ELECTRIC MOTOR CONTROL SYSTEMS AND TECHNOLOGIES IN REFINERIES

by

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ABSTRACT

Many of the processes in refineries require pumping, compression, valve control, fan cooling or blowing, and these are universally driven by electric motors. Motor types are either induction or synchronous, and vary in size from less than one horsepower to in excess of 2,000 horsepower. While the reliable and safe operation of these motors is critical to the productivity of a refinery, concerns in efficient energy consumption and motor life have an impact on refinery profitability.

This report discusses the application, control and protection of electric motors used in refineries. Issues of motor type selection, power ratings, supply voltage, insulation, vibration, and temperature limits, are each discussed relative to applications in pumping, compression, valve drives, fans and blowers. Start-up and shutdown sequences are covered alongside a detailed description of NEMA standard relays which protect against abnormal voltage, current, phase, thermal, and power factor conditions. The report extends into an assessment of the state-of-the-art in motor and monitoring and control technologies, and projects future developments and provides recommendations on motor

systems, integrated protection, and energy management systems.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

GCB = Gas circuit breaker

GIS = Gas insulated switchgear

GFR = Ground-fault relay

GPT = Ground potential transformer

HP = Horse power

IC = Interrupting current

mA = 10^{-3}A

MCC = Motor control center

MF = 10^{-6}F

mil = 10^{-3} inch

MOV = Motor operated valve

P = Pole

PF = Power factor

PLC = Programmable logical controller

RPM = Revoloution per minute

RTD = Resistance temperature detector

TEFC = Totally-enclosed fan-cooled

μm = 10^{-6} meter

UPS = Uninterruptible power supply

WPII = Weather-protected type II

ZCT = Zero phase current transformer

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1. INTRODUCTION

Electric motors and electric motor control systems are critical to the successful and continuing operation of chemical plants and refineries. Motors are used to drive a variety of process elements, including pumps, compressors, valves, coolers and blowers. Motor control systems coordinate the complexities of start-up and shutdown sequences, and provide numerous levels of protection for the safety of the operator and the preservation of capital equipment. At the same time, new technologies and system architectures are being developed, providing enhanced levels of performance and integrated protection schemes. This report addresses these contemporary engineering issues in motor applications and motor control systems in refineries.

While the basic design of the alternating current rotating electric machine dates back to the patents of Nikola Tesla and the 1889 commercialization of the machine by the Westinghouse Corporation (see, for example, "The Story of The Induction Motor" by B.G. Lamme, Journal of the A.I.E.E., March, 1921), new motor applications are strongly influenced by modern developments in materials technology and electronic controls. For example, thermalastic epoxies, frequency controllers, uniterruptible power supplies

(UPS's), programmable logic controllers (PLC's), integrated relays, on-line insulation monitors are becoming widely used. The purpose of this report is to provide a technically informative description of the state-of-the-art and projected developments in motors and motor control systems in refinery applications. The report is primarily addressed to electrical engineers, maintenance engineers and technicians concerned with the operation and development of motor systems in refineries. In particular, it covers the wide variety of motor and motor control issues which fall within the responsibility of refinery engineers.

This report is descriptive at the expense of being technically exhaustive. Methods and techniques relative to motor applications and controls are described in the context of strengths, weaknesses, precautions and operating methods. Intricate technical detail is therefore omitted, and readers who are interested in certain facets of this report will need to consult additional references and manufacturer's specifications for technical particulars.

The organization of the report is such that the dominant motor applications in refineries are covered first. This is followed by a description of existing control and protection systems, and the existing technologies used in the implementation of these systems. The report continues with a discussion on developing technologies and projections on future systems. Recommendations on the best strategies for employing future technologies and systems in refineries conclude the work.

2. MOTOR APPLICATION

2.1 Pump Drives

Although pumps are classified into three categories, namely centrifugal, rotary, and reciprocating, their motor drivers are the same. In general, motors are selected in accordance with the size of the pumps. The following issues are the major items for consideration in pump drive application.

2.1.1 Motor Types

Most motors available for pump drives are three-phase, induction and squirrel-cage types.

A single-phase squirrel-cage (split-phase) motor is used for small pumps like the chemical pump which has a capacity of only 0.75HP or less. A split-phase motor is a single-phase motor equipped with an auxiliary winding which is connected in parallel with the main winding and displaced in magnetic position.

Totally-enclosed fan-cooled (TEFC) motors are widely used in refineries. Most motors used in refineries for outdoor pumps up to 900HP are the TEFC type.

Weather-protected type II motors (WPII) are used for large pumps. In order to reduce costs, WPII motors are selected for outdoor pumps. The capacity can be from 300HP to 2500HP. A WPII motor shall have, in addition to the enclosure defined for a weather-protected type I motor, its ventilating passages at both intake and discharge so arranged that high-velocity air and air-borne particles blown into the motor by storms or high winds can be discharged without entering the internal ventilating passages leading directly to the electric parts of the motor. The interior of the motor shall be so arranged by baffling or separate housings as to provide at least three abrupt changes in direction, none of which shall be less than 90 degrees. In addition, an area of low velocity not exceeding 600 feet per minute shall be provided in the intake air path to minimize the possibility of moisture or dirt being carried into the electric parts of the motor.

Forced-ventilated motors are used for pumps of capacity from 400HP to 3000HP, which are installed in pump houses. This type of motor is ventilated by means of a separate motor-driven blower mounted on the motor enclosure.

An explosion-proof motor is used for pumps installed in hazardous atmosphere division 1 areas. See Tables 1, 2, and 3 for classification of hazardous atmospheres and locations. An explosion-proof motor is a totally-enclosed motor whose enclosure is designed and constructed to withstand an explosion of a specified gas or vapor that may occur within it. The motor is also designed to prevent the ignition of the specified gas or vapor surrounding the motor by sparks, flashes or explosions which may occur within the motor casing.

Safety increased explosion motors are used for pumps which are installed in hazardous atmosphere division 2 areas. A safety increased explosion motor is a totally-enclosed motor whose enclosure is designed and constructed with greater integrity than the TEFC.

Table 1. Classification of Hazardous Atmospheres.

Class	Group	Typical Atmosphere	Ignition Temps.
	A	Acetylene	305C,581F
	B	Butadiene	420C,788F
		Ethylene oxide	429C,804F
		Hydrogen	400C,752F
		Propylene oxide	449C,840F
		Manufactured gases containing more than 30% hydrogen (by volume)	
1 Gases, Vapors	C	Acetaldehyde	175C,347F
		Cyclopropane	500C,932F
		Diethyl ether	160C,320F
		Ethylene	490C,914F
		Unsymmetrical dimethyl hydrazine (UDMH 1, 1-dimethyl hydrazine)	249C,480F
	D	Acetone	465C,869F
		Acrylonitrile	481C,898F
		Ammonia	651C,120F
		Benzene	560C,1040F
		Butane	405C,761F
		1-butanol (butyl alcohol)	365C,689F
		2-butanol (secondary butyl alcohol)	405C,761F
		N-butyl acetate	425C,797F
		Isobutyl acetate	421C,790F
		Ethane	515C,959F
		Ethanol (ethyl alcohol)	356C,689F
		Ethyl acetate	427C,800F
		Ethylene dichloride	413C,775F
		Gasoline (56-60 octane)	280C,536F
		Gasoline (100 octane)	456C,853F
		Heptanes	280C,536F
		Hexanes	225C,437F

Source: NEC 500-3.

Table 1. (Continued)

Class	Group	Typical Atmospheres	Ignition Temps.
1 Gases, Vapors	D	Isoprene	220C,428F
		Methane (natural gas)	482-632C 900-1170F
		Methanol (methyl alcohol)	385C,725F
		3-methyl-1-butanol (isoamyl alcohol)	350C,662F
		Methyl isobutyl ketone	460C,860F
		2-methyl-1-propanol (isobutyl alcohol)	427C,800F
		2-methyl-2-propanol	480C,896F
		(tertiary butyl alcohol)	288C,550F
		Petroleum naphtha	220C,428F
		Octanes	260C,500F
		Pentanes	300C,572F
		1-pentanol (amyl alcohol)	450C,842F
		Propane	440C,824F
		1-propanol (propyl alcohol)	399C,750F
		2-propanol (isopropyl alcohol)	460C,860F
		Propylene	490C,914F
		Styrene	480C,896F
		Toluene	427C,800F
		Vinyl acetate	472C,882F
		Vinyl chloride	530C,986F
		Xylenes	
2 Dust	E	Atmospheres contain metal dust, including aluminum, magnesium, and their commercial alloys, and other metals of similarly hazardous characteristics having resistivity of less than 10^5 ohm-cm.	

Source: NEC 500-3.

Table 1. (Continued)

Class	Group	Typical Atmospheres	Ignition Temps.
2 Dust	F	Atmospheres contain combustible carbonaceous dusts, or other atmospheres containing these dusts sensitized by other hazardous materials, and having resistivity greater than 10^2 thru 10^8 ohm-cm.	
	G	Atmospheres contain combustible dusts having resistivity of 10^5 ohm-cm, or greater.	
3 Fibers		Atmospheres contain easily ignitible fibers or combustible flyings.	

Source: NEC 500-3.

Table 2. Definitions of Hazardous Location (by Divisions).

Division	Class	Definitions of Divisions
1 Normally Hazardous	1	Class 1, Division 1 is an area where the hazard exists under normal operating conditions. These situations include transferring flammable or combustible liquids from one container to another, open vats, paint spray booths or any location where ignitible mixtures are used. This also includes locations where the hazard is caused by frequent maintenance or repair work or frequent equipment failure.
	2	Class 2, Division 1 is an area where combustible dust is normally in the air in sufficient quantities to produce ignitible mixtures or where mechanical failure or abnormal operation of equipment might produce ignitible mixtures. These locations also include: (1). Operations where this hazard exists because of frequent mechanical failure of machinery or equipment. (2). Where electrically conductive combustible dusts (all Group E and some Group F) are present in hazardous quantities.
	3	Class 3, Division 1 is an area where easily ignitible fibers or materials producing combustible flyings are handled, manufactured or used.

Source: NEC 500-5, 6, and 7.

Table 2. (Continued)

Division	Class	Definitions of Divisions
	1	Class 1, Division 2 is an area where ignitible gasses or vapors are handled, processed or used, but which are normally in closed containers or closed systems from which they can only escape through accidental rupture or breakdown of such containers or systems.
	------	------------------------------------
2 Not normally hazardous	2	Class 2, Division 2 is an area where combustible dust is not normally in the air in sufficient quantities to produce ignitible mixtures or interfere with the operation of electrical equipment, or where dust is present as a result of infrequent malfunctioning of processing or handling equipment. These locations also include situations where combustible dust accumulations may interfere with the safe dissipation of heat from electrical equipment.
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	3	Class 3, Division 2 is an area where easily ignitible fibers are stored or handled.

Notes: 1. Source: NEC 500-5(a), 500-6(a) and 500-7(a).
2. In outdoor areas or large indoor areas where there are few or no partitions, Class 1, Div. 1 and Class 1, Div. 2 areas characteristically exist adjacent to each other-the Div. 1 location being near the point of vapor release and Div. 2 being at a given distance from the point of release or from the flammable liquid.

Table 3. Definitions of Hazardous Locations (by Class).

