerometer include linearity over a wide frequency range and a large dynamic range.

Another sensor you can use to measure vibration is the proximity probe. Unlike accelerometers, which measure acceleration to determine vibration, proximity probes are noncontacting transducers that measure distance to a target. These sensors are almost exclusively used in rotating machinery to measure the vibration of a shaft. An example of a common application is machine monitoring and protection measurements for mechanical systems like turbo machinery. Because of the flexible fluid film bearings and heavy housing, vibrations do not transmit well to the outer casing, so you use proximity probes instead of accelerometers to directly measure shaft motion.

Fig.63 Accelerometers are versatile sensors used for high or low frequency vibration as well as shock measurements.

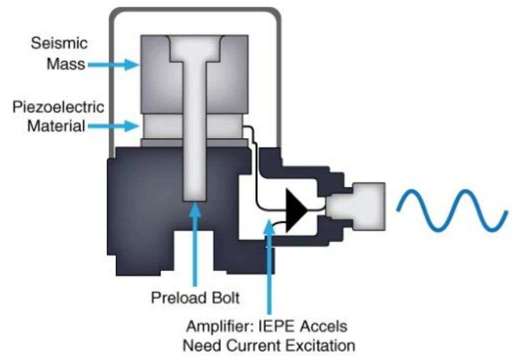


Fig.64 IEPE accelerometers output voltage signals proportional to the force of the vibration on the piezoelectric crystal.

4. How do accelerometers work?

Most accelerometers (Figs.63-64) rely on the use of the piezoelectric effect, which occurs when a voltage is generated across certain types of crystals as they are stressed. The acceleration of the test structure is transmitted to a seismic mass inside the accelerometer that generates a proportional force on the piezoelectric crystal. This external stress on the crystal then generates a high-impedance, electrical charge proportional to the applied force and, thus, proportional to the acceleration.

Piezoelectric or charge mode accelerometers require an external amplifier or inline charge converter to amplify the generated charge, lower the output impedance for compatibility with measurement devices, and minimize susceptibility to external noise sources and crosstalk. Other accelerometers have a charge-sensitive amplifier built inside them. This amplifier accepts a constant current source and varies its impedance with respect to a varying charge on the piezoelectric crystal. These sensors are referred to as Integrated Electronic Piezoelectric (IEPE) sensors. Measurement hardware made for these types of accelerometers provide built in current excitation for the amplifier. You can then measure this change in impedance as a change in voltage across the inputs of the accelerometer.

5. How to choose the right accelerometer?

Because accelerometers are so versatile, you have a variety of designs, sizes, and ranges to choose from. Understanding the characteristics of the signal you expect to measure and any environmental constraints can help you sort through all of the different electrical and physical specifications for accelerometers.

a. Vibration Amplitude

The maximum amplitude or range of the vibration you are measuring determines the sensor range that you can use. If you attempt to measure vibration outside a sensor's range, it distorts or clips the response. Typically, accelerometers used to monitor high vibration levels have a lower sensitivity and lower mass.

b. Sensitivity

Sensitivity is one of the most important parameters for accelerometers. It describes the conversion between vibration and voltage at a reference frequency, such as 160 Hz. Sensitivity is specified in mV per G. If typical accelerometer sensitivity is 100 mV/G and you measure a 10 G signal, you expect a 1000 mV or 1 V output. The exact sensitivity is determined from calibration And usually listed in the calibration certificate shipped with the sensor. Sensitivity is also frequency dependent. A full calibration across the usable frequency range is required to determine how sensitivity varies with frequency. Figs.65-66 show the typical frequency response characteristics of an accelerometer. In general, use a low sensitivity accelerometer to measure high amplitude signals and a high sensitivity accelerometer to measure low amplitude signals.

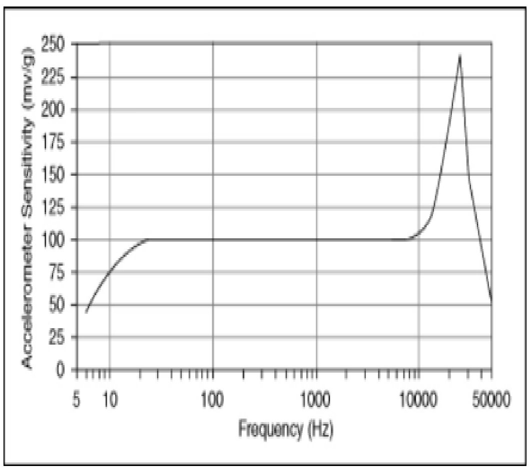


Fig.65 Accelerometers have a wide usable frequency range where sensitivity is relatively flat.

Method	Frequency Limit
Handheld	500 Hz
Magnetic	2,000 Hz
Adhesive	2,500 to 5,000 Hz
Stud	> 6,000 Hz

Table 7 Frequency Limits for Mounting a 100 mv/G Accelerometer.

c. Number of Axes

You can choose from two axial types of accelerometers. The most common accelerometer measures acceleration along only a single axis. This type is often used to measure mechanical vibration levels. The second type is a triaxial accelerometer. This accelerometer can create a 3D vector of acceleration in the form of orthogonal components. Use this type when you need to determine the type of vibration, such as lateral, transverse, or rotational.

d. Weight

Accelerometers should weigh significantly less than the structure you are monitoring. Adding mass to the structure can alter its vibrational characteristics and potentially lead to inaccurate data and analysis. The weight of the accelerometer should generally be no greater than 10 percent of the weight of the test structure.

e. Mounting Options

Another consideration for your vibration measurement system is how to mount the accelerometer to the target surface. You can choose from four typical mounting methods:

1. Handheld or probe tips
2. Magnetic
3. Adhesive
4. Stud mount

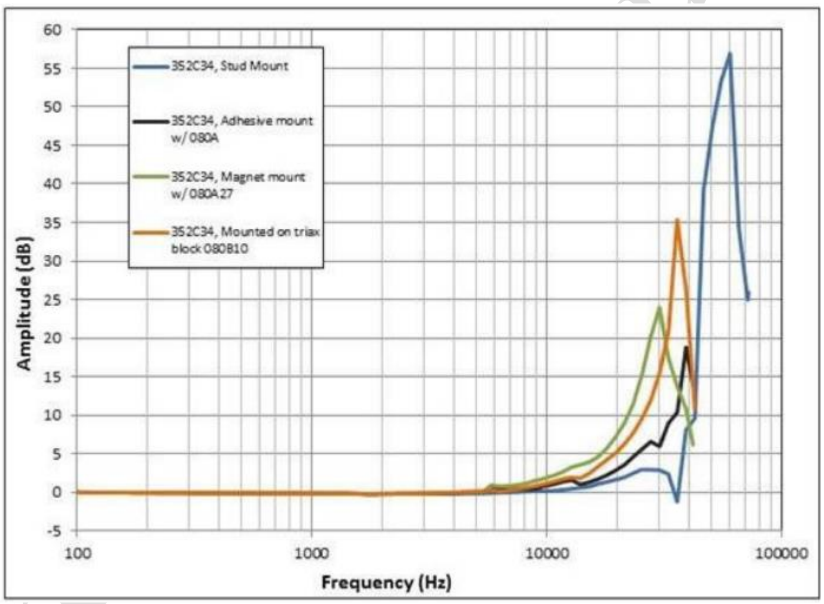


Fig.66 The different frequency ranges of different mounting techniques.

Stud mounting is by far the best mounting technique, but it requires you to drill into the target material and is generally reserved for permanent sensor installation. The other methods are meant for temporary attachment. The various attachment methods all affect the measurable frequency of the accelerometer. Generally speaking, the looser the connection, the lower themeasurable frequency limit. The addition of any mass to the accelerometer, such as an adhesive or magnetic mounting base, lowers the resonant frequency, which may affect the accuracy and limits of the accelerometer's usable frequency range.

Consult accelerometer specifications to determine how different mounting methods affect the frequency measurement limits. Table 7 shows typical frequency limits for a 100 mV/G accelerometer. Fig.66 shows the approximate frequency ranges of different mounting techniques, including stud mounts, adhesive mounts, magnet mounts, and triax block mounts.

f. Environmental Constraints

When choosing an accelerometer, pay attention to critical environmental parameters such as maximum operating temperature, exposure to harmful chemicals, and humidity. You can use most accelerometers in hazardous environments because of their rugged and reliable construction. For additional protection, industrial accelerometers built from stainless steel can protect the sensors from corrosion and chemicals.

Use a charge mode accelerometer if the system must operate in extreme temperatures. Since these accelerometers do not contain built-in electronics, the operating temperature is limited only by the sensing element and materials used in the construction. However, since they do not have built-in conditioning and charge amplification, charge mode accelerometers are sensitive to environmental interference and require low-noise cabling. If the environment is noisy, you should use an inline charge converter or IEPE sensor with a built-in charge amplifier.

Humidity specifications are defined by the type of seal an accelerometer has. Common seals include hermetic, epoxy, or environmental. Most of these seals can withstand high levels of moisture, but a hermetic seal is recommended for fluid immersion and long exposure to excessive humidity. Although charge mode and IEPE accelerometers have similar costs, IEPE accelerometers have a significantly lower cost for larger, multichannel systems because they do not require special low-noise cables and charge amplifiers. In addition, IEPE accelerometers are easier to use because they require less care, attention, and effort to operate and maintain.

6. Accelerometer Options

There are 2 types, the single-axis and triaxial accelerometers (Tables 8, 9)

7. Signal conditioning for accelerometers

When preparing an accelerometer to be measured properly by a DAQ device, you need to consider the following to ensure you meet all of your signal conditioning requirements:

1. Amplification to increase measurement resolution and improve signal-to-noise ratio
2. Current excitation to power the charge amplifier in IEPE sensors
3. AC coupling to remove DC offset, increase resolution, and take advantage of the full range of the input device
4. Filtering to remove external, high-frequency noise
5. Proper grounding to eliminate noise from current flow between different ground potentials
6. Dynamic range to measure the full amplitude range of the accelerometer

Single Axis ICP® Accelerometers

	Test			Industrial		
				 (Half Scale)	 (Half Scale)	 (Half Scale)
	PCB® Model 352A21 NI Part Number 784172-01	**PCB® Model 352C03 NI Part Number 780988-01**	**PCB® Model 352C33 NI Part Number 780989-01**	**IMI® Model 602D01 NI Part Number 784175-01**	**IMI® Model 603C01 NI Part Number 780985-01**	**IMI® Model 622B01 NI Part Number 784176-01**
Sensitivity	10 mV/g	10 mV/g	100 mV/g	100 mV/g	100 mV/g	100 mV/g
Measurement range	±500 g pk	±500 g pk	±50 g pk	±50 g pk	±50 g pk	±50 g pk
Frequency range	1 to 10,000 Hz (-5%)	0.5 to 10,000 Hz (-5%)	0.5 to 10,000 Hz (-5%)	0.5 to 8,000 Hz (±3dB)	0.5 to 10,000 Hz (±3dB)	0.2 to 15,000 Hz (±3dB)
Key attributes	Miniature Lightweight Adhesive mount	General purpose Stud or adhesive mount	High sensitivity Stud or adhesive mount	Low profile Case isolated Through bolt mount	General purpose Case isolated Stud mount	High frequency Case isolated Stud mount
Applications	Small component testing Environmental testing Space restricted installations	Routine vibration testing Product testing Structural testing		Industrial Vibration Monitoring Permanent installations		Industrial Vibration Monitoring Permanent installations Route-based PdM
Cable	Supplied 10 ft. cable with 10-32 plug termination	Optional 10 ft. cable, 10-32 plug to BNC plug termination **PCB® Model 003C10** **NI Part Number 780986-01**		Optional 30 ft. cable, composite 2-socket MIL to blunt cut **IMI® Model 052BR030BZ** **NI Part Number 784390-01**		
NI Input Module	NI 9234 & NI PXIe-4497			NI 9234 & NI PXIe-4497		

Table 8 Single-Axis Accelerometer Options

Triaxial ICP® Accelerometers

	PCB® Model 356A01 NI Part Number 780990-01	PCB® Model 356B21 NI Part Number 784173-01	PCB® Model 356A32 NI Part Number 784174-01	PCB® Model 356A02 NI Part Number 784169-01	PCB® Model 356A15 NI Part Number 784170-01	PCB® Model 356B18 NI Part Number 784815-01
Sensitivity	5 mV/g	10 mV/g	100 mV/g	10 mV/g	100 mV/g	1000 mV/g
Measurement range	±1000 g pk	±500 g pk	±50 g pk	±500 g pk	±50 g pk	±5 g pk
Frequency range (-5%)	2 to 5,000 Hz	2 to 7,000 Hz	1 to 4,000 Hz	1 to 5,000 Hz	2 to 5,000 Hz	0.5 to 3,000 Hz
Key attributes	Miniature Integral cable Adhesive mount	Miniature Low mass Stud or adhesive mount		General purpose Stud or adhesive mount 1/4 - 28 four pin connector	High sensitivity Stud or adhesive mount 1/4 - 28 four pin connector	
Applications	Small component testing Environmental testing Space restricted installations			General purpose vibration testing Modal analysis Vibration control		Low level vibration testing
Cable	Supplied 10 ft. cable with BNC plug termination			Optional 10 ft. cable, 1/4-28 4-socket to BNC plug termination **PCB® Model 034G10** **NI Part Number 784171-01**		
NI Input Module	NI 9234 & NI PXIe-4497					

Table 9 Triaxial Accelerometer Options

4.13 Signal Conditioning Overview

Many applications involve environmental or structural measurements, such as temperature and vibration, from sensors. These sensors, in turn, require signal conditioning before a data acquisition device can effectively and accurately measure the signal. Signal conditioning is one of the most important components of a data acquisition system because without optimizing real-world signals for the digitizer in use, you cannot rely on the accuracy of the measurement. Signal conditioning needs vary widely in functionality depending on your sensor, so no instrument can provide all types of conditioning for all sensors. For example, thermocouples produce very low-voltage signals, which require linearization, amplification, and filtering, while strain gages and accelerometers need excitation. Other signals may need none of these but strongly rely on isolation from high voltages. The key to a successful signal conditioning system is to understand the circuitry you need to ensure an accurate measurement whatever your channel mix.
This section covers the specific conditioning requirements you need for the most common sensor types and discusses key considerations for developing and maintaining a conditioned measurement system.

Sensor-Specific Signal Conditioning
To achieve the best measurements, understanding the signal conditioning needs for each measurement type is paramount. Based on the sensors you require to perform an application, certain types of signal conditioning you need to consider certain types of signal conditioning to ensure the best measurements possible. Tables 10-12 provides a summary of signal conditioning types for the different sensors and measurements.

	Amplification	Attenuation	Isolation	Filtering	Excitation	Linearization	CJC	Bridge Completion
Thermocouple	✓	–	✓	✓		✓	✓	–
Thermistor	✓	–	✓	✓	✓	✓	–	–
RTD	✓	–	✓	✓	✓	✓	–	–
Strain Gage	✓	–	✓	✓	✓	✓	–	✓
Load, Pressure, Torque	✓	–	✓	✓	✓	✓	–	–
Accelerometer	✓	–	✓	✓	✓	✓	–	–
Microphone	✓	–		✓	✓	✓	–	–
LVDT/RVDT	✓	–	✓	✓	✓	✓	–	–
High Voltage	–	✓	✓	–	–	–	–	–

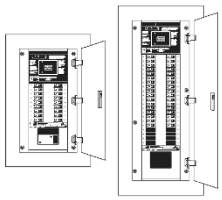
Table 10.Unique Requirements for Sensor-Based Measurements

Integrated Signal Conditioning	Custom-Built Signal Conditioning
Best for: ▪ Mixed-measurement systems ▪ Flexible systems or systems exposed to potential expansion ▪ Short project timeframes/deadlines ▪ Systems that may be reproduced ▪ Systems that must be maintained for a long time	Best for: ▪ Smaller, fixed functionality; fixed-channel-count systems ▪ Low hardware budget projects with team proficiency in analog design ▪ Long project timeframes ▪ Extreme specialization on signal input

Table 11 Use cases for integrated and custom-built signal conditioning:

Sensor	Advantages	Disadvantages	Applications
Limit Switch	·High Current Capability ·Low Cost ·Familiar "Low-tech" Sensing	·Requires Physical contact with target ·Very Slow response ·Contact Bounce	·Interlocking ·Basic End-of-travel Sensing
Photoelectric	·Senses all Kinds of Materials ·Long Life ·Longest Sensing range ·Very Fast Response Time	·Lens Subject to contamination ·Sensing Range affected by Color and reflectivity of Target	·Packaging ·Material handling ·Parts Detection
Inductive	·Resistant to Harsh envir-onments ·Very Predictable ·Long Life ·Easy to Install	·Distance Limitations	·Industrial and machines ·Machine Tool ·Senses Metal-only targets
Capacitive	·Detects Through some Containers ·Can Detect non-Metallic targets	·Very Sensitive to Extreme environmental changes	·Level Sensing
Ultrasonic	·Senses all materials	·Resolution ·Repeatability ·Sensitive to temperature changes	·Anti-Collision ·Doors ·Web Brake ·Level Control

Table 12 Most common sensor technologies.



CHAPTER 5

Residential Electrical Wiring

5.1 Introduction

This chapter explains the basic fundamentals of architectural drawing, defines and shows the application of the graphic symbols used on residential wiring drawings.

Fig. 1 An electrical floor plan of a small house "ANSI standards".

5.2 Basic Architectural Drafting

The principle type of drawing used by architects is called a ***floor plan***, which defines the location of the various rooms, windows, doors, stairs, closets, hallways, etc. Fig. 1 shows a floor plan along with an elevation drawing of a small one-bedroom house. The standard scale used for residential drawings is ¼" = 1'

5.3 Electrical Symbols

Symbols are used on residential electrical wiring drawings to specify the type and location of the switches or outlets required. Fig. 2 illustrates the most commonly used symbols and their meaning. Fig. 3 illustrates how these symbols may be added to a floor plan to create an electrical wiring drawing, in which wiring paths are drawn as freehand (or using a French curve as a guide) hidden lines so that they are easily distinguishable from the floor plan lines. Electricians need only be shown the location and type of fixture required and they will be responsible to insure that the fixture is wired properly in accordance with the code.