Classes	Definitions of Locations
1 (Gases)	Class 1 Location is an area where flammable gasses or vapors are or may be present in the air in quantities sufficient to produce explosive or ignitible mixtures.
2 (Dust)	Class 2 Location is an area where presence of combustible dust presents a fire or explosion hazard.
3 (Fiber)	Class 3 Location is an area where made hazardous because of the presence of easily ignitible fibers or flyings, but in which such fibers or flyings are not likely to be in suspension in the air in quantities sufficient to produce ignitible mixtures.

Source: NEC 500-5, 500-6, 500-7.

2.1.2 Power Ratings

According to the Chinese Petroleum Corporation, the largest induction motor in use is at the Kaohsiung Refinery, Taiwan. It is rated at 2250HP which is used for the reactor charge pump in the Hydrocracking Unit. Most of the motors used for pumps have continuous ratings, and some of them have 1.15 service factor. The percentage distribution of power ratings for pump motors in refineries, are as the following:

300HP	and	above	----------	5%
125HP	to	250HP	----------	5%
60HP	to	100HP	----------	6%
10HP	to	50HP	----------	44%
7.5HP	and	below	----------	40%

2.1.3 Motor Voltage

Motor voltage is usually determined by the available electrical system and its voltage ratings. The most frequently used voltages for different motor sizes are as follows:

4000HP	and	above	-------	6600V or 13200V
300HP	to	3500HP	-------	3300V or 4160V

	or	6600V
250HP and below ------- 220V	or	380V
	or	480V
Single-phase for small motor ----110V	or	220V

2.1.4 <u>Insulation System</u>

The insulation systems used on most motors are rated Classes B and F. See Table 4 for insulation materials and Table 5 for their permissible maximum temperature. The temperature at the hottest spots of each insulation of machinery and apparatus shall not exceed the permissible maximum temperature listed in Table 5. For the limits of temperature rise, see Table 6. Sometimes, the motor manufactures is asked to provide a Class F insulation but Class B temperature rise. The larger size motors, above 500HP, are rated Class F and have insulation systems based on mica and epoxy.

The temperature rise of the winding of a rotating machine is not uniform. There are considerable differences among the temperature rises of the various parts. For example, the coil insulation, insulation of the connection between coils or lead wires, insulation of coil-end support, wedge filler of slot, collar of field winding, all experience different thermal characteristics. Therefore it is not always necessary to use the insulations of the same class for all parts. For example, in the case of a machine having coils of Class B insulation, the use of Class A insulation for some part of the lead wires would not always have an adverse effect on the performance and the life of the machine.

Table 4. Classification of Materials for Insulation.

Class	Insulation Materials
A	When impregnated or when immersed in a liquid dielectric (e.g. insulation oil): Cotton, silk, paper, other natural vegetable or animal fibre. Regenerated cellulose fibre. Polyamide fibre. Paper and paper products. Pressboard. Vulcanized fibre. Wood. Varnished cloth (based on cotton, silk, other natural vegetable or animal fibre, regenerated cellulose, cellulose acetate or polyamide fibre. Varnished paper. Laminated wood. Cellulose acetate film. Cellulose acetate butyrate film. Cross-linked polyester resins. Wire enamel of oleo-resinous type. Wire enamel based on polyamide resin. Wire enamel based on polyvinylformal.
E	Wire enamel based on polyurethane resins. Wire enamel based on epoxy resins. Moldings with cellulose fillers. Cotton fabric laminates. Paper laminates. Cross-linked polyester resins. Cellulose triacetate film. Polyethylene terephthalate film. Polyethylene terephthalate fibre. Varnished polyethylene terephthalate cloth.

Source: JIS C-4003.

Table 4. (Continued)

Class	Insulation Materials
B	Glass fibre. Asbestos. Varnished glass fibre cloth. Varnished asbestos. Built-up mica (with or without supporting materials). Glass fibre laminates Asbestos laminates. Mouldings with mineral fillers. Wire enamel based on silicone resins. Wire enamel based on polyethylene terephthalate. Polyfluoroethylene resins
F	Glass fibre. Asbestos. Varnished glass fibre cloth. Varnished asbestos. Built-up mica (with or without supporting materials.
H	Glass fibre. Asbestos. Varnished glass fibre cloth. Varnished asbestos. Rubber glass cloth. Built-up mica (with or without supporting materials). Glass fibre laminates. Asbestos laminates. Silicone elastomer.
C	Mica, Porcelain, Glass, Quartz. Other inorganic substances possessing similar thermal stability listed above. Varnished glass fibre cloth. Varnished asbestos mica product.

Table 5. Permissible Maximum Temperature for Each Insulation Class.

Class of Insulation	Permissible Maximum Temperature (°C)
A	105
E	120
B	130
F	155
H	180
C	above 180

2.1.5 <u>Temperature Limits</u>

"Temperature rise" is defined to be the highest temperature, measured in running motor under full load when it has reached thermal equilibrium, minus the ambient temperature.

Table 6 gives the limits of permissible temperature rise above the coolant temperature for air-cooled rotating machines (excluding those for electric railway vehicles) under the rated load.

For rotating machines operating on intermittent duty, the limits of temperature rise given in Table 6 may be exceeded by 10 degrees C.

For rotating machines with continuous ratings, the temperature-rise test shall be continued until thermal equilibrium has been reached. For rotating machines with intermittent ratings, duration of the test is that specified for the rating. For rotating machines with other ratings, the test shall be continued until thermal equilibrium has been reached. Temperature measurements shall be made at the end of the period of the greatest load value in each cycle for the purpose of ascertaining that thermal equilibrium has been reached.

The temperature of each part of the rotating machine shall, whenever possible, be measured during the period of the temperature test and immediately after shutdown. The final temperature is the highest temperature measured. In the case of rotating machines with ratings other than continuous ratings, the final temperature is the temperature at the middle of the period of the greatest load value in the last cycle of test.

When the embedded temperature detector method is used, at least six detectors, suitably distributed round the stator, and placed in the direction of the shaft at the points at which the highest temperature is likely to occur, shall be built into the machine.

For the stator windings of an a.c. machine having output of 5000KW (or KVA) or more, or having a stator core length (including ventilating duct) of 1 m or more, the embedded temperature detector method shall be used, unless any prior agreement has been made between the parties concerned.

In the case of rotating machines having water-cooled heat exchangers, the temperature rises may, by agreement between the parties concerned, be measured with respect to the water, if the temperature of the water at the intake of the heat exchanger does not exceed 25°C. The limits of temperature rise in Table 6 are then increased by 10°C.

For stator windings of air-cooled rotating machines, fully insulated for rated voltage in excess of 11000V, the limits of temperature rise shall be corrected by the following values per 1000V (or part thereof) above 11KV:

-1.5°C per 1000V when measurements are made by a thermometer.

-1°C per 1000V when measurements are made by an embedded temperature detector.

When the voltage is in excess of 17KV, the following correction shall be added per 1000V (or part thereof) above 17KV, to both the measurements by the thermometer method and the embedded temperature detector method:

-0.5°C per 1000V.

If the purchaser wishes to have a thermometer reading taken in addition to the values determined by the resistance method, the temperature rise determined by thermometer, when placed at the hottest accessible spot, which shall be the subject of special agreement, but it shall in no cases exceed:

65°C if the windings are according to Class A.

80°C if the windings are according to Class E.

90°C if the windings are according to Class B.

110°C if the windings are according to Class F.

135°C if the windings are according to Class H.

For rotating machines of the frame surface cooled type, the limits of temperature rise by the thermometer method for 2a, 2b, 2c of Table 6 shall be increased by 5°C for each insulation class.

Table 6. Limits of Temperature Rise of Air-cooled Rotating Machine.

No	Part of Rotating Machines	Class E Method: 1	Class E Method: 2	Class B Method: 1	Class B Method: 2	Class F Method: 1	Class F Method: 2
1	Armature windings of motor having output of 5000KW or more, or having a core length of 1 m or more.	--	75	--	80	--	100
2a	Armature windings of a.c. motor having outputs less than 5000KW or having a core length less than 1 m.	65	75	70	80	85	100
2b	Field windings of a.c. and d.c. motor having d.c. excitation other than those in NO. 3 and 4.						
2c	Armature windings of rotors having commutators.						
3	Field windings of turbine-type machine having d.c. excitation.	--	--	--	90	--	100
4a	Low-resistance field windings of more than two layer, and compensating windings	75	75	80	80	100	100

Source: JIS C-4004.

Table 6. (Continued)

No	Part of Rotating Machines	Class E Method: 1	Class E Method: 2	Class B Method: 1	Class B Method: 2	Class F Method: 1	Class F Method: 2
4b	Single-layer windings with exposed bare or varnished metal surface.	80	80	90	90	110	110
5	Permanently short-circuited windings.	75	--	80	--	100	--
6	Magnetic core and other parts in contact with windings.	75	--	80	--	100	--
7	Commutators and slip-rings.	70	--	80	--	90	--
8	Bearing (free convection type).	40 deg C when measurements are made on the surface. 45 deg C when measurements are made by embedding a temperature detector in the bearing metal. 55 deg C when measurements are made on the surface and in the case where a lubricant of good heat resistance is used.					

Notes: 1. Source: JIS C-4004.
2. Unit: deg C.
3. Method 1 is the temperature measured by thermometer and 2 is by resistance.

2.2 Compressor Drives

The principal compressor types used in the refinery industry are reciprocating, centrifugal, and axial flow, In addition, rotary compressors are used for special services. Reciprocating compressors are considered for applications where the inlet gas rate is about 3,000 acfm or less. They are favored for low-flow, high-pressure services. Centrifugal compressors are used for process applications from about 500 to 200,000 acfm (inlet), and axial flow compressors from about 75,000 to 600,000 acfm (inlet). Axial-flow compressors are more efficient than centrifugals, and can be provided in higher capacities. However, centrifugals are more common in the process industry. Centrifugal compressors have wider operating ranges. Axials are generally used only for air, or clean, non-corrosive gases.

Electric motors perform well as compressor drives. With their high efficiency, they fit today's need to save energy. In the past, the decision to use electric motors for centrifugal compressor drives has been made only after all other possibilities to use either a steam or gas turbine have been exhausted, or so it has seemed to motor suppliers. This picture may, however, be changing as a result of the increase in fuel costs, particularly petroleum. In addition to the considerations of heat balance and investment cost, a third factor, which is the availability of feed stock, must be considered.

2.2.1 Motor Speed and Type

Centrifugal compressors of higher speeds are being used more frequently than ever before. The top motor speed available is 3600 rpm on a 60 Hz system. To meet speed requirements higher than 3600 rpm, it necessary to use step-up gears.

Introduction of a step-up gear permits a normal induction motor speed of 1800 rpm. For 500 to 20,000HP drives, 1800 rpm is the lowest first-cost induction motor. Similarly, the lowest first-cost synchronous motor speed is 1200 rpm in sizes from 5000HP and up. There is really no size limit when building a motor.

There are three types of motors available for compressor drives:

1. Induction
2. Synchronous
3. Wound rotor induction

The induction motor is the first choice for drives from 500 to 5000HP because it has one insulated stator winding and one uninsulated, shorted rotor winding. For 1200, 1800, and 3600 rpm compressors, no step-up gear is required. The 1800 rpm motor is the least expensive of the three speeds. Therefore, this speed is usually selected for higher speeds using step-up gears.

The synchronous motor is usually the preferred choice for very large ratings because of price, especially when power factor and efficiency are prime considerations. These motors have three windings: one insulated winding on the stator and two windings on the rotor. The windings on the rotor consist of one insulated and one uninsulated armature winding that is used for starting only.

The insulated synchronous motor rotor winding requires a DC power supply that is usually supplied from a brushless exciter mounted on the motor shaft.