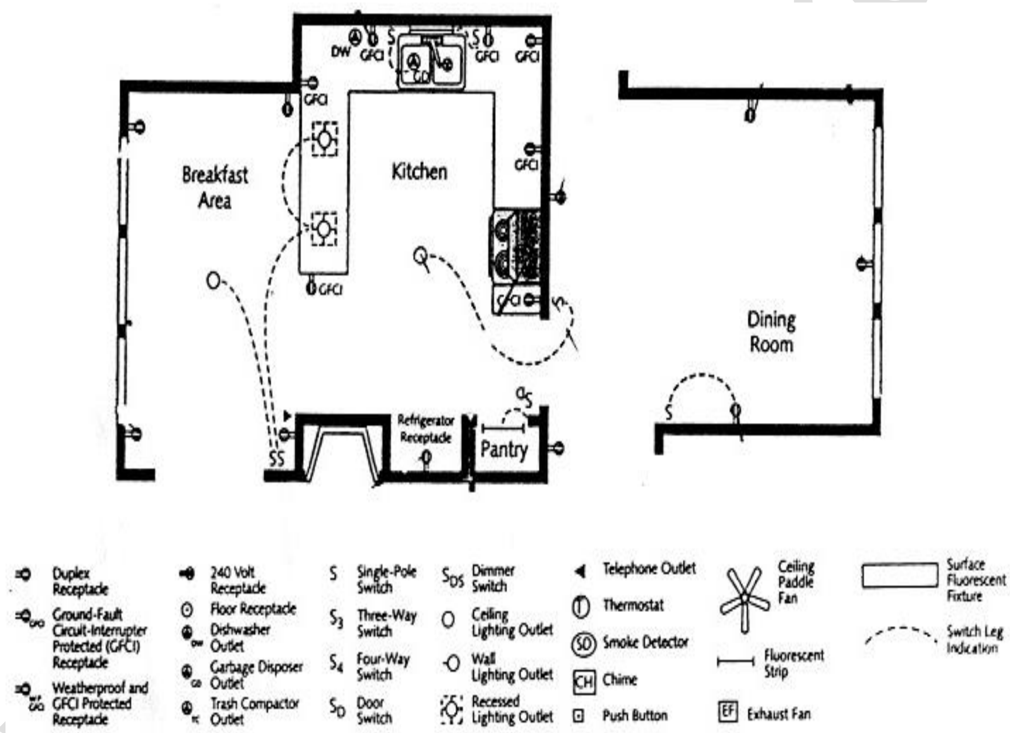


Fig. 2 Electrical symbols for residential wiring drawings“British standards” .

Every residential electrical wiring drawing you create, should include a ***symbol ledger, which*** illustrates each symbol used on the drawing and defines its meaning. If a special or specific type of switch or outlet is required, it must also be defined on the drawing. This is usually done by printing the manufacturer’s name and the part number of the fixture next to the appropriate symbol on the drawing.

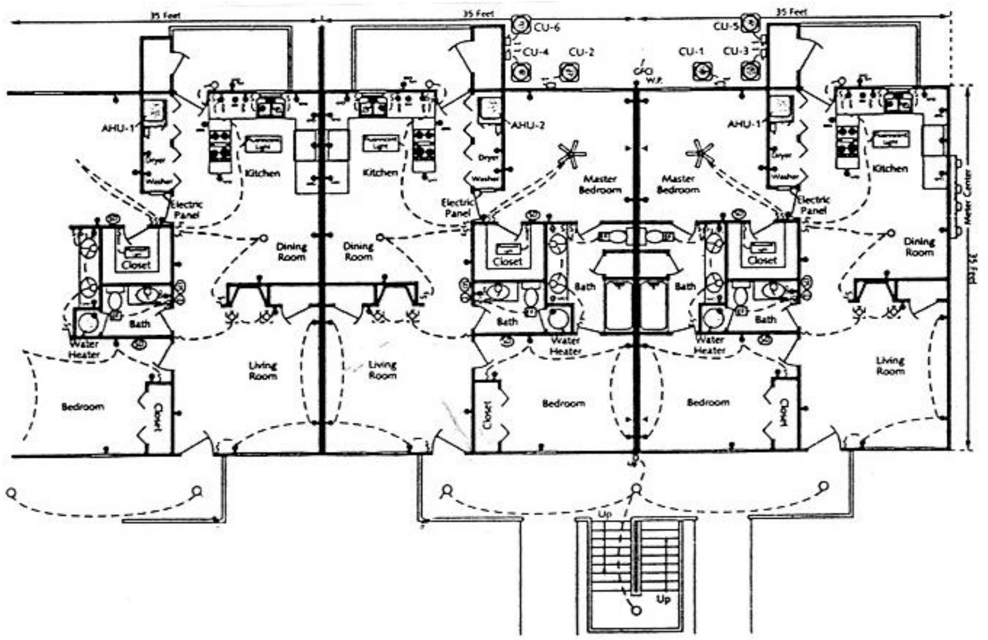


Fig. 3 An example of a residential wiring drawing.

5.4 Electrical Installation Design

5.4.1 Small House

To illustrate a basic, cost-conscious electrical installation. The outline of basic requirements for a 3-bedroom house with 120 m^2 floor area (Fig. 4).

A. Wiring regulations

1. Sockets supplying portable equipment for use outdoors must be provided with 25 mA rcd protection.
2. No 220 V sockets are permissible in bathrooms or shower rooms.
3. There should be more than one lighting circuit.
4. Light in the bathroom or shower room must be operated by a pull cord switch (alternatively the light switch may be outside the bathroom door).

The electrical requirements are shown in Table 1.

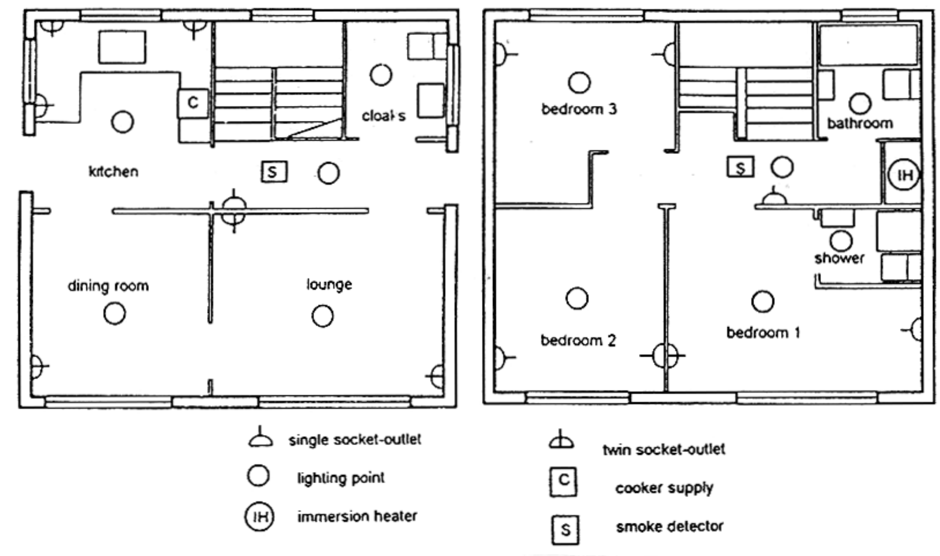


Fig. 4 Three bedroom house.

13 A socket outlets (twin sockets count as two outlets(s)		
Room	**Outlets**	**Notes**
Kitchen/utility	6	Where homes have separate area, the kitchen should have a minimum of 4 outlets and the utility room two. Where appliances are provided, at least 3 outlets should be for general use
Dinning room	2	
Living room	4	At least one double outlet family room should be near the TV aerial outlet.
Bedroom	3(2)	Three for main bedroom. Two for other bedrooms.
Landing	1	
Hall	1	
Combined rooms should have sockets equal to the sum of the number for individual room with a minimum of seven in the case of kitchen/utility and another room		
Lighting Every room should have at least one lighting point. Two-way switching should be provided to staircases.		
Smoke detectors For this two storey house two mains operated, interconnected alarms are required.		

Table 1. Electrical requirements.

B. Domestic supply

1. Prospective short circuit current at the origin not more that 16 kA and most likely less than 2 kA.
2. External earth fault loop impedance $Z_e < 0.35\ \Omega$ and most likely $< 0.2\ \Omega$.
3. Main fuse rating is 100 A.

C. Project specifications

This is shown in Table 2, and it is used initially for pricing purposes.

100 A main switch (4+4 way)		63 A, 30 mA rcd M6 type 2 mcbs		
Circuit	Rating, A	Cable size, mm^2	Maximum length, m	Lights, points,g=gang
1. Cooker	30	6.0	43	1
2. Ring 1, upstairs	30	2.5	71	....1g 2g
3. Ring 2, downstairs	30	2.5	71	....1g 2g
4. ring kitchen	30	2.5	71	....1g 2g
5. Immersion heater	15	2.5	35	1
6. Lights upstairs, bathroom, fan	5	1.0	43	
6. Lights downstairs	5	1.0	43	
8.Boiler	5	1.0	43	
9.Smoke detector	5	1.0	43	

Table 2. Project specifications.

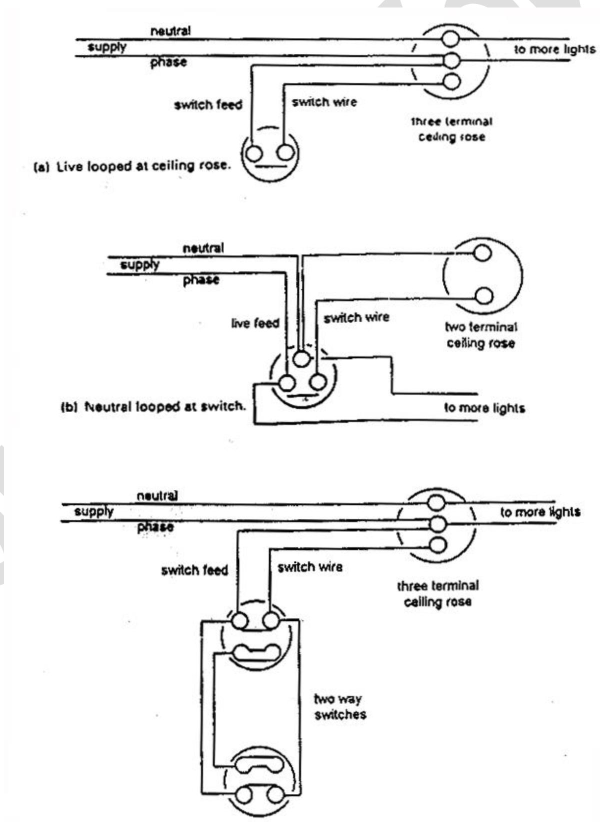


Fig. 5 Lighting circuitry using twin cable.

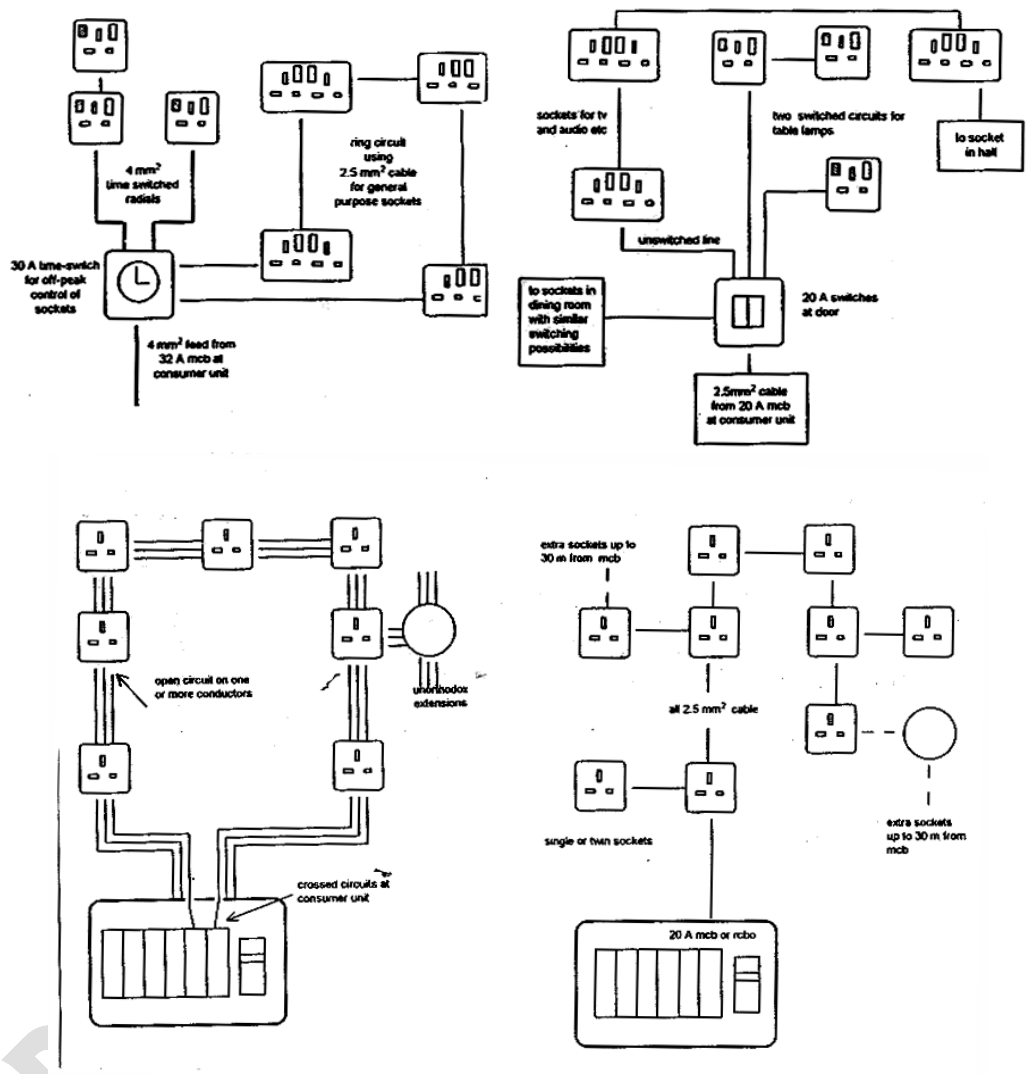


Fig. 6 Tree, ring and ring-radial systems.

D. Lighting

Wiring should be arranged with phase/neutral or feed/return cables twinned to minimise interference. Separate single core cable runs should be avoided. For the same reason the most suitable two-way switching arrangement as shown in Fig. 5

E. Socket outlets

As shown in Fig. 6, ring or tree circuits can be used, noting that ring circuits are not always best way to service sockets.

F. Arrangement of circuits

This is shown in Fig. 7.

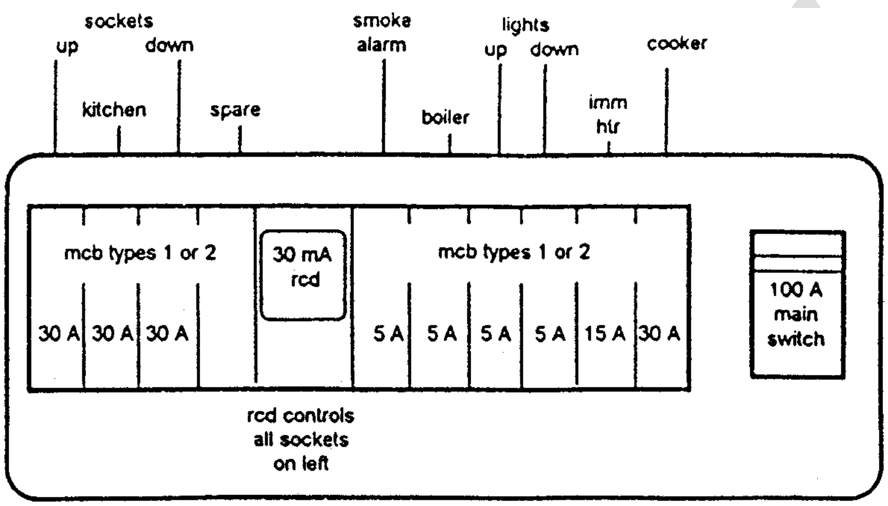


Fig. 7 Arrangement of circuits.

5.4.2 An Architect's Office

A. Layout and furniture

The office plan is shown in Fig. 8

B. Electrical requirements

This is shown in Table 3, while Fig.9 shows the preliminary lighting arrangement and Fig. 10 shows provisional power requirements. The project specification format is shown in Table 4

C. Loading and diversity

Lighting and loads are likely to be used simultaneously at maximum capacity on occasions.

1. Lighting: fluorescent lamp ratings must be multiplied by 1.8 to take into account control gear losses.
   Fluorescent load = 22 lamps x 70 W x 1.8 / 220 = 12.6 A
   ELV spotlight load = 17 x 50 W / 220 = 3.9 A
2. Storage heaters:

Electric load = 9 x 3000 W / 220 = 122.7 A

3. Print machine:
   Electric load = 20 A
4. Socket outlets: these are used for desktop equipment. A suitable estimation of desktop loading is between 1 A and 3 A per station
   Electric load = 2 A/ desk x eight desks = 16 A

Total current = 12.6 + 3.9 + 122.7 + 20 + 16 = 175.2 A
This will be distributed across 3 phases, and 100-A three-phase supply will be appropriate.

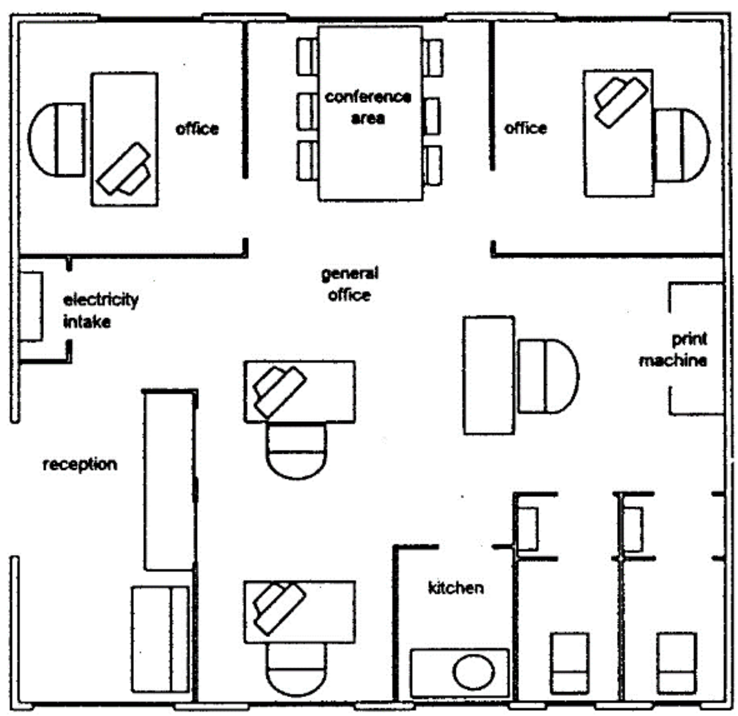


Fig. 8 Office layout.

D. Circuits arrangement

A possible spread of circuits across the 3 phases are shown in Table 5.

E. Distribution boards

Two, 3-phase DBs are used as shown in Fig. 11, while cable sizes are shown in Table 6.

Lighting	
General office lighting	9 × 1.8 m 70 W twin fluorescents
Two executive offices	2 × 1.8 m 70 W twin fluorescents
Conference area	9 × 50 W elv spotlights
Reception area	8 × 50 W elv spotlights
Toilets and kitchen	6 × 24 W low energy fluorescents
Direct acting heaters	
Three wall panel heaters in the kitchen and toilets, with individual thermostatic control	4 × 1 kW
Storage heaters on off-peak supply	
Nine block storage units	9 × 3 kW
Print Machine	
A single-phase 20 A supply has been requested	
Socket outlets	
Some discussion and decision is required at this early stage. Two systems are suggested: (1) Conventional general purpose 13 A sockets. (2) Special clean lines for computers. One dedicated socket per desk place. Consideration may be given eventually to an uninterruptible power suppl/ (UPS) service.	

Table 3. Electrical requirements.

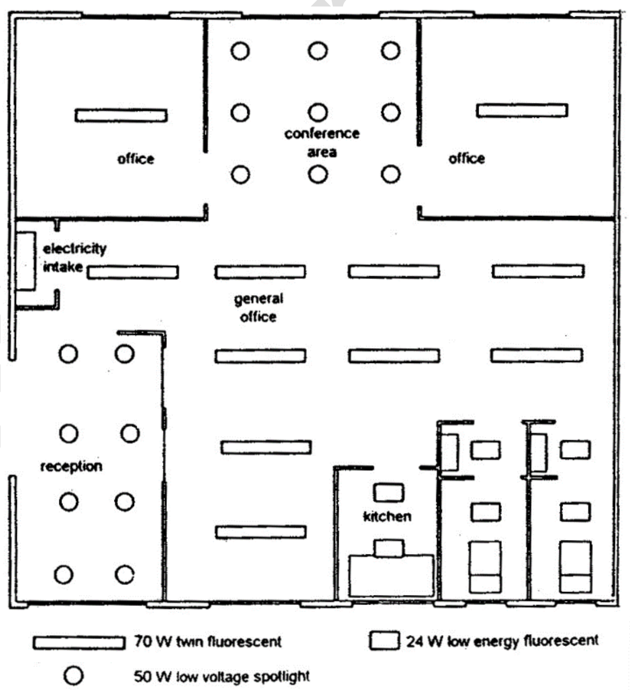


Fig. 9 Lighting arrangement.

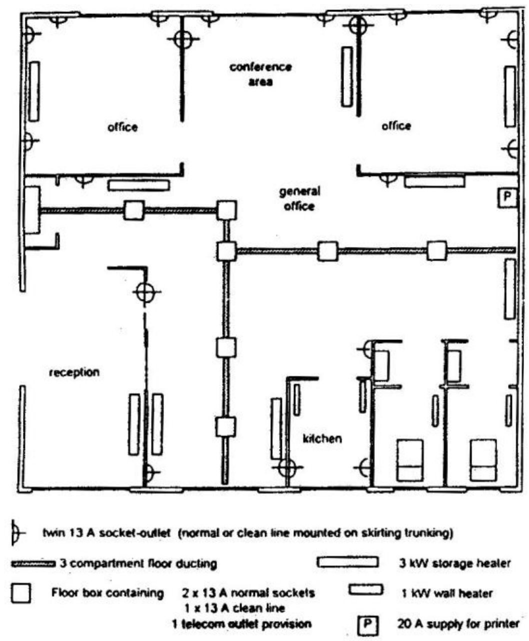


Fig. 10 Power arrangement.

Project Specification				
Office Unit				
Name........................ Location........................				
Reference................. Date........................				
Three phase 240 V 50 Hz. TN-C-S. Supply fuse 100 A				
PFC less than 16 kA. Earth loop impedance less than 0.35				
100 A TP main switch				
Two Type B distribution boards Normal and off-peak suppl' ;				
Normal supply				
Circuits	Rating (A)	Cable size (mm²)	Max length (m)	Lights/points g = gang
1. Sockets 1	32	2.5	71	10 x 2g
2. Sockets 2	32	2.5	71	8 x 2g
3. Sockets floor	32	2.5	71	7 x 2g
4. Sockets clean line	32	2.5	71	5 x 2g
5. Lights 1	10	1.5	55	11
6. Lights 2	10	1.5	55	13
7. Lights 3	10	1.5	55	10
8. Print machine	20	2.5	45	
9. Heaters in toilets	20	2.5	45	4
Off-peak service				
1-9 Storage heaters	20 A	2.5	25	9

Table 4 Project specification.

Phase		Amps (approx.)
Red	*Lights*	
	Executive offices and conference area	4.0
	Storage heaters	37.5
	Print machine	20
	Possible total	62
Yellow	*Lights*	
	Centre office and toilets	8.4
	Storage heaters	37.5
	Window wall sockets	10
	Inside wall sockets	10
	Possible total	66
Blue	*Lights*	
	Inside office and reception	3.7
	Storage heaters	37.5
	Floor sockets	10
	Dedicated sockets (clean line)	10
	Heaters in toilets	12
	Possible total	71

Table 5 Circuits arrangement across phases.

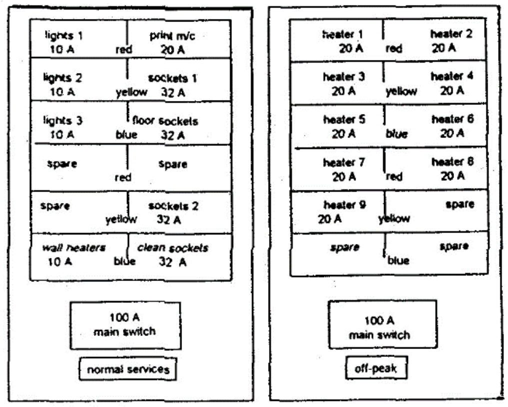


Fig. 11 Two DBs for the office under consideration.

Circuit	*Full load (A)*	*mcb rating (A)*	*Cable type (ref.)*	*Size (mm²)*	*Max. length (m)*
Lighting					
(Enclosed in conduit or trunking)					
1	4.0	10	singles 6491X	1.5	55
2	8.4	10	singles 6491X	1.5	55
3	3.7	10	singles 6491X	1.5	55
(Unenclosed)					
1	4.0	10	T & E 6242Y	1.5	55
2	8.4	10	T & E 6242Y	1.5	55
3	3.7	10	T & E 6242Y	1.5	55
Power sockets Floor and wall outlets Alternative possibilities with cables enclosed in skirting or underfloor trunking					
3 circuits each	20 A max	20	Radial singles 6491X	2.5	40
3 circuits each	32 A max.	32	Radial singles 6491X	4.0	45
3 circuits each	32 A max	32	Ring singles 6491X	2.5	70
Dedicated power circuit for computers As above for power circuits with cables enclosed in skirting or underfloor trunking					
Storage heaters All similar with a maximum of three circuits enclosed in skirting trunking					
9 × 3 kW	12.5	16	singles 6491X	2.5	45
Wall heaters One circuit, three heaters with cables enclosed in skirting trunking					
3 × 3 kW	12.5	16	singles 6491X	2.5	45

Table 6 Cable sizes.

5.4.3 Small Restaurant

A. Electrical requirements

The electrical layout is shown in Fig. 12 and Fig. 13. The electrical schedule is shown in Table 7. The project specification is shown in Fig. 14

B. Loading and diversity

The biggest load on this project is the oven in the kitchen and it is unlikely that the fully loaded 10 kW condition will coincide with full loading on other appliances.

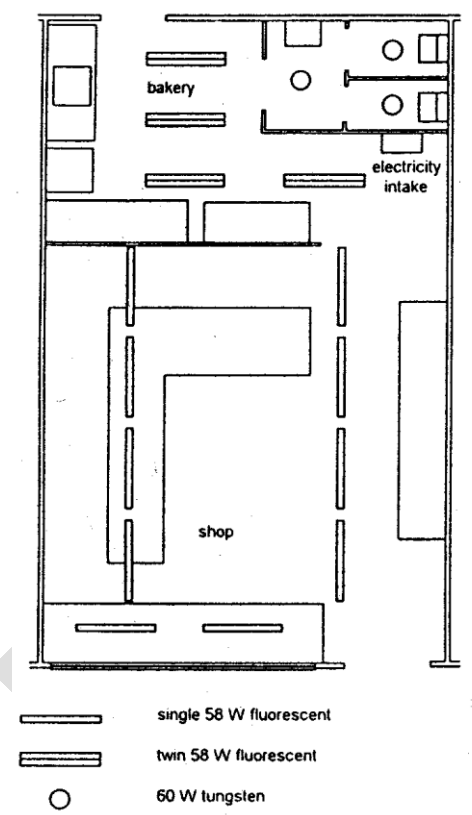


Fig. 12 Lighting layout.

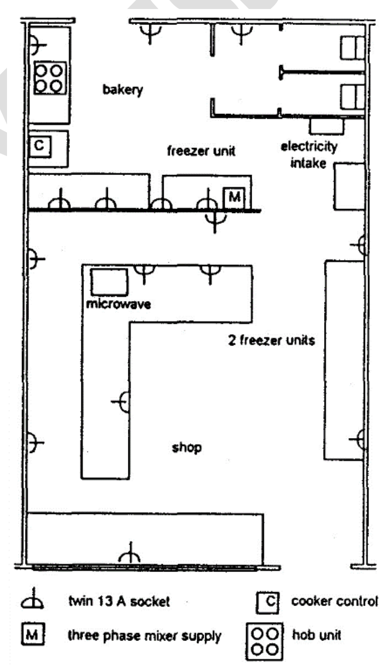


Fig. 13 Power outlets

Shop	Bakery
Lighting	
10x58 W	8x58 W 4x60 W
Twin 13A sockets	
Display units 2	Freezer 1
Microwave oven 1	Refrigerator 1
Freezers 2	Small mixers 2
General purpose 6	Gerenal purpose 4
Other loads	
	Three-phase mixers 750 W Ovem, 10 kW Hob unit, 4x1.5 kW

Table 7 Electrical requirements.

Three phase 240 V 50 Hz. TN-C-S.
Supply fuse 100 A

PFC less than 16 kA, Earth loop impedance less than 0.35

100 A TP main switch

Type B distribution board

Circuits	Rating (A)	Cable size (mm^2)	Max length (m)	Lights/points g = gang
1. Sockets shop 1	32	2.5	71	4 x 2g
2. Sockets shop 2	32	2.5	71	5 x 2g
3. Sockets bakery	32	2.5	71	7 x 2g
4. Lights 1	10	1.5	55	11
5. Lights 2	6	1.0	55	13
6. Lights 3	6	1.0	55	10
7. Hob unit	32	6.0	40	
8. Oven	50	10.0	40	
9. Mixer 3-phase	6	1.0	55	

Fig. 14 Project specification.

C. Lighting

Diversity factor of 90% is considered. Fluorescent lamp ratings must be multiplied by 1.8 to take into account control gear losses. An assumption of 100 W /outlet is considered to tungsten lamps. Two lighting circuits are assumed for the bakery shop.

Shop lighting load = 10 x 58 x 1.8 = 1044 W
At 90% diversity 1044 x 90% / 220 = 4.27 A

Bakery lighting load = (8 x 58 x 1.8) + (4 x 60) = 1075.2
At 90% diversity 1075.2 x 90% / 220 = 4.4 A

D. Socket outlets

Three circuits would be appropriate. Phase balancing has to be considered among the three phases. Diversity allowances are 100 % for the first circuit and 40% of all others, i.e. 30 A, 12 A, and 12 A. (30+12+12 = 54 A or 18A/circuit).

E. Other appliances

Mixer, at 50% diversity = 750 W x 50% / (220 x 3) = 0.57 A / phase
Oven, at 100% diversity = 10 kW x 1000 / 220 = 45.5 A
Hob unit, at 80% diversity = 6 kW x 1000 x 80% / 220 = 21.82 A

F. Phase balance

It is essentially to balance loads across three phases as far as possible. Table 8 indicates a reasonable arrangement. A proposed arrangement for the distribution board is shown in Fig. 15.

Phase	Load type	Amps
A	Sockets mixer	54 0.57 **54.57**
B	Lights Hob Mixer	8.67 21.8 0.57 **31.04**
C	Oven mixer	45.5 0.5 **46.0**

Table 8 Electrical schedule.

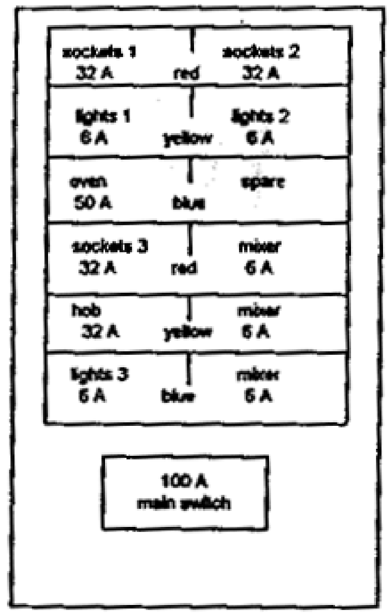


Fig. 15 Distribution board.

5.5 Electrical Floor Plans

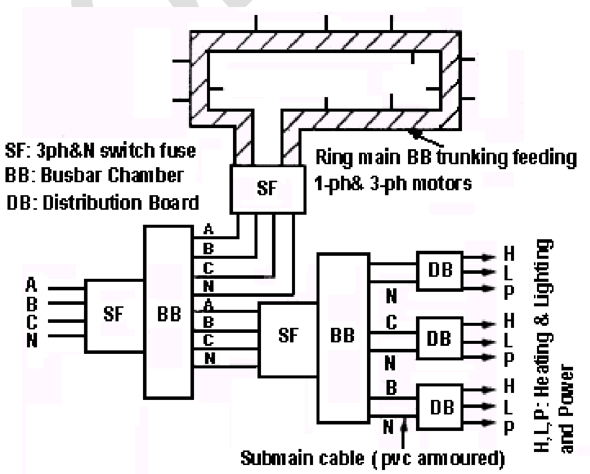


Fig. 16 Typical layout of an industrial installation.

After completing the design phase, it is necessary to record the design details whether in the form of a schedule for small installations or on drawings for the more complex installation. These drawing may be of the block, interconnection, layout, etc., type. Figs.16, 17 and 18 indicate some typical drawings, noting that the details of the design calculations shown on Fig. 18 are essential information for the testing and inspection procedure.