Synchronous motors are available at the same speeds as induction motors. However, in practice, only the 1200 rpm speed is used. Step-up gears are always used to match compressor speed requirements. Control and operation of synchronous motors requires more auxiliary equipment, but this is well understood and very reliable. The system is such that the operator controls the machine in the same way as an induction motor.

Synchronous drives are more efficient, can operate at 1.0 pf or 0.8 pf, and are lower in first cost in the larger horsepower sizes. Recent changes in motor prices have altered specific relationships of synchronous versus induction motor prices.

Wound-rotor induction motors have not been used for compressor drives because of their cost and high losses when resistors are used for speed control.

Most of the synchronous motors used for compressors are force-ventilated type. This type of motor is usually installed in compressor house and ventilated by means of a separate motor-driven blower mounted on the motor enclosure.

Some of the synchronous motors used in hazardous locations are pressurized in the enclosure with clean air or inert gas. Explosion-proof motors are not generally available above 500HP.

2.2.2 Power Ratings

An installed motor that is too small to start the machine to which it is coupled represents exceedingly poor design. There is no excuse for this problem because the widespread use of computers by machine designers makes it practical to predict accurately the brake horsepower requirements of the compressor. It is easy to avoid the problem of unmatched sizes because motors are available in standard ratings in larger horsepower sizes in average increments of about 15%. Therefore, a practice of selecting the standard motor rating that matches or exceeds the brake horsepower of the driven machine will result in a 0% to 15% margin.

The practice of adding 10% to the calculated brake horsepower and then using the next larger standard horsepower motor will result in margins of 10 to 25%.

According to the Kaohsiung Refinery in Taiwan, almost all the compressors drives above 700HP are synchronous motors. The biggest synchronous motor is 20,000HP and is used for an air compressor in Kaohsiung Refinery.

2.2.3 Motor Voltage and Starting Method

Selection of the appropriate motor voltage is usually determined by the available electrical system and its rating. The most frequently used voltages for different sizes are the same as those discussed in Section 2.1.3.

When motors are started, they draw high inrush current that depresses the line voltage. The amount of voltage drop depends upon the capacity of the electrical system. Standards usually indicate this voltage dip should be less than 10 percent; however, there are many good systems where the motor driving a compressor is the largest in the plant and where voltage dip is 20 to 30 percent or more.

The motor's torque varies as the square of the applied voltage. This reduced available torque usually requires that motor-driven compressors be started with inlet valves or guide vanes closed. Most compressors will operate under these conditions for a short time (usually 60 to 120 seconds) without damage from heating or surge until the motor reaches full speed.

With low starting torque requirements, it is possible on large rating systems to design special low-inrush low-torque motors that will cause less voltage drop when starting. For example, the 20,000HP air compressor in Kaohsiung Refinery requires only 3 times full load current to start, using the direct full voltage starting method.

The two commonly used methods of reduced-voltage starting in use at present are the reactor start and the auto-transformer start. The most popular of the two is the auto-transformer start. Reduced voltage starting is never a drive requirement, but it is a requirement to prevent or limit electrical system disturbance.

2.2.4 Insulation System

The insulation system used on most motors in the 500 to 20,000-HP size is rated Class B or F and is based on mica and epoxy. Mica has long been referred to as the standard for dielectric capability, particularly in the area of corona resistance. Mica is applied to the coils, and then by use of various vacuum pressure methods, the coils are impregnated with epoxy which is highly resistant to moisture. Epoxy is inert to most chemicals, has excellent mechanical characteristics, and because of the impregnation process, serves to enhance the mechanical strength of the winding by completely filling it and bonding it together. The mechanical strength of the epoxy-mica system is excellent. A bracing system, utilizing polyester glass materials to mold a support system, is typically added to the end turns. This system is designed to support motor end turns and render them practically immobile during high-current starting conditions.

See Table 4 for insulation materials, Table 5 for permissible maximum temperature, and Table 6 for the limits of permissible temperature rise. Class B insulation, normally furnished with NEMA standard 100 percent rated motors, operating at 80°C rise by resistance in a 40°C ambient temperature, has a design life of approximately 15 to 20 years, which matches normal plant life. Because the rate of an oxidation reaction is doubled for each 8-12°C rise in temperature, the life of a motor insulating system is cut in half for each 8-12°C that the total temperature of the winding is increased. Therefore, to apply motors more conservatively, a lower than standard temperature rise must be specified. For example, a motor with class F insulation, but a limitation to a Class B temperature rise, might be specified. Most motors will operate at approximately a 55°C temperature rise at a 75 percent load.

2.2.5 Temperature Detectors

Temperature detectors, which respond to resistive heat dissipation in the stator winding are available in all motors being considered. Resistance temperature detector (RTD) and thermocouple detectors are used. The standard RTD is Platinum (PT 100) and 100 ohm at 0°C. Alternates are Copper 10 ohm at 25°C or Nickel 120 ohm at 0°C. Four types of thermocouple are available: 1.Copper-Constantan, 2.Iron-Constantan, 3.Chromel-Constantan, and 4.Chromel-Alumel.

PTC thermistors, with one or two fitted per phase, can be installed in the endturns of the motor. A suitable electronic monitoring relay is normally mounted in the control panel. Thermostats can be provided, which will automatically reset with normally closed contacts. One can be added per phase with leads suitable for connection in series with the control circuit.

With relays installed in the control system, the signal from these detectors can be made to sound an alarm when there is an abnormal change in the motor winding temperature. This signal can be used as an indication of motor distress so that the operator can check for overload, clogged filters or other obstructions in the ventilating passages to the motor. A second relay can be arranged to shut the machine down when operating temperature exceeds the design limit by a nominal amount (approximately 10°C).

Temperature detectors are also available on the sleeve bearing to minimize damage. Two types of detectors are used for monitoring bearing temperature.

1. Distant-reading thermometer:

In this case, only RTD or thermocouple sensors are fitted on bearings; indicating or monitoring devices are mounted on the control panel.

2. Thermometers:

These are supplied with dials on the motor and for limiting value monitoring.

Bearing temperatures usually do not change unless a loss of oil film (caused by foreign material in the oil, loss of supply, change in alignment, etc.) has caused bearing damage. These devices are available for all motors and should be used on all drives where downtime must be held to a minimum. High-temperature alarms and high-temperature cutoffs are available and should be set at a nominal amount above normal operating temperature and at the maximum temperatures permitted by the designs. These devices may not give sufficient warning to save the bearings, but journal and rotor damage will be prevented.

2.2.6 Lightning and Surge Protection

Lighting arrestors and surge protection should be installed on all motors rated 1,000HP and larger or 4,000V and higher. It may be desirable to protect even smaller machines on critical drives. Lightning arrestors can be located in the control system or at the main plant substation if there is no exposed line between this point and the motor. Surge protection must be located at the motor terminals. These surge capacitors suppress the voltage surges caused by switching other equipment. In the same fashion, surge tanks or flow restricting devices soften hydraulic surges caused by valving in hydraulic systems. The capacitors are analogous to the hydraulic systems, in that there is little benefit in locating surge tanks far from where the surge can cause damage. Over-size terminal boxes with lightning arrestors and surge protection capacitors are optional accessory items for large motors. For example, in the terminal box of a 1,000HP 3,300V high voltage induction motor, there is one 3 pole 4,160VAC 1.5MF capacitor and three 4.5KV G.E. Model 9L11MGB004 arrestors for surge and lightning protections.

2.3 Motor Operated Valves

Motor operated valves, called MOV's, are widely used on process pipe lines in chemical plants. Especially, and in the higher or hazardous locations, the MOV is very convenient and safe.

2.3.1 Motor Types

The motors used on MOV's are high starting torque, totally enclosed motors. They are furnished in weatherproof, explosion-proof or submersible enclosures. All motors are furnished with ball bearings and provided with grease seals. No lubrication of these motors is necessary since they are lubricated at the factory for lifetime operation.

The motors used on MOV's are AC, 3-phase squirrel-cage type. Their duties are generally only 30 min. Hence, MOV's cannot be opened and closed too frequently. Repeated use may cause the motor to overheat.

2.3.2 Control Devices

There are two major control devices for MOV's, the rotor-type limit switch and the torque switch, which confirm that the MOV is really closed or open. These devices must be rechecked after installation. Directions in the instruction manual must be used to check or adjust the switches to make sure they are working properly.

In general, the two train geared limit switch (rotor type) employs two rotary drum switches, each having four contacts. When the rotor is properly set to trip at the desired position, two of these contacts open electric circuits and two contacts close electric circuits. Generally, one rotor is set to trip at the full open position of the valve, and the other rotor is set to trip at the full close position of the valve. Each drum switch may be adjusted independently of the other.

2.3.3 Control Diagram

Figure 1 is a typical control diagram for the MOV.

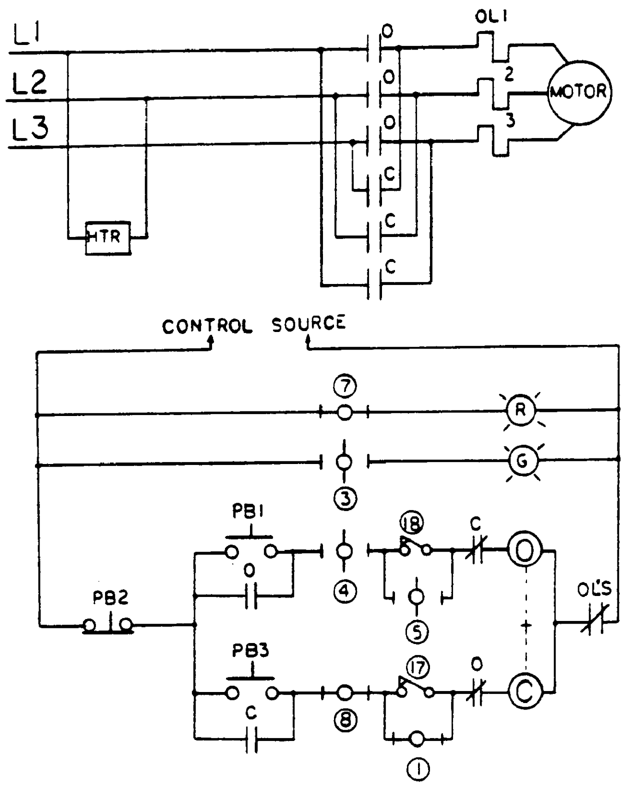


Figure 1. Typical Control Diagram for MOV.

Notes:
1. Valve shown in fully open position.
2. Functions of limit switch (see Table 7).
3. (17) Closing torque switch interrupts control circuit, if mechanical overload occurs during closing cycle.
4. (18) Opening torque switch interrupts control circuit, if mechanical overload occurs during opening cycle.

Legends:
1) (C) Closing coil.
2) (O) Opening coil.
3) (G) Green ind. light.
4) (R) Red ind. light.
5) PB1 Open pushbutton.
6) PB2 Stop pushbutton.
7) PB3 Close pushbutton.
8) OL's Overload relay.
9) HTR Space heater.
10) +- Mechanical interlock.

Table 7. Functions of Limit Switches.

ROTOR	Limit Switch Compartment		
	Contact	Valve Position	Function
		Full Open Full Closed	
1	1	**¦-----¦---¦-----¦--	Bypass closed
	2	**¦-----¦---¦-----¦--	Spare
	3	--¦*****¦***¦*****¦**	Indicating light
	4	--¦*****¦***¦*****¦**	Open limit
2	5	--¦-----¦---¦-----¦**	Bypass open
	6	--¦-----¦---¦-----¦**	Spare
	7	**¦*****¦***¦*****¦--	Indicating light
	8	**¦*****¦***¦*****¦--	Closed limit

Notes: 1) **** Closed contact.
2) ---- Open contact.