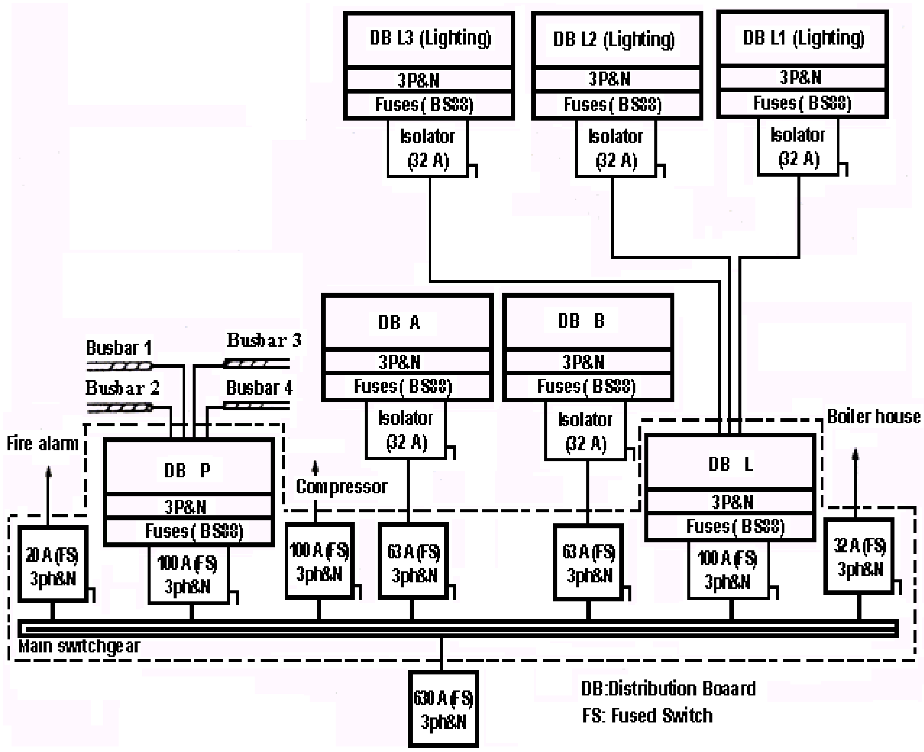
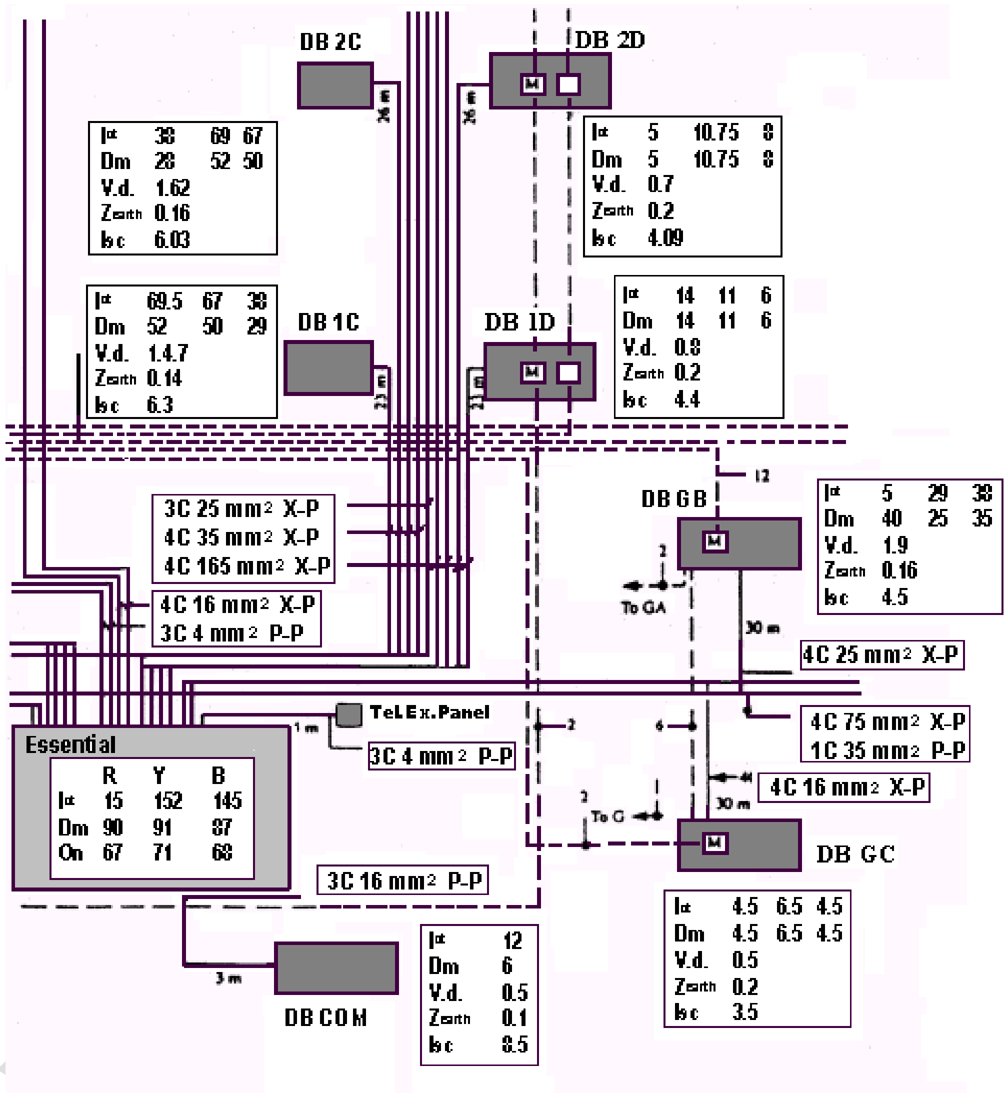


Fig.17 A block type distribution system.

With the large installations, an alphanumeric system is normally used to cross-reference between block diagrams and floor plans showing architectural symbols, as shown in Fig.19. The floor plans show which circuits are fed from DB3, and the number and phase colour of the protection. For example, the fluorescent lighting in the main entrance hall is fed from fuse or MCB1 on the red phase of DB3, and is therefore marked DB3/R1. Similarly, the water heater circuit in the female toilets is fed from fuse or MCB2 on the yellow phase, i.e. DB3/Y2. Figs. 20, 21 and 22 illustrate a simple scheme for a small garage/workshop. Fig.20 is an isometric drawing of the garage and the installation, from which direct measurements for materials may be taken. Fig.21 is the associated floor plan, which cross-references with the DB schedule and interconnection details shown on Fig. 22.



I_{ct}: circuit current in A.
V.d.: voltage drop in V
I_{sc}: prospective fault or SCC in kA.
X-P: XLPE/SWA/PVC insulation
Dm: assumed maximum demand in A.
Z_{earth}: earth loop impedance in Ohms
P-P: PVC/SWA/PVC insulation

Fig.18 Interconnection type distribution system.

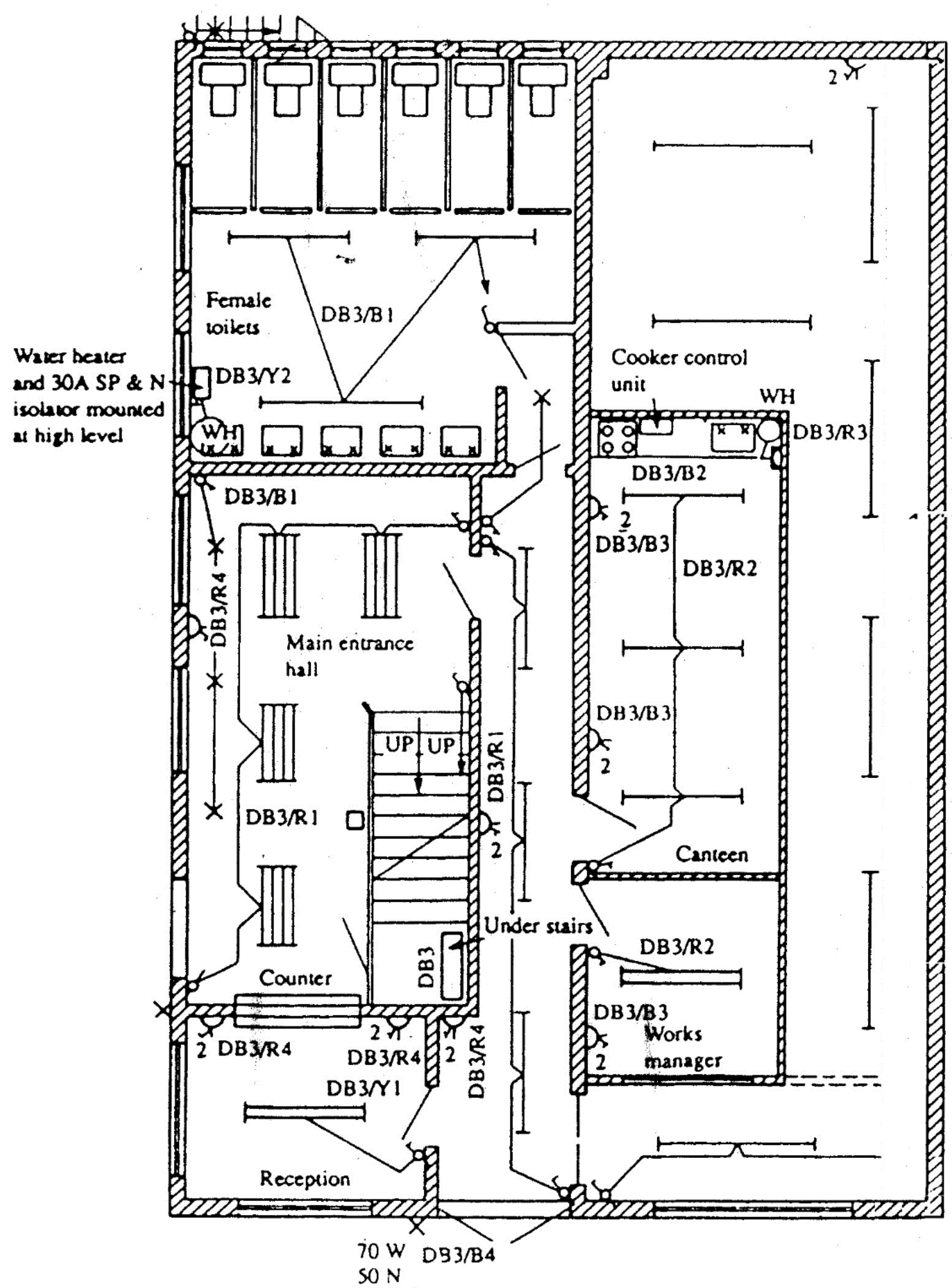


Fig.19 An electrical floor plan.

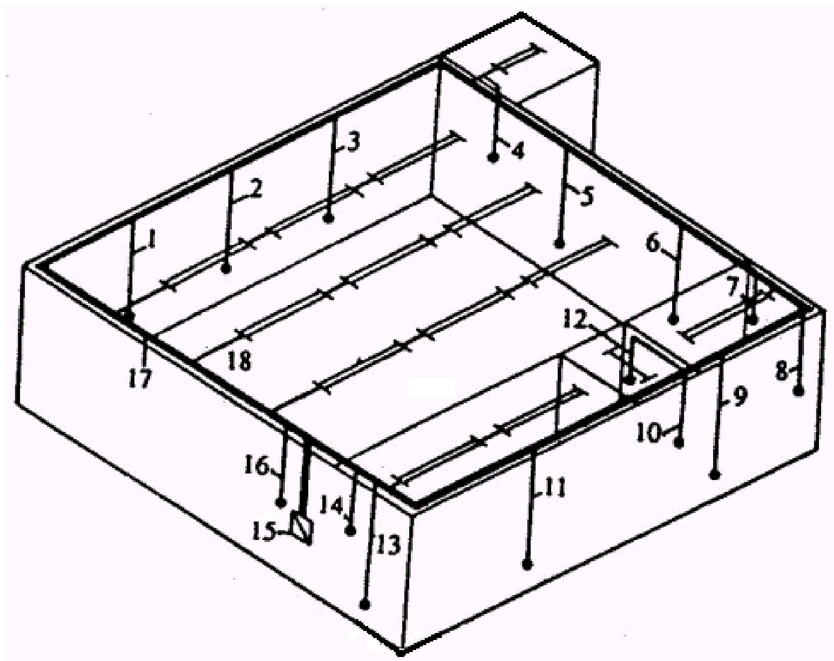


Fig.20 Isometric drawing for garage / workshop.

Explanations:

1. Three -phase supply to ramp: 20mm^2 conduit.
2. Single-phase supply to double sockets: 20 mm^2 conduit. Also 3, 5, 6, 9, 11,13.
4. Single -phase supply to light switch in store: 20 mm^2 conduit.
7. Single-phase supply to light switch in compressor: 20 mm^2 conduit.
8. Three-phase supply to compressor: 20 mm^2 conduit.
10. Single-phase supply to heater in WC: 20 mm^2 conduit.
12. Single-phase supply to light switch in WC: 20 mm^2 conduit.
14. Single-phase supply to light switch in office: 20 mm^2 conduit.
15. Main intake position.
16. Single-phase supplies to switches for workshop lights: 20 mm^2 conduit.
17. 50 mm x 50 mm steel trunking.
18. Supplies to fluorescent fittings: 20 mm^2 conduit.

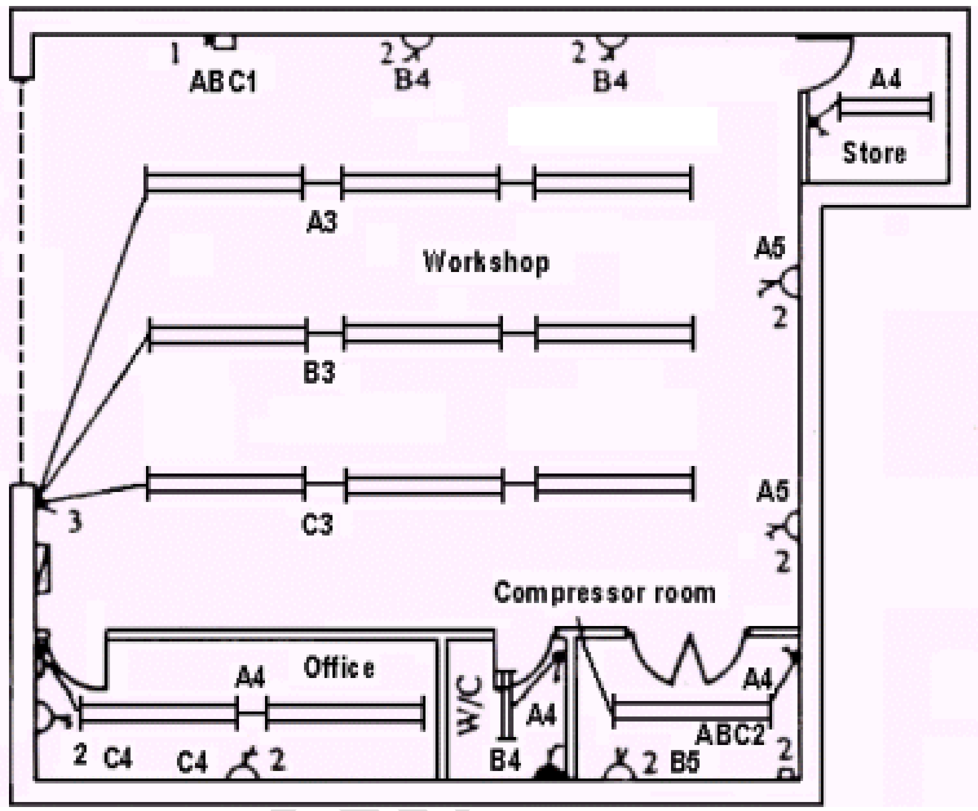
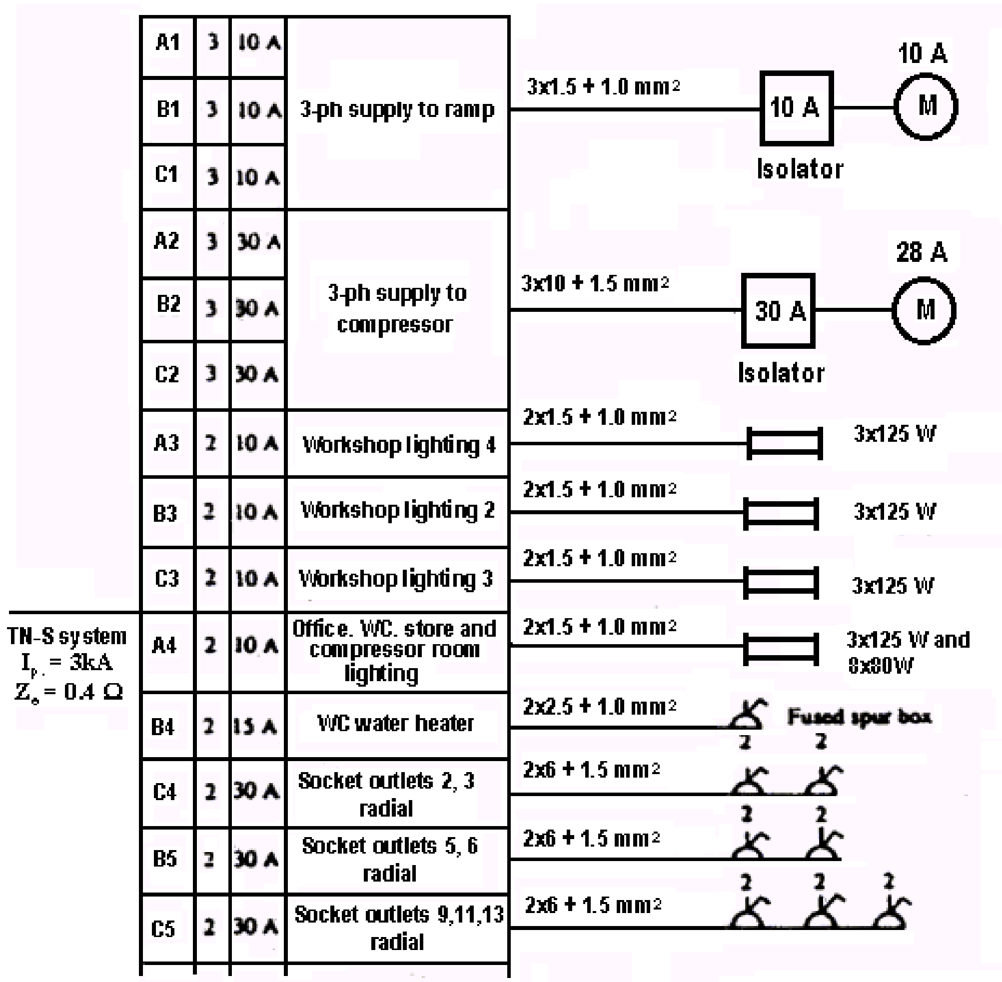
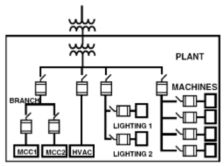


Fig.21 Electrical floor plan for garage / workshop.



1. Cables are single core with circuit protective conductor (cpc).
2. 3x1.5 + 1.0 mm^2 means 3, 1.5 mm^2 single-core conductors with cpc cross sectional area 1.0 mm^2.
3. 125 W fluorescent lamps are double and 2m length. 80 W fluorescent lamps are double and 1.2m length.