2.4 Air Cooler Drives

Air coolers are also known air fans. It is a fan rotated by a motor through a v-belt or gear set. The fan is used to cool the temperature of a variety of media.

2.4.1 Air Cooler Types

There are two types of air cooler. The first is used to lower the temperature of a process. The second is used to lower the temperature of cooling water. In general, the first type is mounted on a steel structure adjacent to the process, and the second type is installed on the top of a cooling tower. Hence both types need a vibration switch to protection the equipment from damage due to high vibration amplitude.

2.4.2 Vibration Switch

The vibration switch is used to trip the motor when the vibration amplitude or velocity exceeds a preset value.

A modern vibration switch has many functions. For example, The Rochester Instrument model VT-1215 vibration switch has the following functions:

a) Two adjustable set points for "ALERT" and "DANGER".

b) 4-20mA DC analog output (proportional to vibration velocity).

c) AC vibration waveform output.

In operation, the "DANGER" alarm trip is set to the maximum acceptable vibration level for shutdown or emergency protection. The "ALERT" alarm trip is set for advance warning of increasing vibration.

The DC 4-20mA output is normalized to the "DANGER" alarm trip level. The signal has a range of 4-20mA, with 15mA always corresponding to the "DANGER" alarm trip. A zero, or no vibration level, produces an output of 4mA, while 20mA output corresponds to 150% of the "DANGER" alarm trip level.

The AC millivolt output (proportional to vibration velocity waveform) provides for user analysis of the machine vibration.

Both alarms reset automatically unless a jumper is removed from the terminal strip and a user-provided reset switch is used. In this case the alarms remain energized until the proper remote switch signal is sent to the VT-1215 vibration switch.

A similar user-provided switch may be connected to the terminal strip to inhibit alarm actuation during times of normal high vibration, such as start-up or sudden load changes on rotating equipment.

2.5 Soot-Blower Drives

A soot-blower is used to clean the soot from a heater or furnace. In general, there are several sets of soot-blowers for one furnace. Automatic control sequences operate the soot-blowers one by one through limit switch and step switch input. The control sequences for the soot-blowers are as follows:

a) Open the steam valve to preheat the pipe line for about 5-10 minutes.

b) Close the drain valve. No.1 soot-blower begins to run.

c) No.1 soot-blower runs in reverse automatically when it goes forward to the limit position.

d) No.1 soot-blower goes into reverse to the original position and stops.

e) No.2 soot-blower begins to run because of the step switch rotating one step.

f) The same step for No.2 and then No.3 ... to the last one.

g) Close the steam valve and switch off the control source after completing blowing.

The motor for the soot-blower is a TEFC type, the capacity is about 3/4Hp, the voltage is 3-phase 230/460V, and the duty is continuous.

3. MOTOR CONTROL AND PROTECTION

3.1 Start-up and Shutdown

3.1.1 Normal Operating Start-up

The steps listed below must be fellowed when starting motor equipment:

1) Figure 2 is the standard control circuit diagram for low voltage motors.
2) For safety reasons, the layout only has a "STOP" button on the motor control center (MCC). The motor is started at the remote button station beside the motor.
3) Check the tag number of the motor to ensure that it is the one to be started.
4) Check the lube oil level of the motor and turn the rotor by hand, if possible, to ensure that it rotates freely.
5) Recheck the tag number and close the main breaker (mold case circuit breaker) on the MCC.
6) Push the "START" button momentarily to let the motor start up to the normal speed.
7) Standby motors should be run at least once a week to guard against accumulated moisture condensation and to keep the bearing and shaft from rusting.

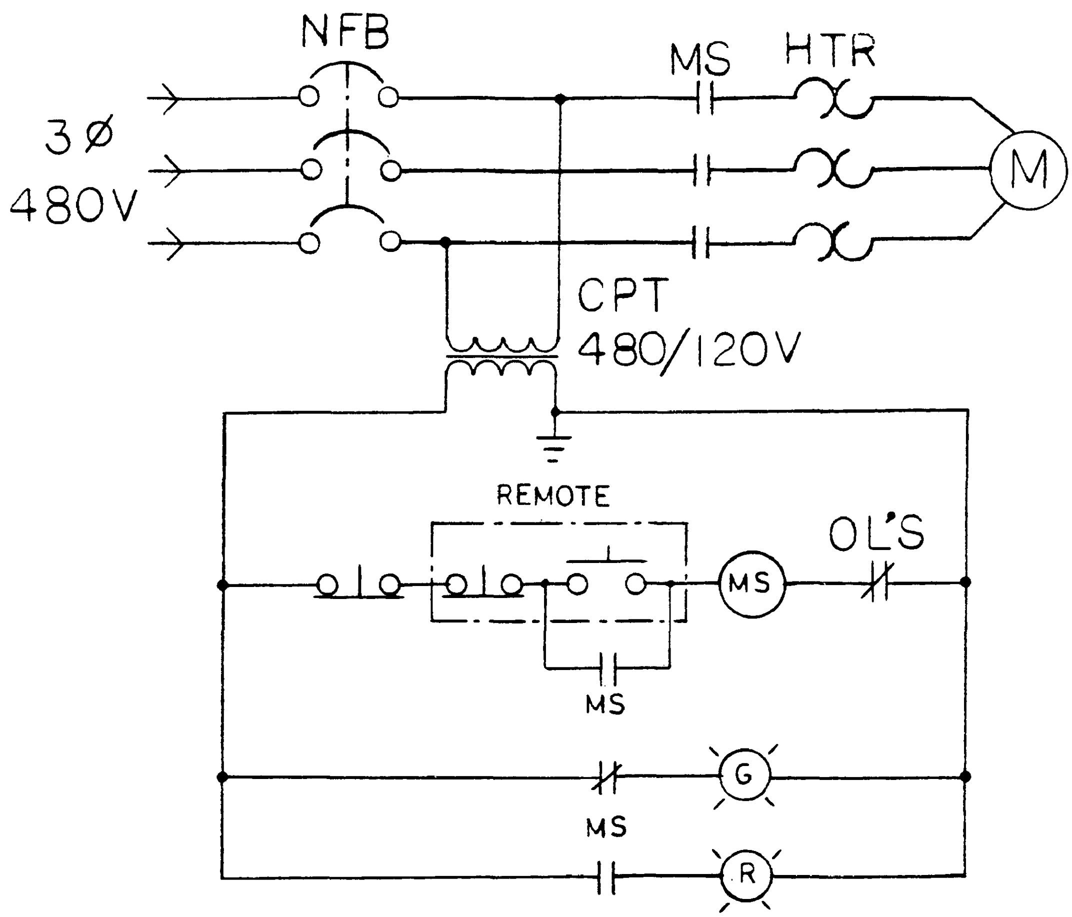


Figure 2. Standard Control Circuit Diagram.

Notes:

1) NFB (No fuse breaker) or MCCB (Molded case circuit breaker) provides the short-circuit protection.
2) MS (Magnetic switch) provides the overload protection.
3) HTR + OL'S = Thermal overload relay.
4) CPT = Control potential transformer.
5) (G) = Green indication light (stop).
6) (R) = Red indication light (running).

3.1.2 Initial Start

The initial start after installation is very important. to the motor. These steps must be followed carefully:

1) Measure the insulation resistance of the stator winding with a "Megger" type instrument; this value should be not less than KV+1 in megohms. For example, a 3300-volt motor should have a minimum insulation resistance of 3.3 + 1 or 4.3 megohms.

2) Motor and control wiring, overload protection and grounding must coincide with the circuit diagram.

3) Ensure that the motor is connected as shown on the nameplate, and that the power supply (voltage, frequency, and number of phases) corresponds with the nameplate data.

4) For sleeve bearing motors, fill the oil reservoirs through the plug or cap on the top of each oil level gauge with a rust and oxidation inhibited turbine oil (viscosity 200 SUS at 100°F for operation at ambient temperature between 30°F and 110°F) to the center or mark of the oil level gauge when the motor is at a standstill.

5) If possible, turn the rotor by hand to ensure that it rotates freely.

6) Examine the external fans for loose objects or debris which may have accumulated to interfere with operation. Check factory-made connections for tightness to ensure none have become loosened during shipment or storage.

7) It is recommended that the motor be initially started uncoupled from the load to check the direction of rotation.

8) The temperature of the bearings, when measured by a bearing temperature detector on sleeve bearings, should not exceed 90°C.

9) When starting a motor for the first time, the bearing temperature should be observed for a minimum of two hours. If at any time the rate of temperature rise appears to be abnormal or if there is excessive vibration or unusual noises, shut down the motor immediately and inspect the machine for possible causes.

10) With the motor connected to the load, check for satisfactory operation. Measure the load current, the amplitude and velocity of vibration, and the temperature rise. The maximum continuous operating temperature of the motor is a rise stamped on the nameplate plus the temperature of the surrounding air (i.e. the ambient temperature).

3.1.3 Jogging and Repeated Starts

Repeated starts and/or jogs of induction motors greatly reduce the life of the winding insulation or the rotor. The heat produced by each acceleration or jog is much more than that produced and dissipated by the motor under full load. These motors are designed to withstand being shut off and restarted once, providing the motor is allowed to coast to rest before being restarted. It is recommended that no restart be made until all conditions affecting operation have been thoroughly checked and the motor examined for evidence of excessive heating.

3.1.4 Normal Operating Shutdown

The following must be done to shut down a motor safely:

1) Ensure the motor is the correct one to be shut down.

2) Push the "STOP" button on the remote button station to stop the motor.

3) Put the stop bar into the slot of the "STOP" button, and lock it if is necessary, to keep the motor from misstarting.

4) Turn off the main switch, MCCB or breaker, of the motor and lock the switch if it is necessary.

3.2 Motor Protection

The frequency of failure in rotating machines is low with modern design practices and improved materials, yet failures can occur and may result in severe damage and long outages. For these reasons, abnormal conditions must be recognized promptly and the potential problem area quickly isolated. Abnormal conditions that may occur with rotating equipment include the following:

a. Faults in the windings

b. Overload

c. Overheating of windings or bearings

d. Short circuit or ground-faults

e. Single-phase or unbalanced current operation.

Motor protection is far less standardized than is generator protection. Although the National Electric Code and NEMA Standards specify basic protection requirements, they do not fully cover the many different types and sizes of motors and their varied applications. There are many other schemes, all of which offer different degrees of protection. As with generator protection, the cost and the extent of the protective system must be weighed against the potential hazards. The size of the motor and the type of service also influence the type of protection required.

A motor must be protected against one or more of the following hazards:

a. Faults in the winding or associated circuits

b. Excessive overloads

c. Reduction or loss of supply voltage

d. Phase reversal

e. Phase unbalance

f. Short-circuit or ground-fault

g. Out-of-step operation for synchronous motors

h. Loss of excitation for synchronous motors.

Protective relays applied for one hazard may also protect against others. For example, a relay designed to operate on an excessive overload could also protect against a fault current in the windings.

Protective devices may be installed on the motor controllers or directly on the motors. The protection is usually included as part of the controller, except for very small motors, which have various types of built-in thermal protection.