Fig.22 Details of connection diagram for garage / workshop.



CHAPTER 6

Distribution Systems

6.1 Distribution Systems

1. Residential distribution

Power purchased from the utility company enters the house through a metering device. The power is then distributed from the panel board to various branch circuits for lighting, appliances, and electrical outlets. The same thing happens in case of industrial loads. This is shown in Figs. 1,2,3 and 4.

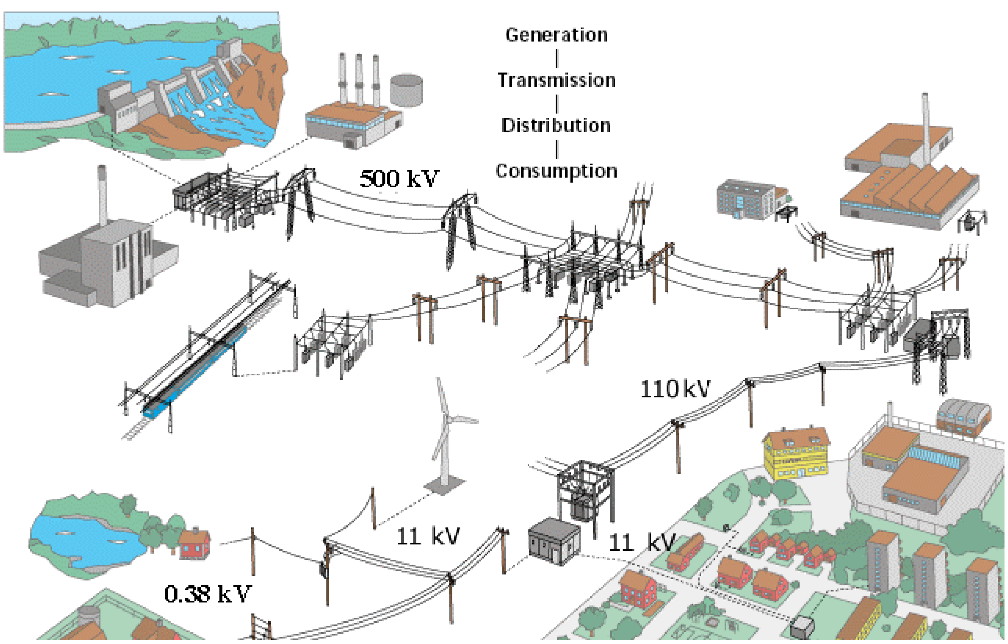


Fig.1 Generation, transmission, distribution and consumption I.

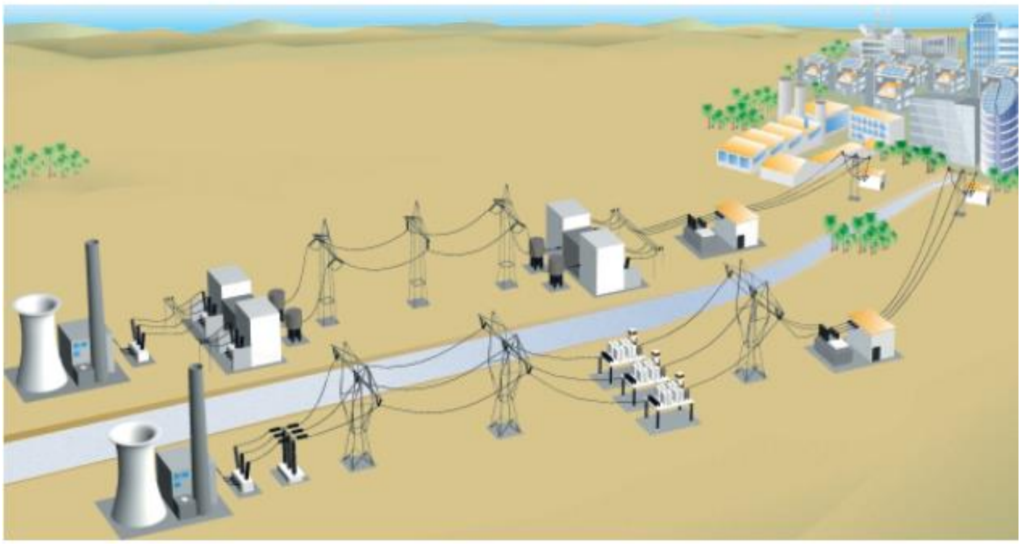


Fig.2 Generation, transmission, distribution and consumption II.

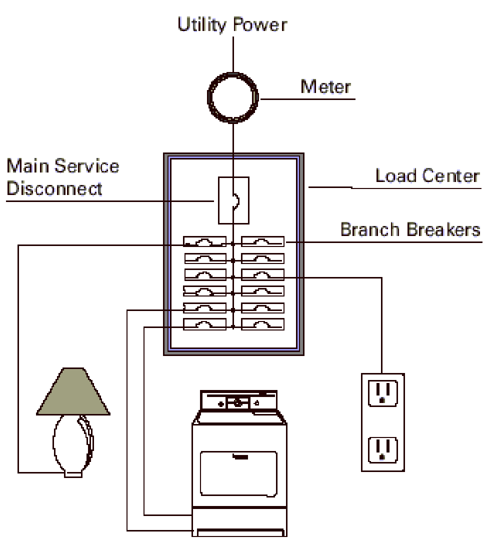


Fig.3 Residential distribution system.

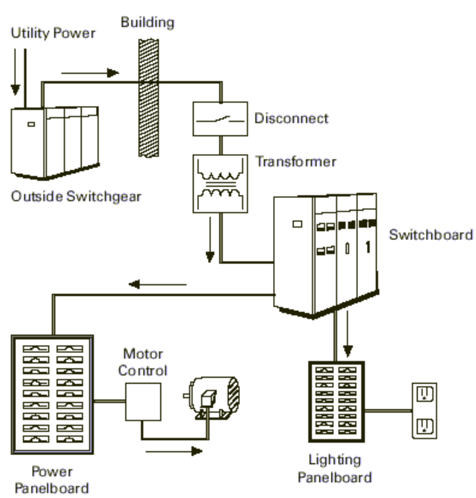


Fig.4 Industrial distribution system.

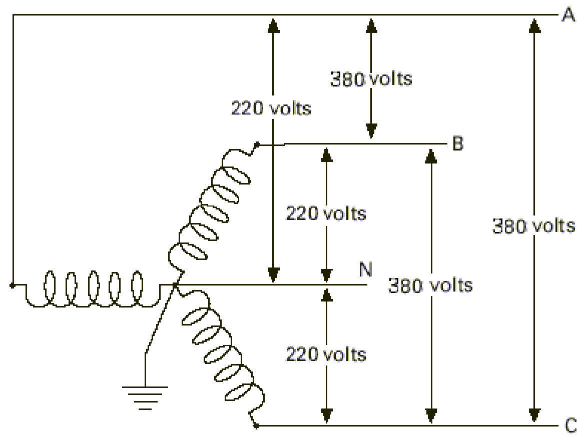


Fig.5 Three-phase, 4-wire system.

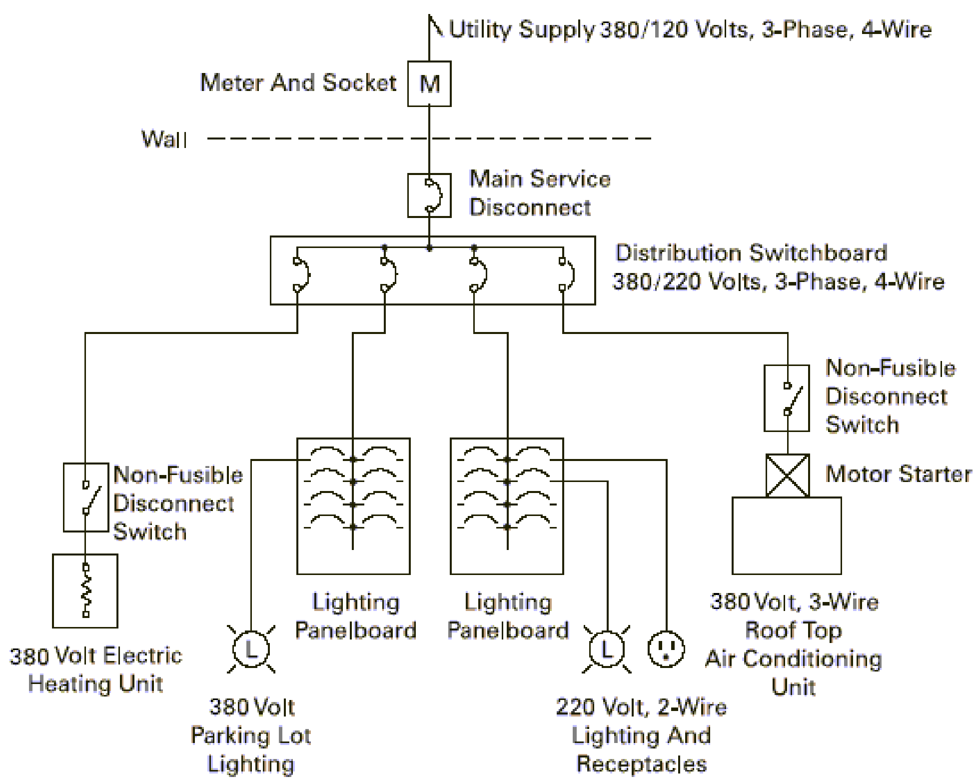


Fig.6 A distribution board supply power to a building through four feeders.

2. Industrial distribution

An industrial distribution system consists of metering devices to measure power consumption, main and branch disconnects, protective devices, switching devices, and transformers. Power may be distributed through various switchboards, transformers and panelboards. A typical three phase four-wire system is shown in Fig. 5, while a typical distribution board is shown in Fig. 6.

3. Major types of distribution systems

The best distribution system is one that will cost effectively and safely supply adequate electric service to both present and future probable loads. In the great majority of cases power is supplied by the utility to a building at the utilisation voltage. In practically all of these cases, the distribution of power within the building is achieved through the use of a simple radial distribution system. Major types of distribution systems are:

1. Simple Radial.
2. Loop-Primary System - Radial Secondary System.
3. Primary Selective System - Secondary Radial System.
4. Two Source Primary - Secondary Selective System.
5. Simple Spot Network.
6. Medium-Voltage Distribution System Design.

6.2 Simple Radial System

The conventional simple-radial system receives power at the utility supply voltage at a single substation and steps the voltage down to the utilisation level. Low-voltage feeder circuits run from the switchgear or switchboard assemblies to panelboards that are located closer to their respective loads as shown in Fig. 7.

A modern and improved form of the conventional simple radial system distributes power at a primary voltage. The voltage is stepped down to utilisation level in the several load areas within the building typically through secondary unit substation transformers. The transformers are usually connected to their associated load bus through a circuit breaker, as shown in Fig. 8.

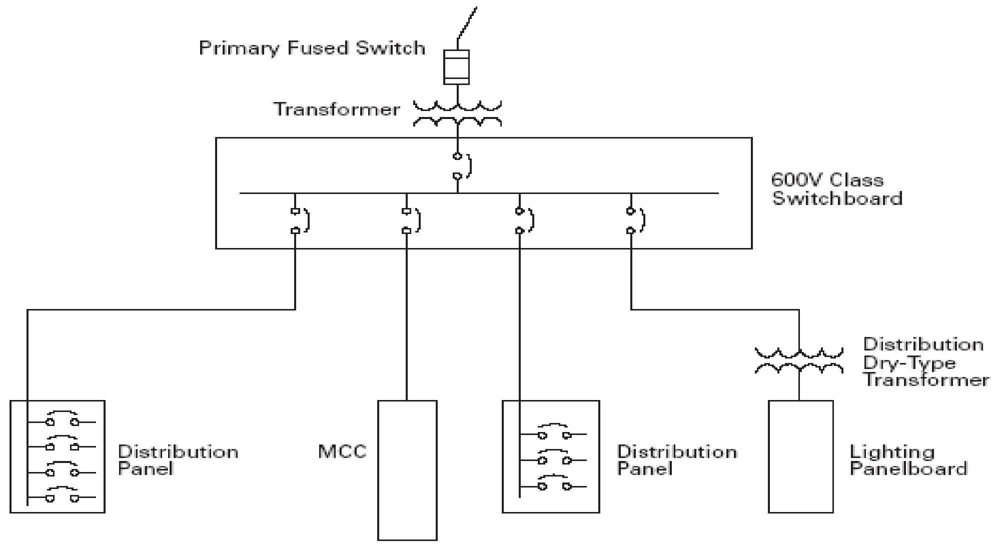


Fig.7 Simple Radial System.

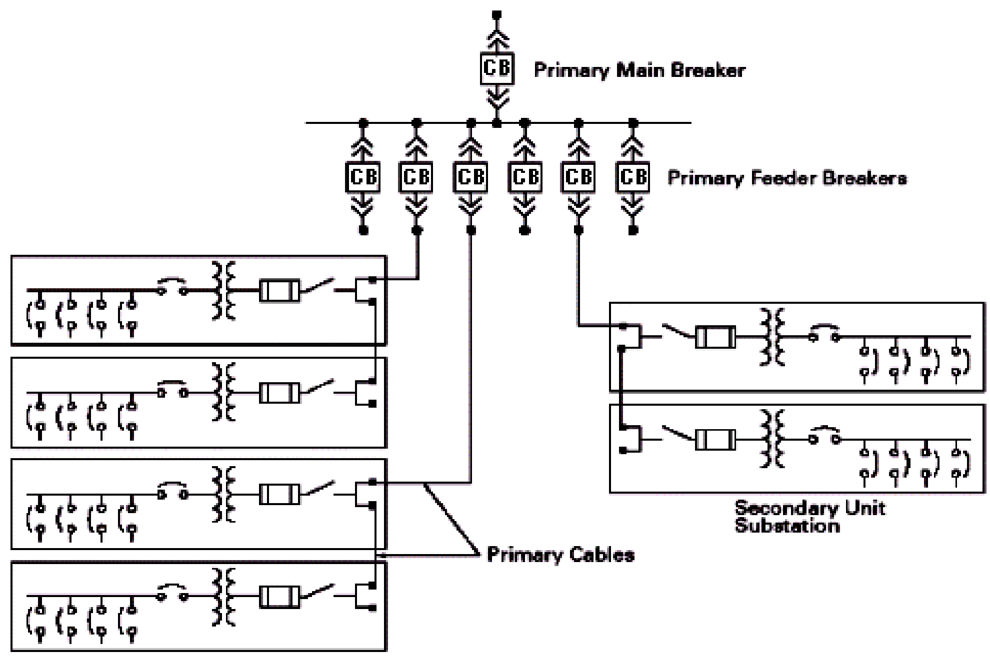


Fig.8 Primary and Secondary Simple Radial System.
CB: Power Circuit Breaker.

6.3 Loop Primary System-Radial Secondary System

This system consists of one or more "PRIMARY LOOPS" with two or more transformers connected on the loop. This system is typically most effective when two services are available from the utility. This is shown in Fig. 9. Each primary loop is operated such that one of the loops sectionalising switches is kept open to prevent parallel operation of the sources.

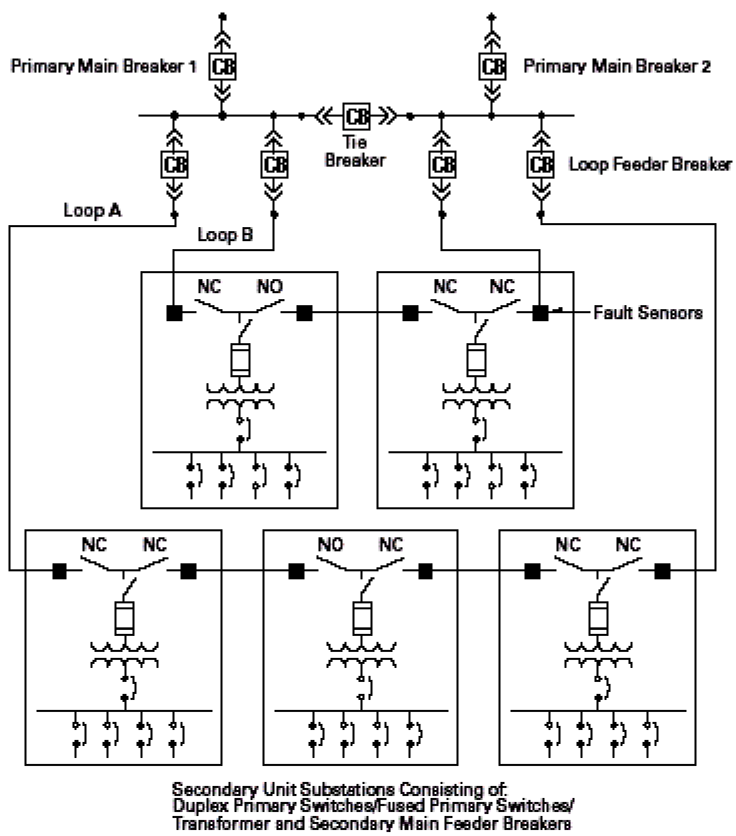


Fig. 9 Loop Primary - Radial Secondary System.
CB: Power Circuit Breaker.

When secondary unit substations are utilised, each transformer has its own duplex (2-load break switches with load side bus connection) sectionalising switches and primary load break fused switch. This is shown in Fig. 10. When pad mounted transformers are utilised, they are furnished with loop feed oil immersed gang operated load break sectionalising switches and drawout current limiting fuses as shown in Fig. 11.

A basic primary loop system which utilises a single primary feeder breaker connected directly to two loop feeder switches which in turn feed the loop is shown in Fig. 12. In this basic system the loop may be normally operated with one of the loop sectionalising switches open as described above.

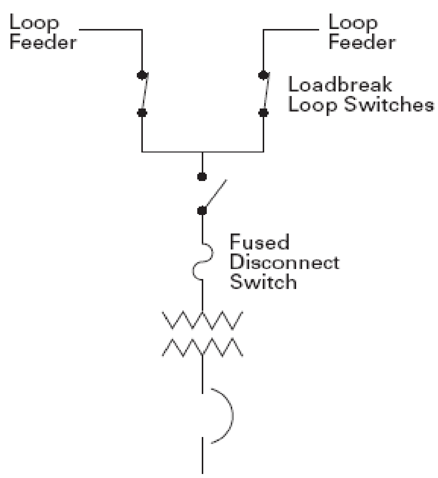


Fig. 10 Secondary Unit Substation Loop Switching.

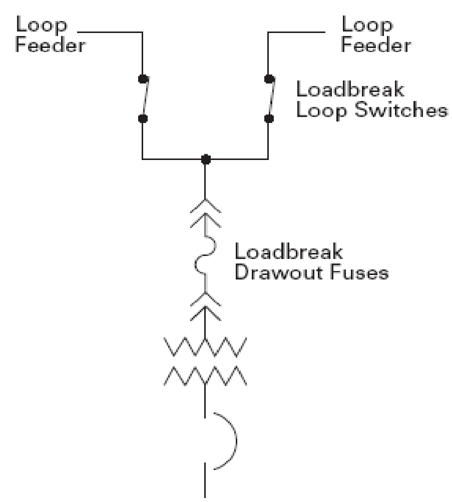


Fig. 11 Pad Mounted Transformer Loop Switching.

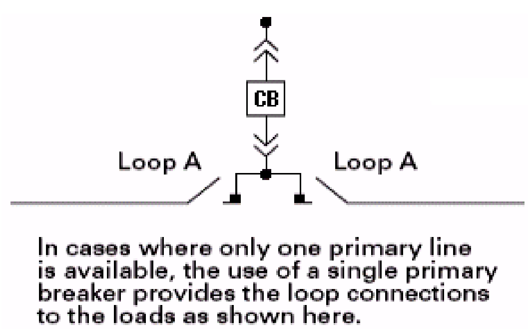


Fig.12 Single Primary Feeder – Loop System.
CB: Power Circuit Breaker.

6.4 Primary Selective System - Secondary Radial System

The primary selective – Secondary radial system shown in Fig. 13 differs from those previously described in that it employs at least two primary feeder circuits in each load area. It is designed so that when one primary circuit is out of service, the remaining feeder or feeders have sufficient capacity to carry the total load. Half of the transformers are normally connected to each of the two feeders. When a fault occurs on one of the primary feeders, only half of the load in the building is dropped. Duplex fused switches shown in Fig.13 and detailed in Fig. 14 are the normal choice for this type of system. Each duplex fused switch consists of two (2) load break 3 pole switches each in their own separate structure, connected together by bus bars on the load side. As an alternate to the duplex switch arrangement, a non-load break selector switch mechanically interlocked with a load break fused switch can be utilised as shown in Fig. 15. In Fig. 13 when a primary feeder fault occurs, the associated feeder breaker opens, and the transformers normally supplied from the faulted feeder are out of service. Then manually, each primary switch connected to the faulted line must be opened and then the alternate line primary switch can be closed connecting the transformer to the live feeder, thus restoring service to all loads. Note that each of the primary circuit conductors for Feeder A1 and B1 must be sized to handle the sum of the loads normally connected to both A1 and B1. Similar sizing of Feeders A2 and B2, etc. Is required.

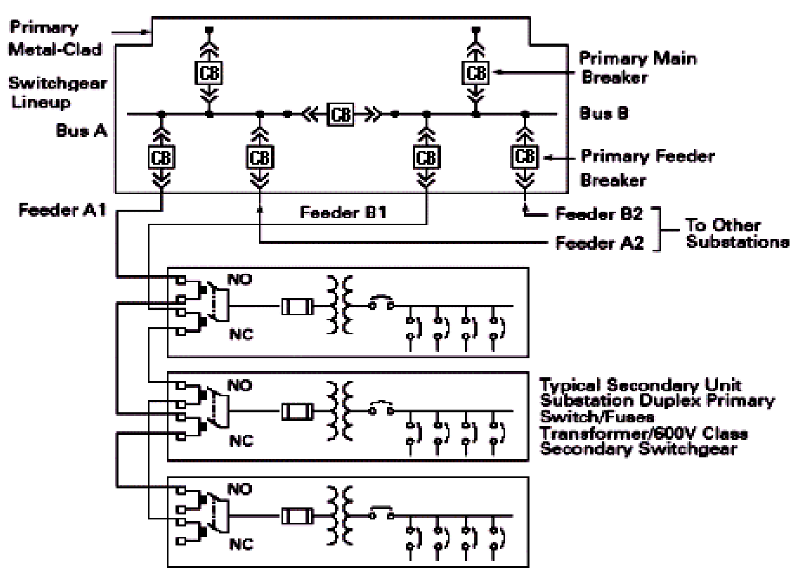


Fig. 13 Basic Primary Selective – Radial Secondary System.
CB: Power Circuit Breaker.

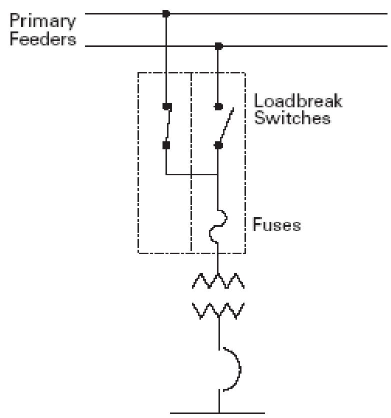


Fig. 14 Duplex Fused Switch In Two Structures.

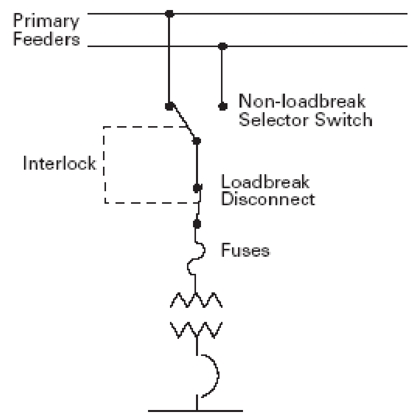


Fig. 15 Fused Selector Switch In One Structure.

6.5 Two Source Primary - Secondary Selective System

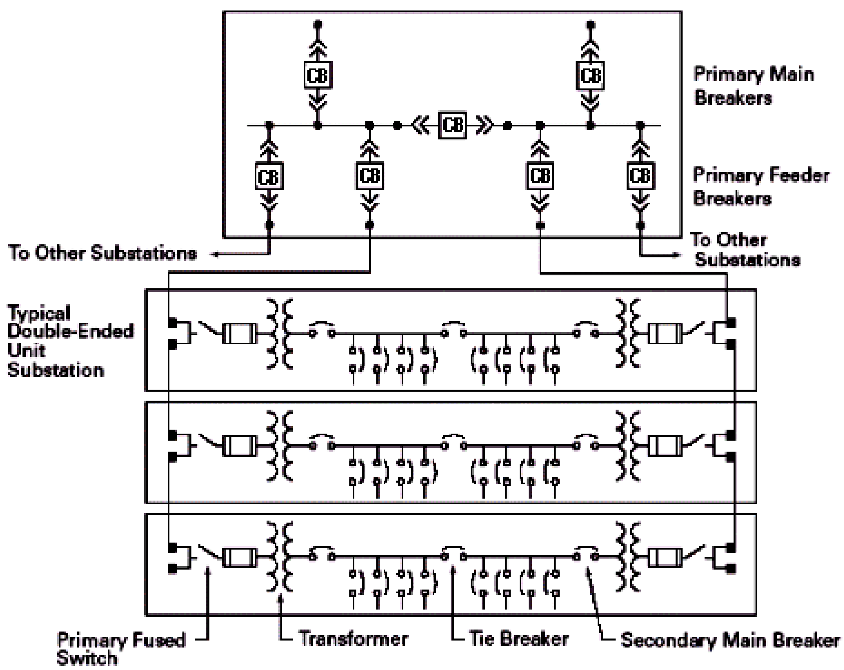


Fig. 16 Two Source Primary - Secondary Selective System.
CB: Power Circuit Breaker.

This system uses the same principle of duplicate sources from the power supply point utilising two primary main breakers and a primary tie-breaker. The two primary main breakers and primary tie breaker being either manually or electrically interlocked to prevent closing all three at the same time and paralleling the sources. Upon loss of voltage on one source, a manual or automatic transfer to the alternate source line may be utilised to restore power to all primary loads. Each transformer secondary is arranged in a typical double-ended unit substation arrangement as shown in Fig. 16. The two secondary main breakers and secondary tie- breaker of each unit substation are again either mechanically or electrically interlocked to prevent parallel operation. Upon loss of secondary source voltage on one side, manual or automatic transfer may be utilised to transfer the loads to the other side, thus restoring power to all secondary loads.

6.6 Simple Spot Network Systems

The ac secondary network system is the system that has been used for many years to distribute electric power in the high-density, downtown areas of cities, usually in the form of utility grids. Modifications of this type of system make it applicable to serve loads within buildings. The major advantage of the secondary network system is the continuity of service. No single fault anywhere on the primary system will interrupt service to any of the systems loads. Most faults will be cleared without interrupting service to any load. Another outstanding advantage that the network system offers is its flexibility to meet changing and growing load conditions at minimum cost and minimum interruption in service to other loads on the network. In addition to flexibility and service reliability, the secondary network system provides exceptionally uniform and good voltage regulation, and its high efficiency (materially) reduces the costs of system losses. Three major differences between the network system and the simple radial system account for the outstanding advantages of the network. Those are:

1. A network protector is connected in the secondary leads of each network transformer in place of, or in addition to, the secondary main breaker, as shown in Fig. 17.
2. The secondaries of each transformer in a given location (spot) are connected together by a switchgear or ring bus from which the loads are served over short radial feeder circuits.
3. The primary supply has sufficient capacity to carry the entire building load without overloading when any one primary feeder is out of service.

The use of spot network systems provides users with the important advantages:

1. They save transformer capacity. Spot networks permit equal loading of transformers under all conditions.
2. Networks yield lower system losses and greatly improve voltage conditions. The voltage regulation on a network system is such that both lights and power can be fed from the same load bus.

3. Much larger motors can be started across-the-line than on a simple radial system. This can result in simplified motor control and permits the use of relatively large low voltage motors with their less expensive control.
4. Network systems provide a greater degree of flexibility in adding future loads; they can be connected to the closest spot network bus.

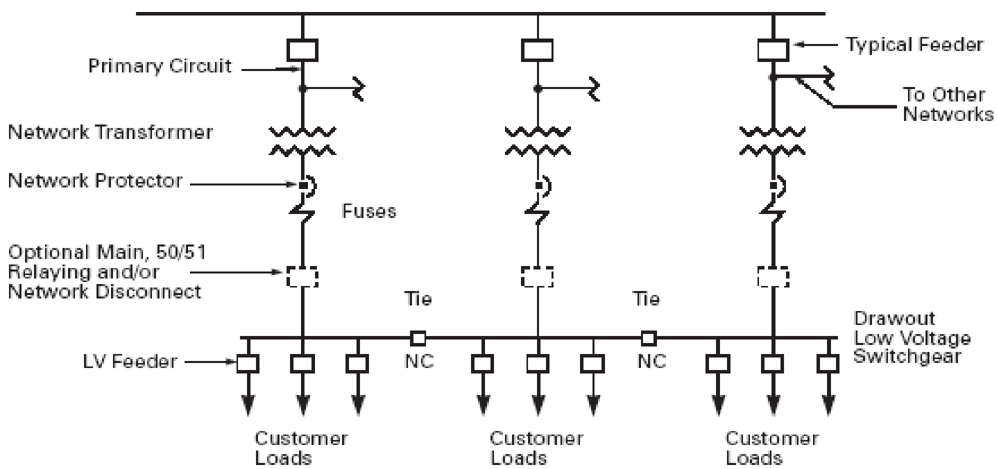


Fig. 17 Three Source Spot Network.

6.7 Medium-Voltage Distribution System Design

1. Single Bus

In Fig. 18 the sources (utility and/or generator(s)) are connected to a single bus. All feeders are connected to the same bus. Generators are used where co-generation is employed. This configuration is the simplest system, however, outage of the utility results in total outage.

2. Single Bus with Two Sources from the Utility

It is the same as the single bus, except those two utility sources are available. This system is operated normally with the main breaker to one source open. Upon loss of the normal service the transfer to the standby Normally open (NO) breaker can be automatic or manual. Automatic transfer is preferred for rapid service restoration especially in unattended stations. This is shown in Fig. 19.

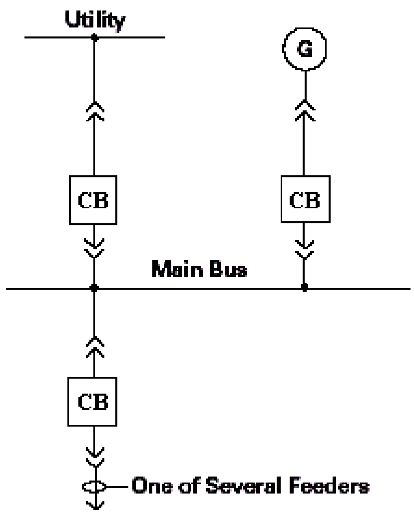


Fig.18 Single Bus.
CB: Power Circuit Breaker.

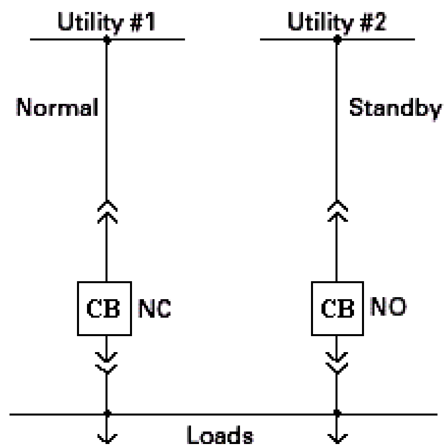


Fig.19 Single Bus with Two Sources.
CB: Power Circuit Breaker.

This scheme is more expensive than scheme shown in Fig. 18, but service restoration is quicker. Again a utility outage results in total outage to the load until transfer occurs. Extension of the bus or adding breakers requires a shutdown of the bus.

3. Multiple Sources with Tie Breaker

This scheme is basically the scheme (2) shown in Fig. 19, but with addition of the tie-breaker. The outage to the system load for a utility outage is limited to half of the system. Again the closing of the tie-breaker can be manual or automatic. The statements made for the retransfer of scheme B apply to this scheme also. This system is more expensive than (2). The system is not limited to two buses only. Another advantage is that if the paralleling of the buses is momentary, no increase in the interrupting capacity of the circuit breakers is required as other buses are added provided only two buses are paralleled momentarily for switching. The third tie breaker shown in Fig. 20 allows any bus to be fed from any utility source.

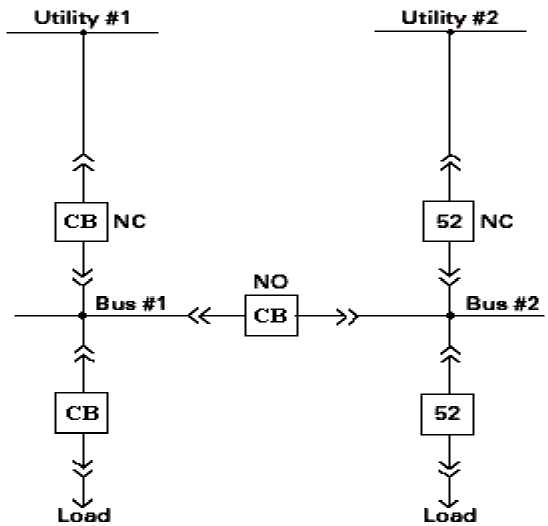


Fig. 20 Two Source Utility with Tie-Breaker.
CB: Power Circuit Breaker.

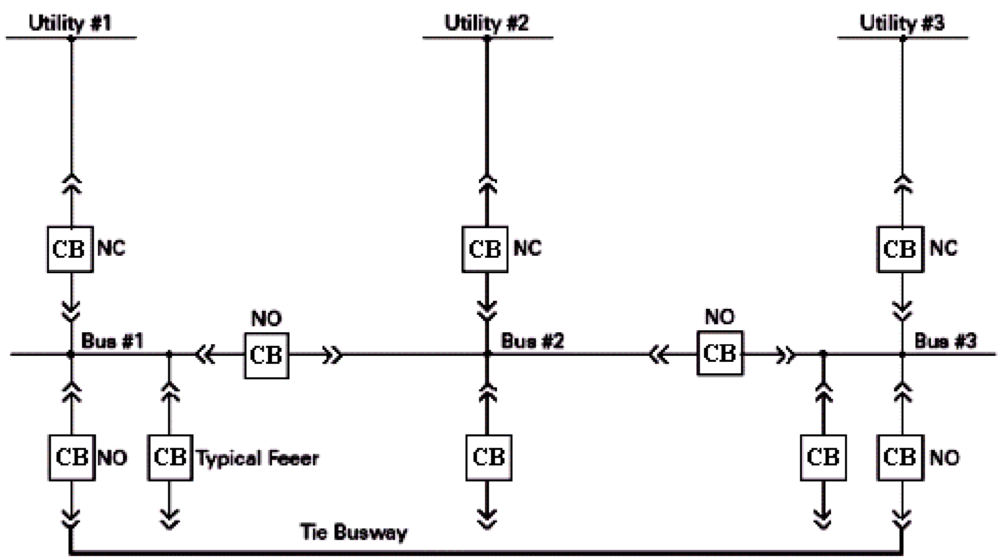


Fig. 21 Triple Ended Arrangement.
CB: Power Circuit Breaker.