Motors rated at 600V or less are generally switched by contactors and protected by fuses or low voltage circuit breakers equipped with magnetic trips. Motors rated from 600 to 4,800V are usually switched by a power circuit breaker or by a contactor (often supplemented by current-limiting fuses to accommodate higher interrupting requirements). Motors rated from 2,400 to 13,800V are always switched by power circuit breakers.

Failures or abnormalities that may occur in a motor circuit vary in types and causes. Unless an appropriate protective device is used, the motor, its circuit, and related equipment may be seriously damaged. It is therefore important to thoroughly understand the nature of failures that may occur and, based on that understanding, to select a protective device that is best suited to the envisioned failure. Table 8 lists some possible failures of motor circuits, as well as some preventive measures.

Table 8. Possible Failures of Motor Circuits.

Classification	Causes	Preventive measures
Problems due to burning	Extremely high ambient temperature	-Ambient temperature detection -Field coil temperature detection
	Poor cooling	-Cooling fan wind pressure detection -Field coil temperature detection
	Poor insulation	-Leakage current detection
	Bearing damage	-Bearing temperature detection
Problems due to overload	Mechanical overload	-Overcurrent detection -Field coil temperature detection
	Circuit voltage drop	-Voltage drop detection -Field coil temperature detection
	Overwork	-Field coil temperature detection
	Intermittent operation at high operating frequency	-Field coil temperature detection
	Continuation of star condition in star-delta starting	-Overcurrent detection -Field coil temperature detection
	Fluctuation in frequency	-Frequency detection -RPM detection
	Unbalanced voltage	-Imbalance detection

Source: OMRON catalog "Fundamentals of Stationary Type Motor Relays".

Table 8. (Continued)

Classification	Causes	Preventive measures
Problems due to slowed or locked revolution	Seized bearing	-Overcurrent detection -Field coil temperature detection -Check lube oil level -Appropriate maintenance
	Continuation of star condition in star-delta starting	-Overcurrent detection -Field coil temperature detection
Problems due to open phase	-Failure in equipment (including blown fuse) -Circuit failure	-RPM detection -Open phase detection -Imbalance detection -Reversed phase detection
Problems due to reversed phase	Circuit failure	-Open phase detection -Imbalance detection -Reversed phase detection
Problems due to leakage current	Poor insulation	-Leakage current detection

The following are the available motor protection devices which are used widely.

1. 3E relay
2. Low voltage relay (27)
3. Phase-unbalance relay (46)
4. Phase-sequence relay (47)
5. Thermal overload relay (49)
6. Overcurrent relay (50/51)
7. Ground-fault relay (GFR)
8. Differential relay (87)
9. Field failure relay (40)
10. Power factor relay (55)

These protective devices are now discussed.

3.2.1 3E Relay

The 3E relay is one of the protective devices most widely used. It is provided with three features ("Elements") to protect motors. It protects motors from overload, open phase, and reverse phase. These three features of the 3E relay are explained:

a. Overload protection:

There are two types of functions for the overload protection feature: inverse type - inverse time both at starting and during operation, and instantaneous type - fixed time at starting and instantaneous during operation (0.5 sec. max. at 140% overload).

With the overload protection feature alone, the motor is protected the majority of the time. To ensure effective protection, it is necessary to correctly set the "must operate voltage" and operate time of the 3E relay.

The operating voltage of the 3E relay is 110/220, 220/240, or 380/415 volts. The rated current and capacity is 1 to 80A or 64 to 160A AC. The setting range of overcurrent operating time is 2 to 40 sec, (value at 500% overload).

b. Open-phase protection:

This feature is used to protect a polyphase motor from damage when it is driven on a single phase - a condition which takes place when such things as severance of the motor's power lines, loose connections, fault contacts of switches, and severance of motor's internal circuit occur. When this happens, the motor's phase current increases conspicuously, as compared with the increase in the line current, causing the field coil temperature to rise. The temperature quickly exceeds the permissible upper-limit value, and, consequently, the motor may burn. In this case, the motor should be protected by detecting the open phase instead of the overload condition.

The open-phase operating value is a maximum of 75% of overcurrent operating value (at open phase) and the current imbalance factor 35±10% (at overcurrent operating value).

The open-phase operating time is 2 sec. max. of the overcurrent operating value (at open phase).

c. Reverse-phase protection:

If the phases are reversed, the revolution of the motor is reversed. The reverse-phase protection feature of a 3E relay is intended to detect reverse phase. If a reverse phase has been detected, the motor is locked. Once a reverse phase has been detected, the reverse-phase protection feature is no longer necessary. Therefore, it can be said that this feature is not of primary importance as a motor protective feature.

The reverse-phase operating value is 80% max. of the rated voltage. The reverse-phase operating time is 0.5 sec. max. at the rated voltag.

3.2.2 Low Voltage Relay (27)

A low voltage relay prevents motors from reaching rated speed on starting, and keeps them from losing speed and drawing heavy overloads. Motors should be disconnected when extremely low voltage conditions persist for more than a few seconds. AC contactors, which generally release from 50 to 70 percent of the rated voltage, provide some low voltage protection. However, time-delayed undervoltage protection is preferred, since it delays contactor release on momentary voltage dips. For switchgear applications, the CV(27), CP(27/47) or CVQ(27/47) relays will accurately detect undervoltage and initiate a trip or alarm, as required.

3.2.3 Phase-Unbalance Relay (46)

Phase-unbalance protection is applied to a feeder supplying a large motor or a group of small motors where there is the possibility of one of the feeder phases opening. Thus will happen as a result of a connector failure, fuse failure, or similar causes. The type CM(46) relay, which contains two induction-disc units , is recommended for these applications. One unit balances I_a against I_b, and the other balances I_b against I_c. When the currents become sufficiently unbalanced, torque is produced in one or both of the units, closing their contacts (which are connected in parallel in the trip circuit) thereby tripping the running motors.

3.2.4 Phase-Sequence Relay (47)

When starting in reverse can be a serious hazard, a reverse-phase relay, such as the type CP(27/47) or CVQ(27/47), should be used. These induction-type relays close their back contacts with abnormal phase sequence voltages. The low voltage contacts, which close by spring action, are the trip contacts, If the phase rotation is correct, and all three voltages are present, the low voltage contact opens and remains open. If the applied voltages are sufficiently unbalanced, the relays will close.

3.2.5 Thermal Overload Relay (49)

There are two types of thermal relays. Those such as the CT and DT-3 which operate from sensing coils embedded in the motor windings. They are applied only to large motors, usually 1,500HP and up.

The DT-3 and CT are bridge-type relays. The sensing coils form part of a Wheatstone Bridge circuit, see Figure 3 and 4, which is balanced at a given temperature. As the motor temperature increases above the balance temperature, operating torque is produced. With the DT-3 relay, only one resistance temperature detector (RTD) (10 ohm for Copper, 100 ohm for PT100, or 120 ohm for Nickel) or sensing coil is required; the CT relay requires two (10 ohm only).

The DT-3 relay is a d'Arsonval-type dc contact-making milliammeter which is connected across the bridge. The bridge is energized by either 125 or 250 VDC or supplied with 120 VAC through a transformer and full-wave bridge rectifier in the relay. The relay scale is calibrated from either 50° to 190°C (or 100° to 160°C). The right- or left-hand contacts close when the temperature rises or falls to the preset value between 50° and 190°C (or 100° and 160°C). The normal setting for class B motor is 120°C.

No current-responsive relay can protect a motor subjected to blocked ventilation. The DT-3 relay overcomes this shortcoming by responding to temperature alone.

The CT operating unit is an induction disc, with the two torque-producing windings connected across the bridge. Current flowing through a current transformer from one phase of the motor supplies energy to the bridge. The relay contacts close when the temperature of the stator windings reaches a predetermined value and the current is sufficiently high. Tripping on thermal overload is also avoided if the duration of the overload is short.

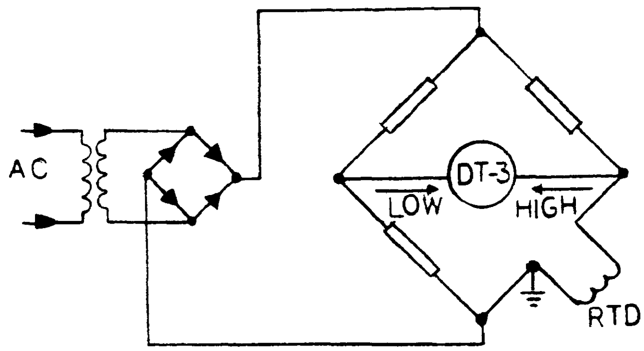


Figure 3. Typical Schematic Diagram of DT-3 Relay (49).

Note: RTD = Resistance temperature detector in motor windings

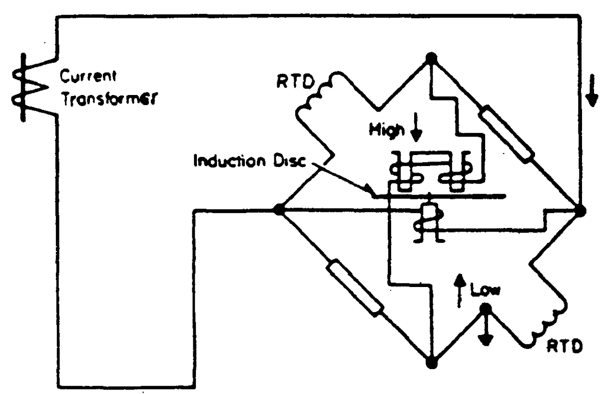


Figure 4. Typical Schematic Diagram of CT Relay (49).

3.2.6 Overcurrent Relay (50/51)

There are several kinds of overcurrent relays which offer motor-overload protection. For example, the induction CO-type overcurrent relay consists of a time overcurrent unit (51), an indicating contactor switch unit (ICS), and an indicating instantaneous trip unit (50) when required.

The electromagnets for the induction CO-type overcurrent relays have a main tapped coil located on the center leg of an "E" type laminated structure that produces a flux which divides and returns through the outer legs. A shading coil causes the flux through the left leg to lag the main pole flux. The out-of-phase fluxes produced in the air gap cause a contact closing torque. We can adjust the time level (or time dial from 1/2 to 11) according to the motor starting time.

Another overcurrent relay type is the COM relay. COM relays are often used where an alarm is desirable for moderate overloads, or where a high speed transfer of power supply is applied.

Figure 5 shows the dc schematic and time curves for the COM-5 relay with the alarm function. The alarm sounds at currents above the CO unit pickup and below the ITH pickup (instantaneous trip with high drop-out). Time-delayed tripping occurs above the ITH pickup and below the IIT pickup (indicating instantaneous trip). If the current drops before the CO unit times out, the high drop-out ratio of the ITH permits the unit to reset. For fault currents above the IIT unit pickup, high speed tripping occurs.

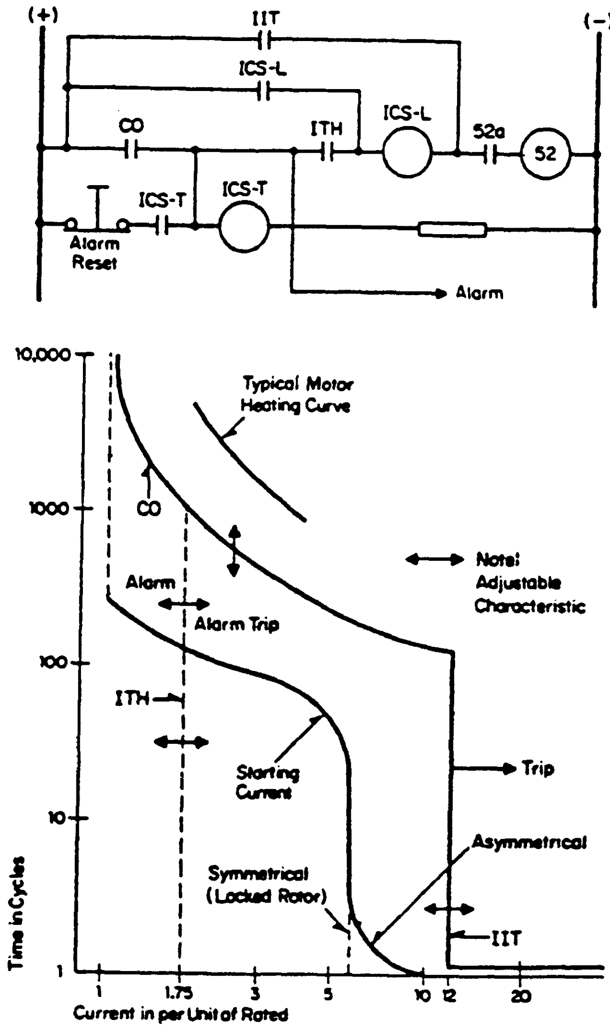


Figure 5. Protective Scheme of COM-5 Relay (50/51).

Notes: 1. CO = Overcurrent unit pickup.
2. IIT = Indicating instantaneous trip.
3. ITH = Instantaneous trip with high drop-out.
4. ICS = Indicating contactor switch.
5. 52 = Main breaker.

3.2.7 Ground-Fault Relay (GFR)

When the ground-fault relays are used in large motors, the relays maybe have mistripping because of the high inrush current during starting the motors. Unequal saturation of the current transformers produces a false residual current in the secondary or relay circuits. Using two- rather than three-phase relays or using three-phase relays with different impedances will tend to increase the effects of false residual currents. If false relay operation is a problem, the ground relay burden should be increased by using a lower relay tap. All three transformers will then be forced to saturate more uniformly, effectively reducing the false residual current. This increased saturation may reduce the sensitivity to legitimatize ground faults and this should be checked. Alternatively, a resistor or reactor can be connected in series with the ground relay.

Ground-fault protection can be categorized into two parts according to the grounded system.

a. For low resistance grounded systems:

The common practice in 2,400-to-14,400-V station service, and in industrial power systems, is to use low resistance grounding. There are two kinds of protection for these systems.

Figure 6 is the BYZ ground relaying scheme (50G). The BYZ zero sequence type current transformer can be used as a supply for the 50(ITH) instantaneous trip unit or 51(CO) time overcurrent relay.

Figure 7 is the ground relaying scheme (50N/51N). Both systems of Figure 6 and 7 offer all the advantages of instantaneous trip units-speed, reliability, simplicity, low cost-without any concern for starting current, fault contributions by the motor, false residual current, or high sensitivity.

The zero sequence type current transformer is also used in the flux balancing differential scheme, in which each phase is equipped as shown in Figure 8. This scheme combines excellent phase- and ground-fault sensitivity with freedom from load current and starting current problems.

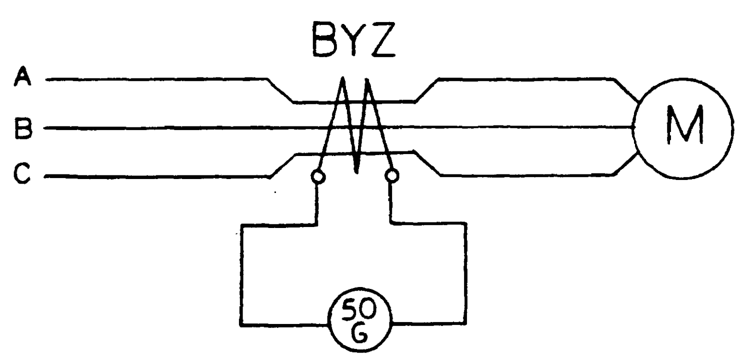


Figure 6. BYZ Ground Relaying Scheme (50G).

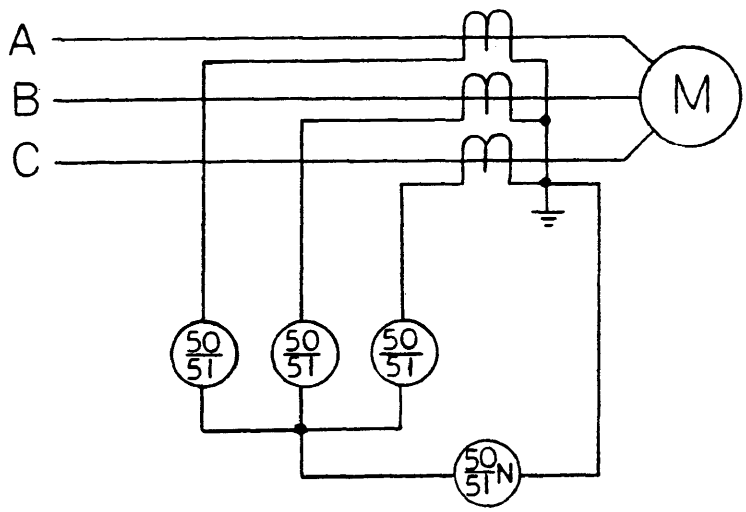


Figure 7. Ground Relaying Scheme (50N/51N).

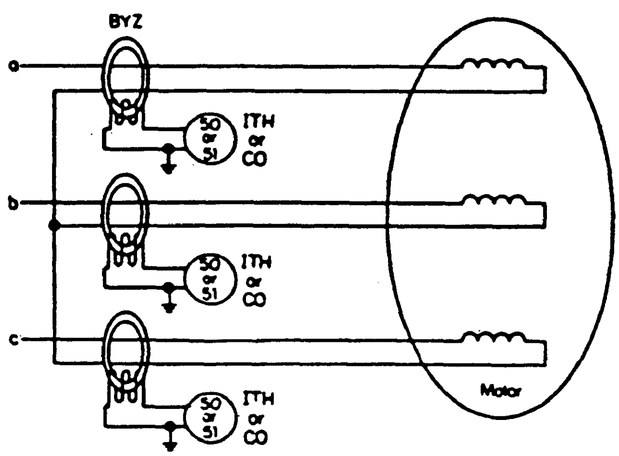


Figure 8. Flux Balancing Differential Scheme.

b. For high resistance grounded systems:

For high resistance grounded systems, where very high sensitivity is required, the direction ground relay (DGR), such as shown in Figure 9, should be considered. The voltage across the grounding resistor, ranging from 16 to 200 ohm, of the grounding potential transformer (GPT), may be used as a voltage polarizing source (Figure 9). The connection of the GPT, as in Figure 9, is Y for primary and open delta for secondary. The zero phase voltage is according to the turns ratio of the GPT. For example, it detects 110V when the turn ratio is 3300:110/1.732 and 190V when the ratio is 3300:110, when the ground-fault occurs.

If a ground-fault occurs at point F, as shown in Figure 10, ground current I_g is expressed by

$$I_g = I_n + I_{c1} + I_{c2},$$

and I_{c1} flows in ZCT1 (ZCT: zero phase current transformer) and $I_n + I_{c1}$ flows in ZCT2. DGR1 is therefore not operated because of the I_{c1} in opposite direction, but DGR2 is operated because it gets the zero phase voltage, 110V or 190V, and ground current $I_n + I_{c1}$.

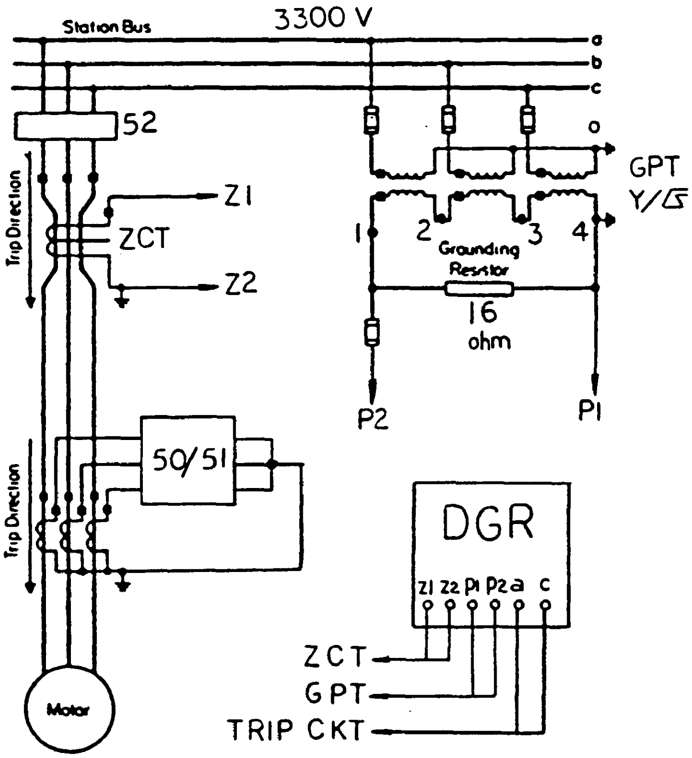
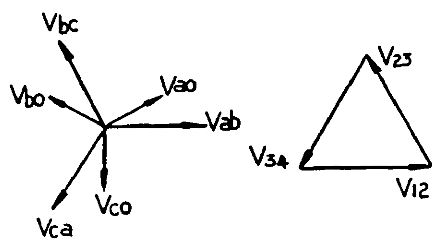


Figure 9. Typical Diagram of DGR for 3300V System.

Notes: 1. GPT = Grounding potential transformer
2. The turn ratio of GPT is 3300 : 110.
3. The vector analysis of zero phase voltage is:
a. In normal condition:

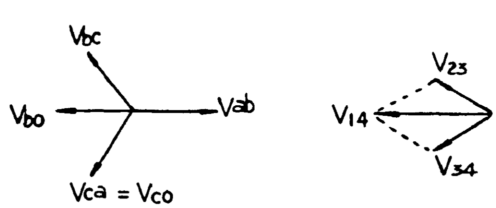


$$V_{ao}=V_{bo}=V_{co}=\frac{3300}{\sqrt{3}}\,V$$

$$V_{12}=V_{23}=V_{34}=\frac{110}{\sqrt{3}}=63.5\,V$$

$$V_{14}=0$$

b. If a ground-fault occurs in phase a:



$$V_{ao}=0$$

$$V_{bo}=V_{co}=3300\,V$$

$$V_{12}=0$$

$$V_{23}=V_{34}=110\,V$$

$$V_{14}=110\sqrt{3}=190.5\,V$$

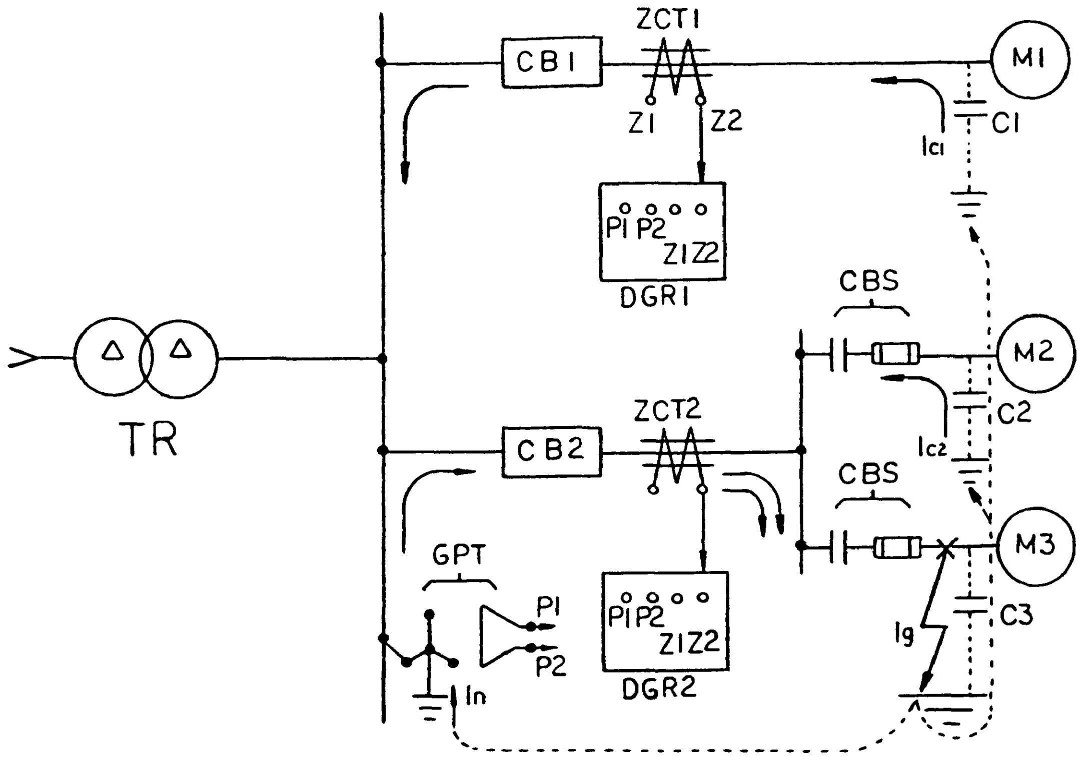


Figure 10. Ground-Fault Current Path.

Notes: 1. C1, C2, C3 = Static capacities between feeders and ground.
2. DGR = Directional ground relay.
3. GPT = Grounding potential transformer.
Connection of GPT : primary Y
secondary open delta.
4. ZCT = Zero phase current transformer.
5. CBS = Combination starter = contactor + power fuse.
6. $I_g = I_n + I_{c1} + I_{c2}$ (ground current).
7. DGR2 is operated, but DGR1 is not operated because of I_{c1} in opposite direction.

3.2.8 Differential Relay (87)

Internal faults in equipment generally develop as a ground in one of the phase windings and may occasionally involve more than one phase. Differential protection is the most effective scheme against multiple-phase faults. In differential protection, the currents in each phase, on each side of the machine, are compared in a differential circuit. Any "difference" current is used to operate a relay.

Figure 11 shows the relay circuits for one phase only. For normal operation or for a fault outside the two sets of current transformers, I_p entering the machine equals I_p leaving the machine in all phases, neglecting the small internal leakage current. On a per-unit basis, the secondary current is equal to the primary current minus the magnetizing current, I_{e1}.

The relay current, $I_{e2} - I_{e1}$, is the difference of the exciting or magnetizing currents. With the same type of current transformers, this current will be small at a normal load. Hence, to prevent relay operation, the relay must be set above this maximum value during normal machine operation. If a fault occurs between the two sets of current transformers, one or more of the left-hand currents will suddenly increase, while currents on the right side may either decrease or increase and flow in the reverse direction. Either way, the total fault current will now flow through the relay, causing it to operate.

Another differential protection is shown in Figure 8. BYZ (zero phase current transformer) will get fault current to operate the relay when a ground-fault occurs.

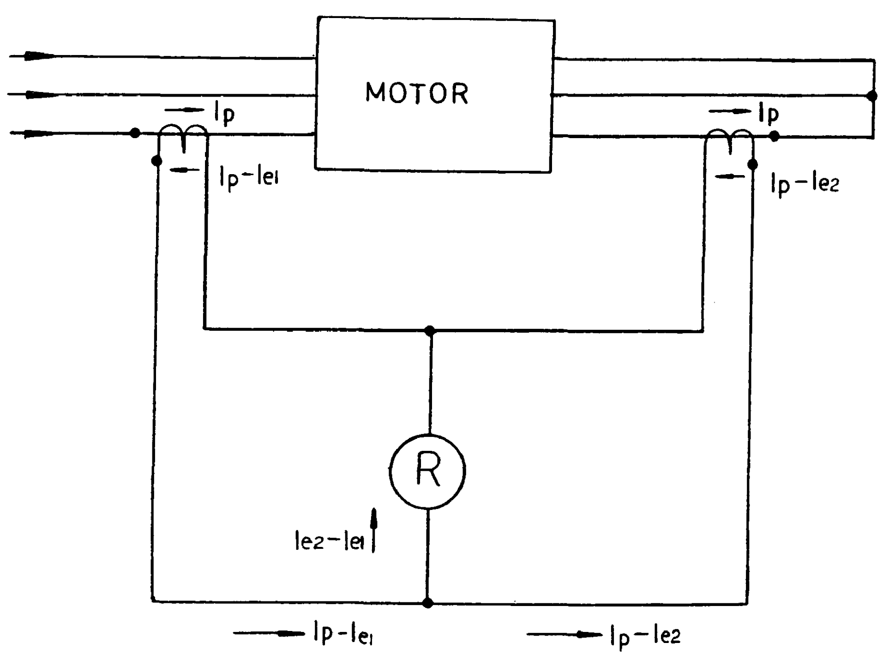


Figure 11. Basic Connection Diagram of Differential Relay.

3.2.9 Field Failure Relay (40)

Synchronous motors can be protected against loss of excitation by a low-set undercurrent relay connected in the field. This relay should have a time delay on drop-out to trip the motor or to alarm the operator. The KLF relay (40) can also be used to protect large motors against loss of field. The undervoltage units of these relays should have their contacts shorted. Loss of excitation of a synchronous motor does not usually depress the voltage enough to reliably operate an undervoltage unit. Unlike undercurrent relays, the KLF relay can detect both partial and complete loss of field, and some out-of-step conditions as well.

3.2.10 Power Factor Relay (55)

Out-of-step protection is applied to synchronous motors and synchronous condensers to detect pullout resulting from excessive shaft load or sub-normal supply voltage. The notching type relay KSN, which counts the power reversals occur, is used for large machines. Both out-of-step and loss-of-excitation conditions can be detected with a CW watt-type (55), connected for zero torque when current lags voltage by an appropriate power factor angle, such as 30 degrees. Use in this way, the CW is referred to as a power factor relay.

The connection shown in Figure 12 gives maximum contact closing torque when current lags unity power factor position by 120 degrees.

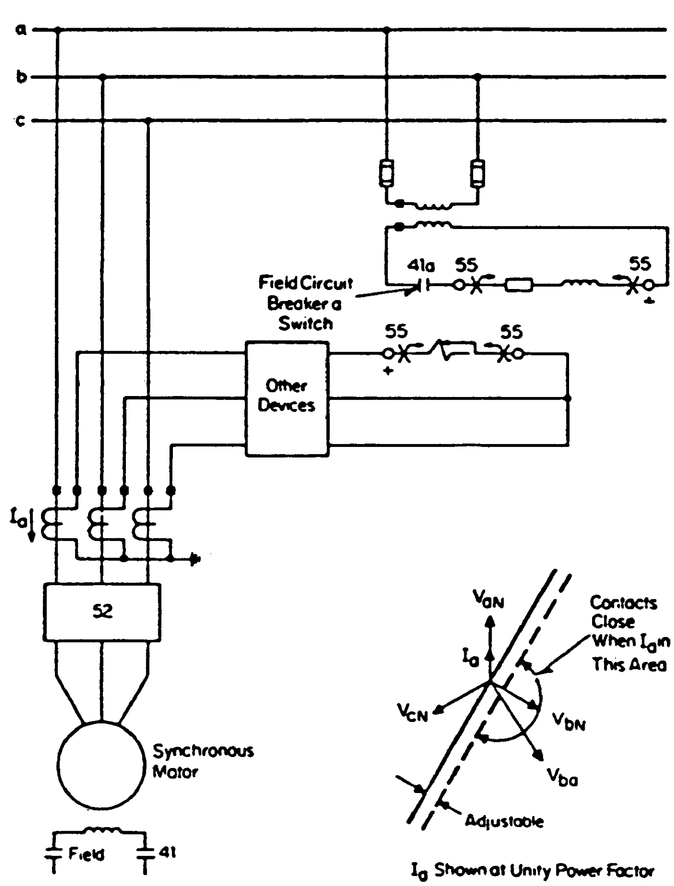


Figure 12. Diagram for Power Factor Relay (55).

Notes: 1. 41 = Field circuit switch.
2. 52 = Main circuit breaker.
3. 55 = Power factor relay, CW Watt-type.

3.2.11 Typical Protection for Motors Below 1,500HP

A typical protection scheme for motors below 1,500HP is shown in Figure 13.

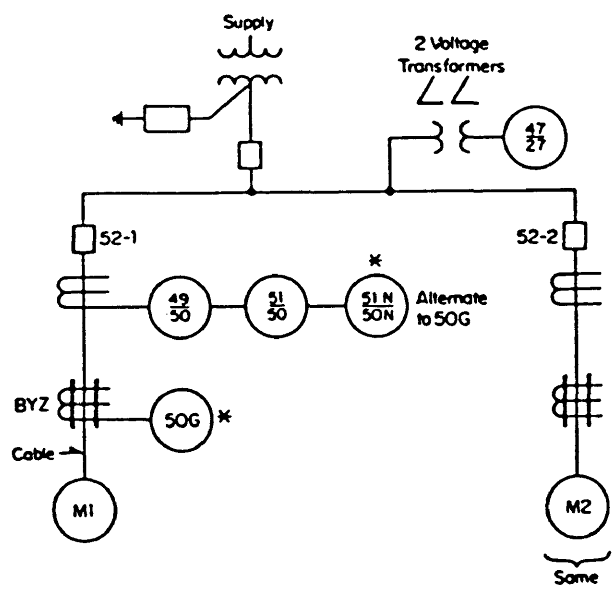


Figure 13. Typical Protection for Motors Below 1,500HP.

Notes:
1. 27 = Low voltage relay.
2. 47 = Phase-sequence relay.
3. 49 = Thermal overload relay.
4. 50 = Instantaneous overcurrent relay.
5. 51 = Time overcurrent relay.
6. 50N = Ground-fault instantaneous overcurrent relay.
7. 51N = Ground-fault time overcurrent relay.
8. 50G = Ground-fault relay (GFR).
9. 52 = Main circuit breaker.
10. BYZ = Zero phase current transformer.

3.2.12 Typical Protection for Motors 1,500HP and Above

A typical protection scheme for motors 1,500HP and above is shown in Figure 14.