Caution for Figs 19, 20 and 21: If continuous paralleling of sources is planned, reverse current, reverse power and other appropriate relaying protection should be added. When both sources are paralleled, the fault current available on the load side of the main device is the sum of the available fault current from each source plus the motor fault contribution. It is required that bus bracing, feeder breakers and all load side equipment is rated for the increased available fault current.

6.8 Summary

The schemes shown are based on using metal-clad medium-voltage draw-out switchgear. The service continuity required from electrical systems makes the use of single source systems impractical. In the design of modern medium-voltage system the engineer should:

1. Design a system as simple as possible.
2. Limit an outage to as small a portion of the system as possible.
3. Provide means for expanding the system without major shutdowns.
4. Relay the system so that only the faulted part is removed from service, and damage to it is minimised consistent with selectivity.
5. Specify and apply all equipment within its published.

Photographs of some main MV and HV power elements are shown in Figs. 22-32.

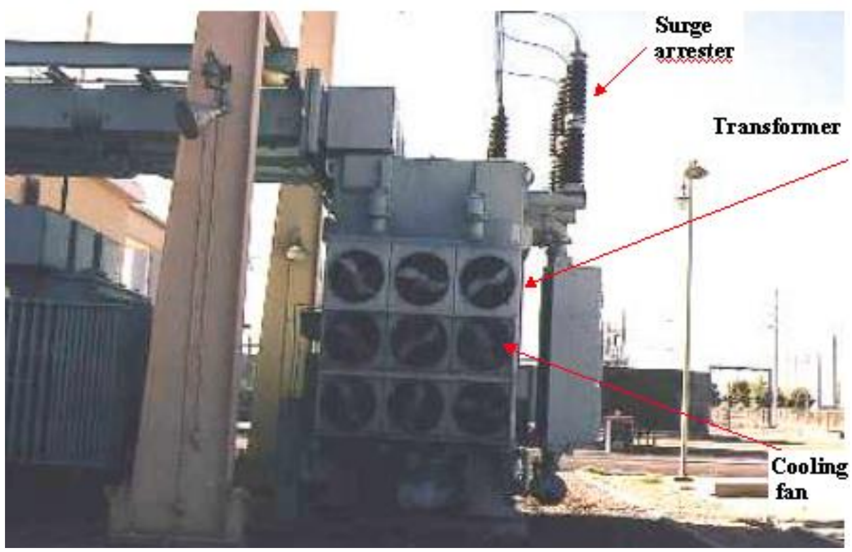


Fig.22 Transformer.

Fig.23 Circuit breaker.

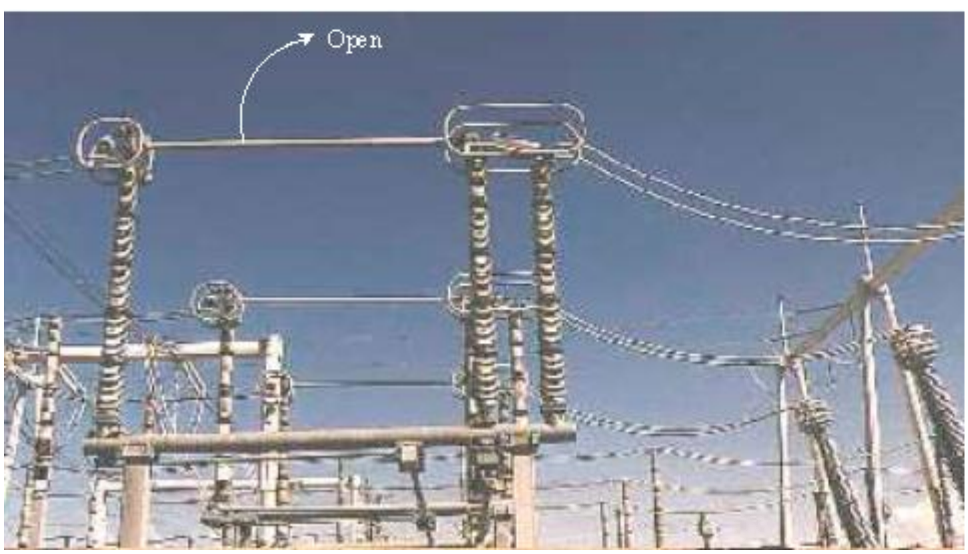


Fig.24 Disconnecting switch.

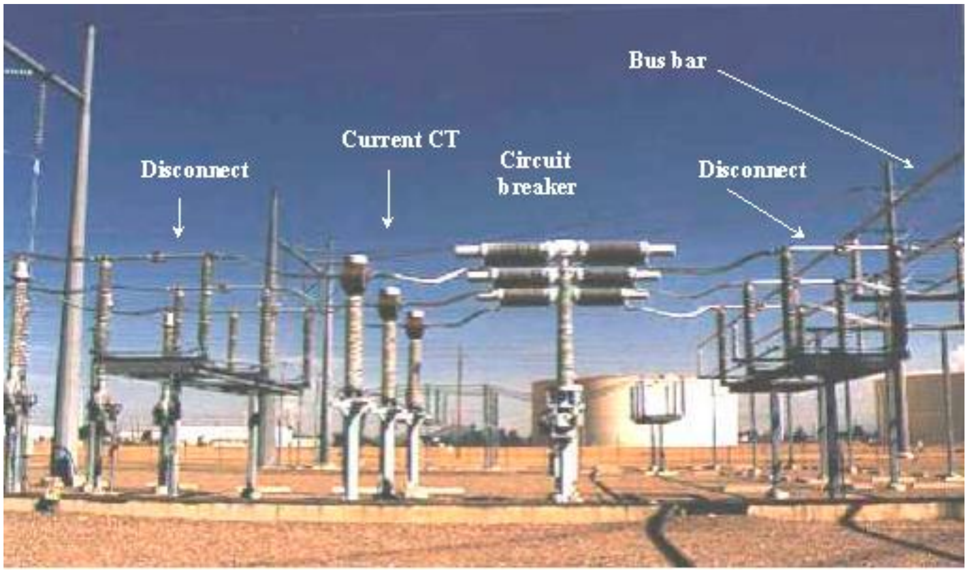


Fig.25 Current transformer and circuit breaker.

Fig. 26 Lightning arrester.

Fig.27 Surge arrester.

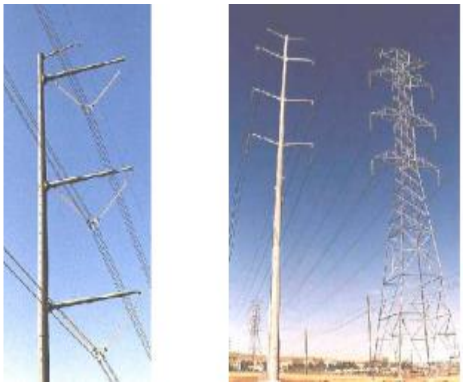


Fig. 28 HV and EHV lines.

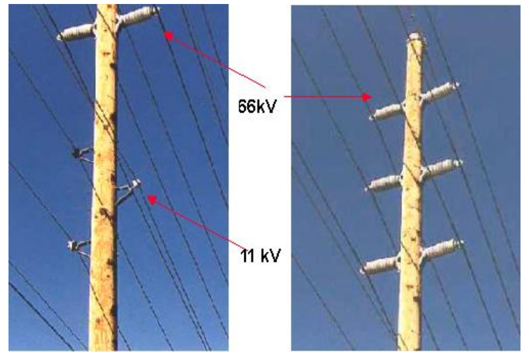


Fig. 29 66kV and 11kV poles.

Fig.30 Insulator discs.

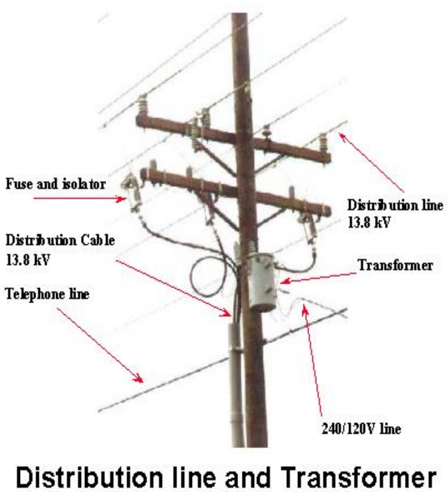


Fig. 31 Distribution line and transformer.

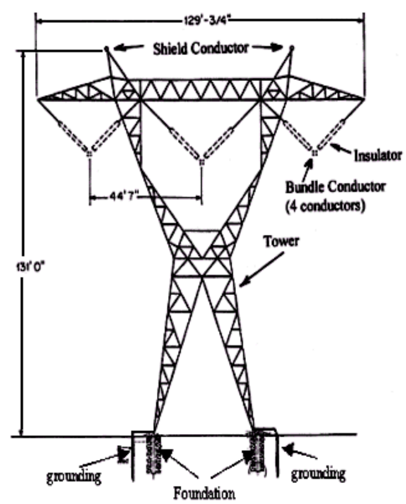
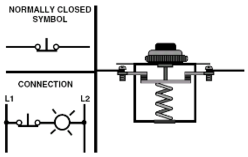


Fig. 32 Typical extra high voltage line.
(765 kV suspension tower)

6.9 Revision Questions

1. Sketch a single line diagram of one of the following distribution systems, and state its main features.
   1. Simple radial distribution system.
   2. Loop-Primary System - Radial Secondary System.
   3. Primary Selective System - Secondary Radial System.
   4. Two Source Primary - Secondary Selective System.
   5. Simple Spot Network.

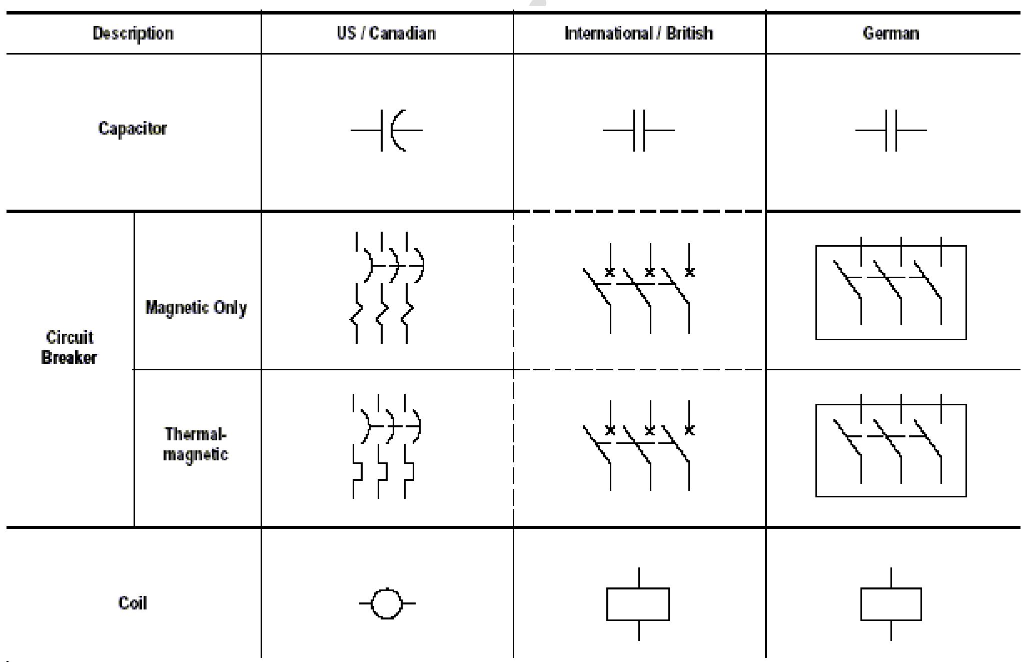


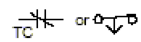
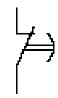
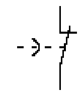
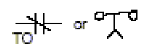
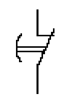
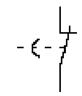
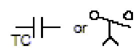
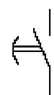
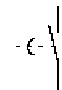
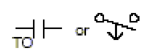
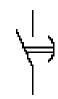
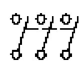
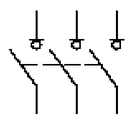
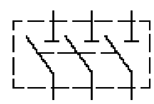
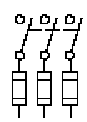
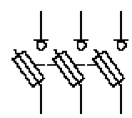
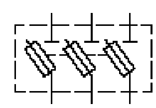
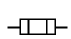
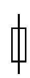
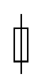
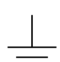
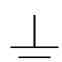
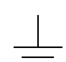
APPENDIX

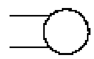
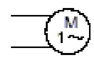
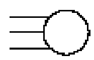
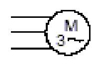
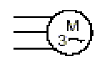
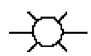
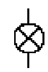
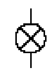
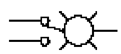
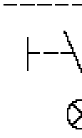
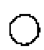
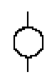
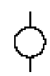
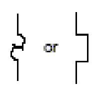
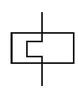
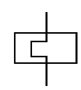
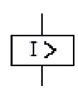
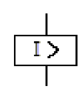
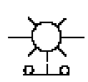
Electrical Symbols

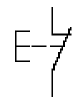
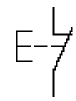
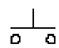
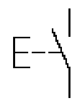
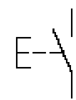
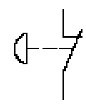
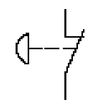
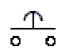
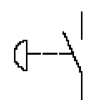
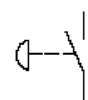
A.1 Schematic Diagrams Symbols (Global Reference)

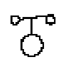
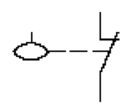
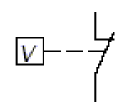
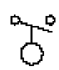
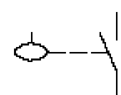
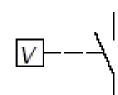
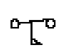
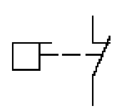
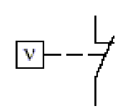
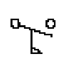
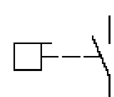
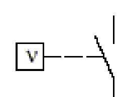
Since the electrical standards adopted in industries by various nations may vary, the markings and symbols used to describe electrical control products can be different, accordingly, the need to recognise these symbols becomes more important. Shown in Fig.1 is a simple cross-reference of common schematic /wiring diagram symbols used throughout various parts of the world, while Fig. 2 shows *an elementary basic motor control circuit in which* the contactor will be controlled by separate start and stop buttons, and an auxiliary contact is used as a hold in contact. i.e. the contactor is electrically latched closed while the motor is operating.

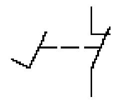
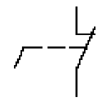
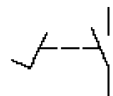
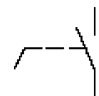


Time Delay Contacts	**N.C., Timed Closed**			
	N.C., Timed Open			
	N.O., Timed Closed			
	N.O., Timed Open			
Disconnect Switch	**Non-Fused**			
	Fused			
Fuse				
Ground				

Induction Motor	**Single Phase**			
	Three Phase			
Lights, Indicating	**Standard**	 Insert color code inside symbol	 Insert color code next to symbol	 Insert color code next to symbol
	Push-To-Test	 Insert color code inside symbol		 Insert color code next to symbol
Meters		 Insert function code inside symbol	 Insert function code inside symbol	 Insert function code inside symbol
Overload Relay	**Thermal Element**			
	Magnetic Element			
Push Button	**Illuminated**			

Push Button	Momentary (N.C.)			
	Momentary (N.O.)			
	Mushroom Head (N.C.)			
	Mushroom Head (N.O.)			

	Float (N.C.)			
	Float (N.O.)			
	Flow (N.C.)			
Switches	Flow (N.O.)			

	Foot (N.C.)			
	Foot (N.O.)			
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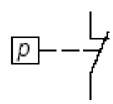
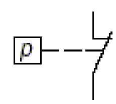
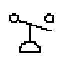
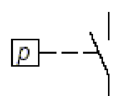
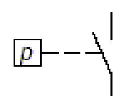
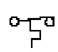
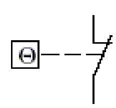
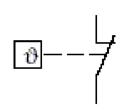
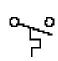
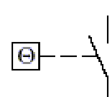
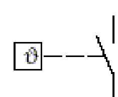
-	Limit (N.O.)			
	Pressure (N.C.)			
Switches	Pressure (N.O.)			
	Temperature (N.C.)			
	Temperature (N.O.)			

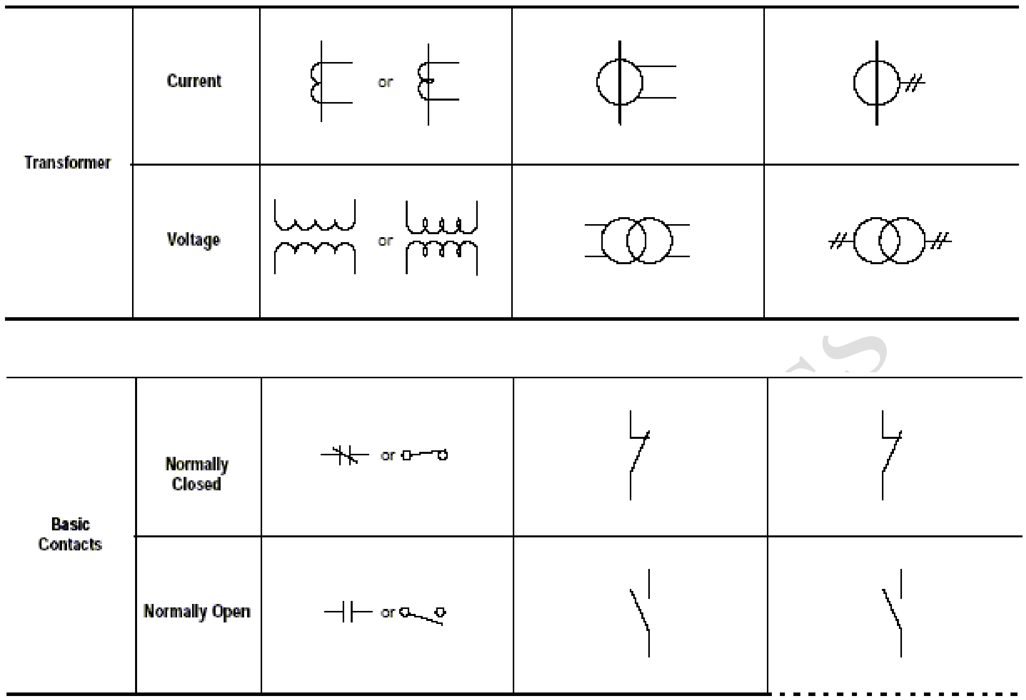


Fig.1 Cross-reference of common schematic / wiring diagram symbols.

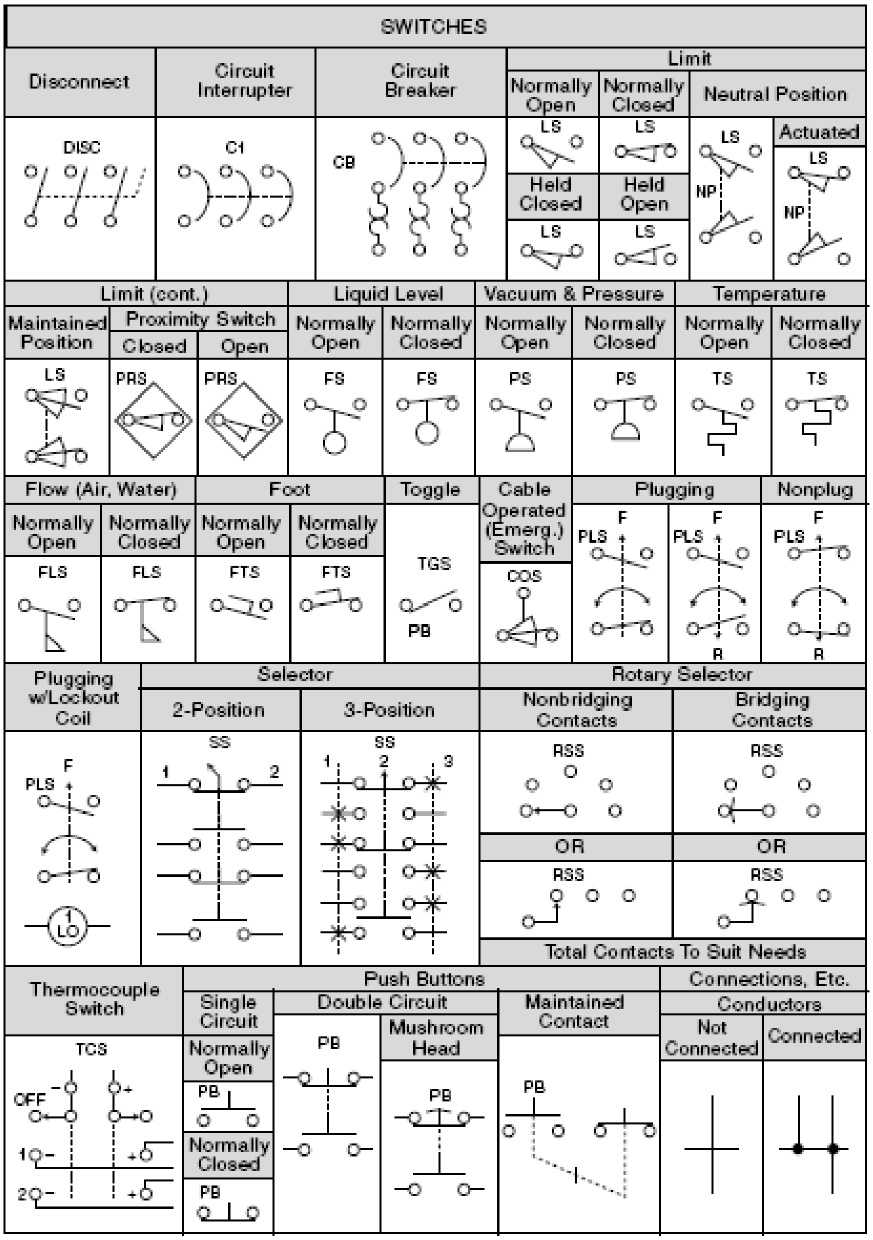


Fig.2 Electrical Relay Diagram Symbols.

Fig.3 Location symbols for installations – British Standards

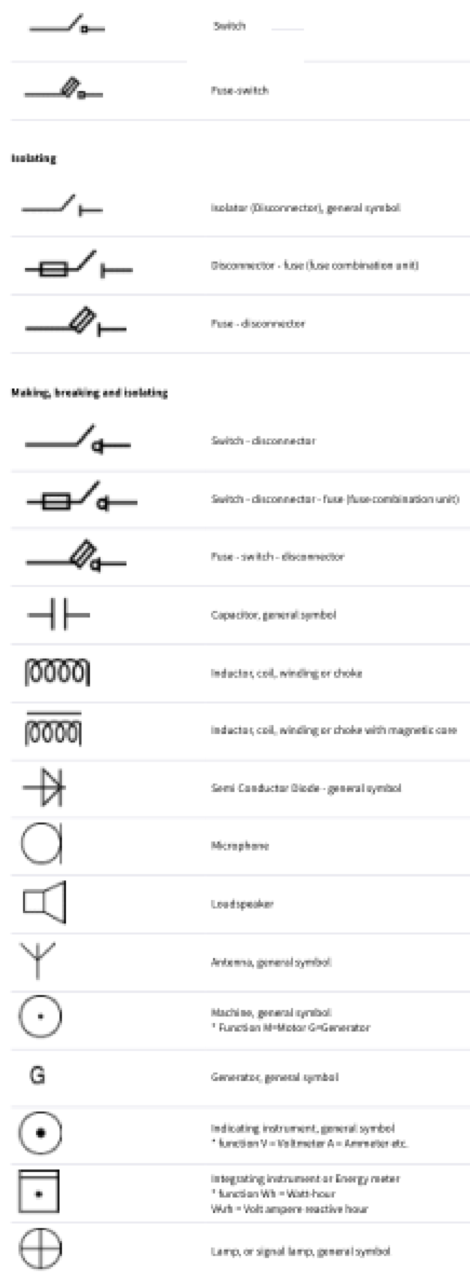


Fig.4 Symbols for making and breaking current– British Standards.

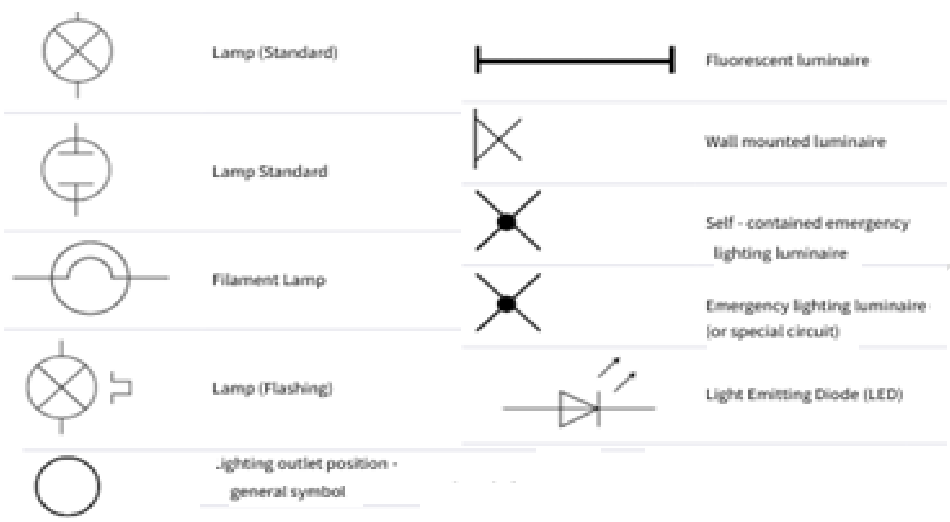


Fig.5 Lamps and lighting-- British Standards.

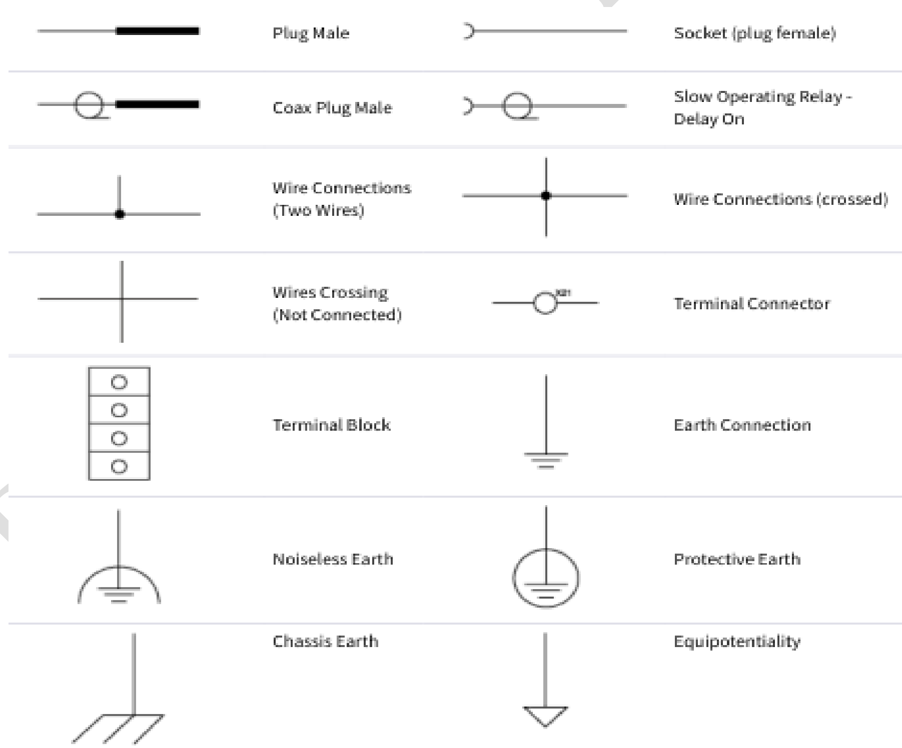


Fig.6 Connectors and earthing.

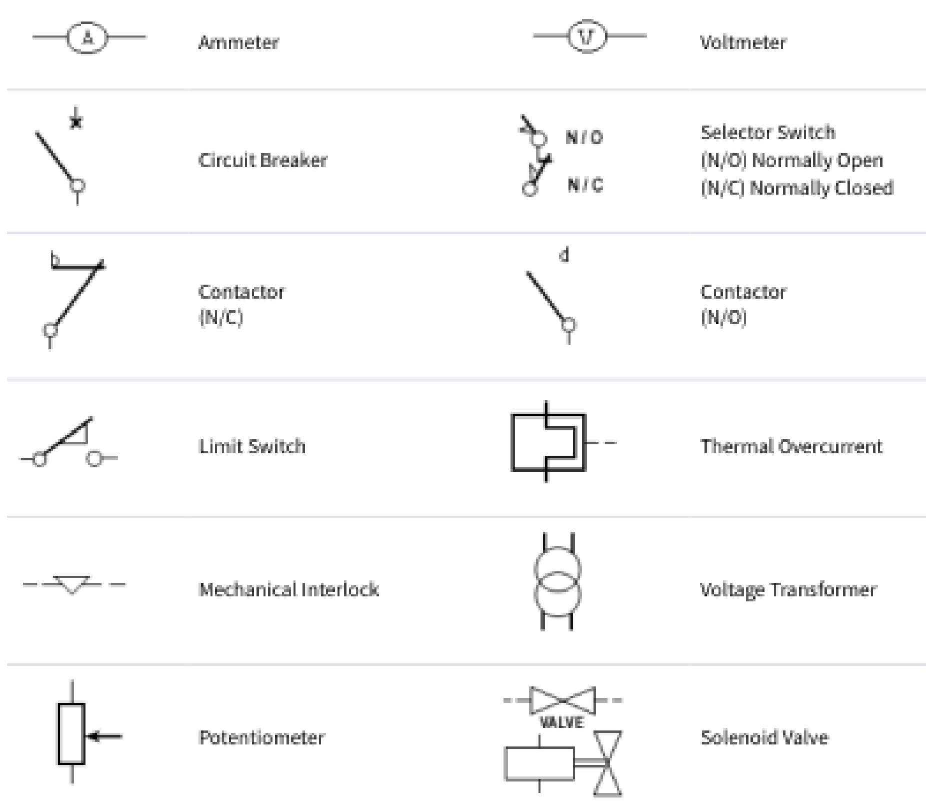


Fig.7 General symbols.

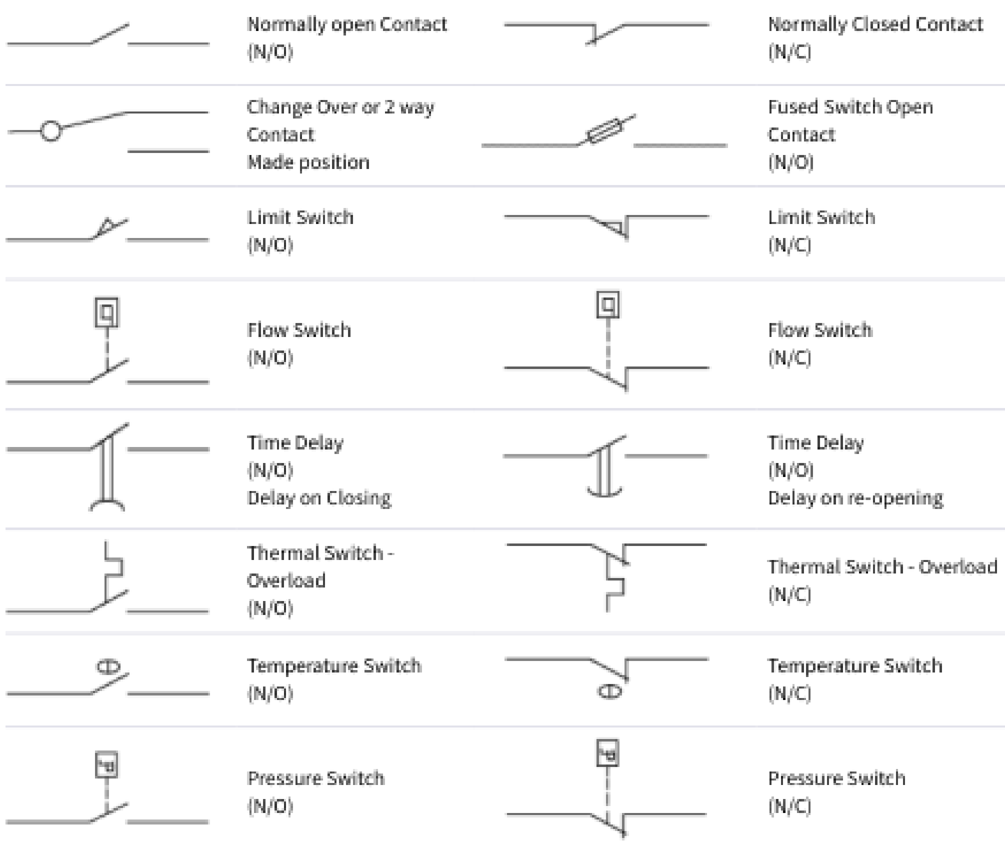


Fig.8 Contactors and switches.

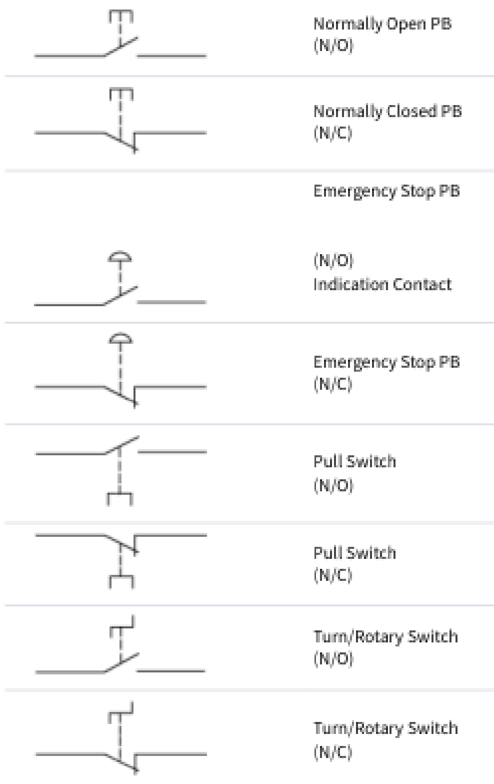


Fig.9 Push buttons.

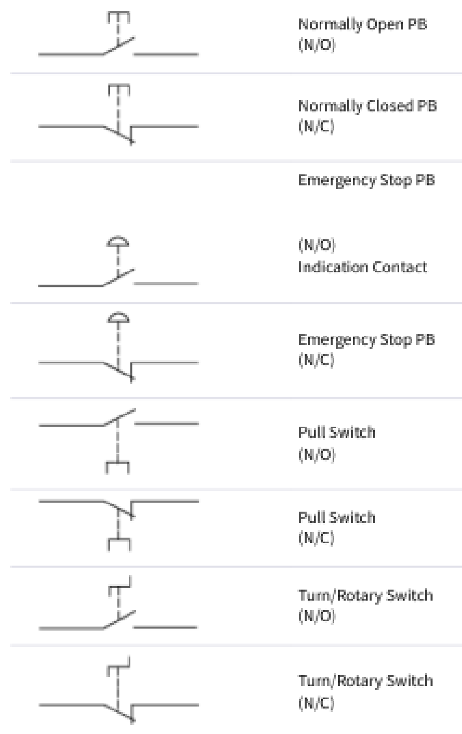


Fig.10 Coils and relays.