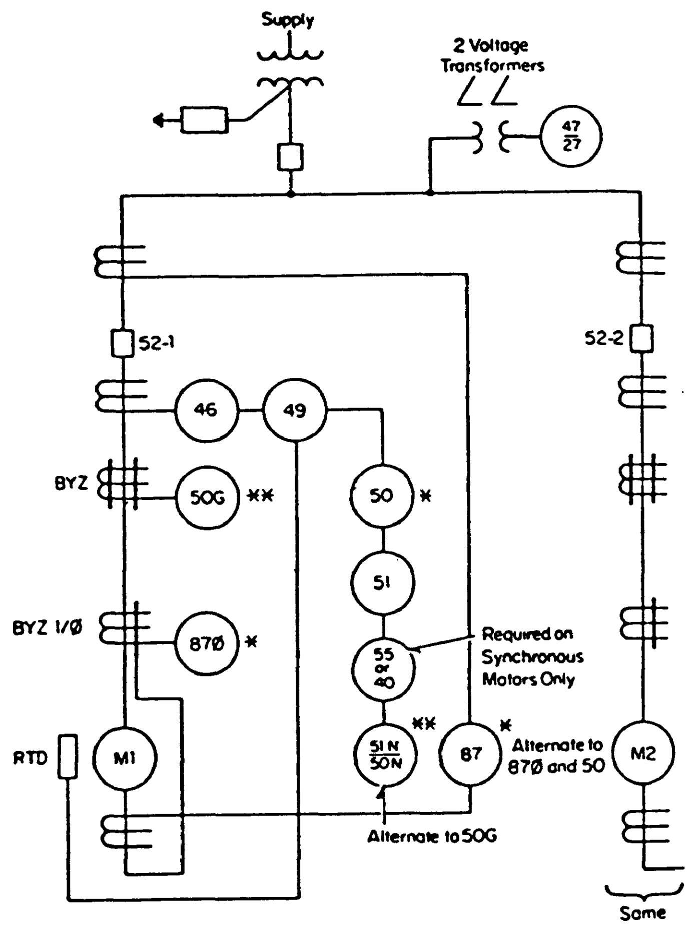


Figure 14. Typical Protection for Motors 1,500HP and Above.

Notes: 1. 27, 47, 49, 50/51, 50N/51N, 50G, 52, and BYZ are explained as the notes of Figure 13.
2. 40 = Field failure relay.
3. 46 = Phase-unbalance relay.
4. 55 = Power factor relay.
5. 87 = Differential relay.
6. RTD = Resistance temperature detector.

4. EXISTING MONITORING AND PROTECTION TECHNOLOGIES

4.1 Monitoring

Machinery often requires the use of a sophisticated continuous monitoring system. Monitors play an important role in protecting equipment and helping to maintain operating requirements.

Vibration and temperature are generally acknowledged as the two most vital measurements to take when monitoring machines. For big motors, above 1000HP, it is better to have vibration and temperature monitors for windings and bearings.

For critical points of a process, the pressure, flow, and level are monitored during operation. Most machine monitors accept input signals from standard vibration and temperature sensors and process transmitters (e.g., 4-20mA pressure, flow, and level transmitters). With these inputs, the monitors provide ALARM and TRIP set points, individual channel and system relays, analog outputs, and local and/or remote displays.

4.1.1 Vibration Monitor

The performance of most motors will deteriorate after a period of time. The earlier a fault in a motor can be detected, the easier it is to correct the abnormalities. Much can be learned about a motor's condition and its problems by simply analyzing its vibration characteristics. Hence, the vibration monitor is very important in the smooth operating of a motor. The following items should be considered when selecting a vibration monitor: Sensor selection, Set point levels, Sensor installation, and Calibration.

a. Sensor selection:

In general, smaller motors often have anti-friction bearings requiring seismic pickups. Seismic sensors (peak-to-peak displacement or velocity pickups) and seismic monitoring are used.

The seismic velocity vibration pickup consists of a coil of fine wire supported by springs with low stiffness. A permanent magnet is firmly attached to the case of the pickup. It provides a strong magnetic field around the suspended coil.

When the case of the velocity pickup is attached to or held against a vibrating part, the permanent magnet (being firmly attached to the case) follows the motion of vibration. The coil of wire (conductor), supported by springs with low stiffness, remains stationary in space. Under these conditions, the relative motion between the magnetic field and the coiled conductor is the same as the motion of the part relative to a fixed point in space; and the voltage generated by the pickup is directly proportional to this relative motion. The faster this motion, the larger the voltage. In other words, the voltage output of the pickup is proportional to the velocity of the vibration. As the velocity of the vibrating part changes, the voltage generated changes proportionately. Hence the name "VELOCITY PICKUP."

Velocity pickups are self-generating devices that measure "seismic" motion, usually at the bearing housing. Their low impedance AC output signal is in proportion to the vibration velocity, making them ideal for many applications. Both low and high temperature, and axis sensitive, low frequency models are available. Larger motors generally have sleeve (or journal) bearings, and proximity probes and displacement modules are often used in these cases.

b. Set point levels:

Set point levels should be decided based on the manufacturers recommendation, engineering judgement and historical or comparative data on the motor being monitored.

The five characteristics of vibration are vibration velocity, displacement, acceleration, frequency, and phase. The vibration velocity, displacement, and acceleration are often monitored for a motor and are explained as follows:

1. Vibration velocity:

The velocity of the motion is a particular characteristic of the vibration, but since it is constantly changing throughout the cycle, the highest or "peak" velocity is selected for measurement.

Vibration velocity is normally expressed in terms of inches per second peak. In Metric units, it is expressed in millimeter-per-second peak.

2. Vibration displacement:

The total distance traveled by the vibrating part, from one extreme limit of travel to the other extreme limit of travel is referred to as the "peak-to-peak displacement".

Peak-to-peak vibration displacement is normally expressed in mils, where 1 mil equals one-thousandth of an inch (0.001 inch). In metric units, the displacement is usually expressed in microns, where 1 micron equals onemillionth of a meter (10^{-6} meter) or (10^{-3} millimeter).

3. Vibration acceleration:

Vibration acceleration is normally expressed in"g's"peak, where one "g" is the acceleration produced by the force of gravity at the surface of the earth. The value of 980.665 cm/sec^2 = 386.087 inches/sec^2 = 32.1739 feet/sec^2 has been chosen as the standard acceleration due to gravity.

In general, vibration levels listed below are considered acceptable for a motor.

Vibration velocity	:	0.1 - 0.3 in/sec
		or 3 - 8 mm/sec
Vibration displacement	:	1 mil (for 2-pole motor)
		or 25 μm (10^{-6} m)
		1.5 mils (for 4-pole motor)
		or 38 μm (10^{-6} m)
		2 mils (for 6-pole motor)
		or 50 μm (10^{-6} m)
Vibration acceleration	:	2 - 3 g
		or 20 - 30 m/sec^2

To properly determine set point levels, an analysis of the potential motor defects (e.g., imbalance, loose foundation, seal rub) and the relevant vibration frequency (e.g., 1 x RPM, 2 x RPM, 300-650Hz) to be monitored should be made.

c. Sensor installation:

Sensor installation also requires a thorough evaluation, especially of proximity probes. Seismic sensors are easier to install, but care must be taken in mounting the devices. Firm attachment to a solid surface (usually on the bearing housing) is necessary. It is often best to survey the motor with a portable analyzer to locate the point with the highest vibration and mount the velocity pickup there.

d. Calibration:

Calibration verification of sensors and monitoring systems are initially made during start-up commissioning. A check of the calibration is strongly recommended on at least a yearly basis thereafter. A portable calibrator for sensors and a portable tester for monitoring systems are both very useful.

4.1.2 Temperature Monitor

Temperature monitors for motor windings and bearings have been in use longer and are good for warning of rapidly approaching critical conditions. For early detection and diagnosis of a motor's condition, temperature detectors permit predictive maintenance, thereby eliminating unnecessary and unplanned downtime, costly equipment damage, and potential catastrophic failure.

Temperature monitors provide reliable alarm and shutdown (trip) motor protection using popular thermocouple and RTD temperature sensing devices. For example, the Rochester Instrument Module TM-2474 temperature monitor thermocouple module accepts direct inputs from K, T, J, or E thermocouples, with alarm and shutdown functions, and with an output for display of the monitored and set point temperatures in degrees F or C. It also provides expanded relay capability (i.e., an alarm relay and a trip relay for each point) and offers a choice of either a current or voltage analog output.

The following are usually used for resistance temperature detectors (RTD):

a. Platinum:

Resistance of PT-100 is 100 ohm at 0°C.

b. Copper:

Resistance of copper is 10 ohm at 25°C.

c. Nickel:

Resistance of nickel is 120 ohm at 0°C.

Most RTD module temperature monitors provide three monitoring channels for platinum, copper, or nickel RTD inputs, and provide independent alarm or shutdown functions for each. Per-channel ALARM and TRIP setpoints are fully adjustable. Voltage or current outputs are also available.

The setpoint levels for temperature monitors should be based on the manufacturers recommendation that should be according to the insulation class (see Section 2.1.4 on Insulation Systems).

Some detector modules for temperature monitors have automatic built-in sensor failure detection. This feature will cause an alarm (but inhibits shutdown) on both open-circuit and short-circuit sensor conditions when high/high trip mode is specified. (Note: With thermocouple sensors an alarm on open-circuit conditions only is provided.)

4.2 SF_6 Gas Circuit Breaker (GCB)

A non-inflammable and non-toxic gas, SF_6 has a dielectric strength 2.5 times that of air at atmospheric pressure. At the pressure at which the breakers are filled and within the normal limits of utilization, there is no risk of the liquefaction of the gas.

The remarkable thermal and electro-negative properties of SF_6 make it an ideal medium for current interruption.

The following are some applications and features of the GCB.

a. Application:

The SF_6 gas circuit breakers are widely used as a primary breaker for transformers, transmission lines, and capacitor banks. Due to its compactness, a GCB can be installed in a substation as well as in a densely populated area.

For application in a substation, the GCB is also called a SF_6 gas insulated switchgear (GIS).

b. Rated voltage:

SF_6 GCB's can be used for rated voltages from 3 to 800KV.

c. Rated current:

The rated currents vary. They are determined by types and manufacturers. The following are the examples of rated currents:

1. ALSTHOM France, SF_6 GCB type FP61

400 to 630A for voltages 3.6 to 24KV

SF_6 GCB type FP62

630 to 3150A for voltages 3.6 to 24KV

2. TOSHIBA Japan, SF_6 GIS

800 to 3150A for voltages 72.5 to 170KV

2000 to 8000A for voltages 245 to 800KV

d. Rated interrupting current (IC):

The rated interrupting currents are also determined by types and manufacturers. The following are examples of rated interrupting currents:

1. ALSTHOM France, SF_6 GCB

Type FP61 18.4 KA (rms) at 3.6KV

16 KA (rms) at 24KV

Type FP62 26.3 KA (rms) at 3.6KV

25 KA (rms) at 24KV

2. TOSHIBA Japan, SF_6 GIS

20 to 40 KA at 72.5 to 145KV

31.5KA at 170KV

40 to 63 KA at 245 to 800KV

e. Operating mechanism and principles:

Like the other kinds of circuit breakers, all types of GCB's are equipped to utilize energy stored in springs for closing and tripping (there is a spring for closing and a spring for tripping). Closing and tripping are each achieved by the sudden release of a spring. The springs are linked to a drive shaft which operates the circuit breaker.

The release of each of the springs can be initiated either manually (control button on the front face of the equipment) or electrically (electromagnetic due to a closing coil or tripping coil).

The restoration of the tension (rearming) in the tripping spring occurs automatically during the closing operation. That of the closing spring is performed either manually by means of a lever or a handle, or else automatically by means of an electric motor.

f. Maintenance:

The poles of GCB are so manufactured as to constitute a unit sealed for the whole life of the device. Maintenance is thus limited to simple operations such as the lubrication of the operating mechanism.

g. Safety:

The SF_6 circuit breakers operate at low pressure (nominal filling pressure 3.5 bars). The internal rise in pressure at the instant of current interruption caused by the compression and the heating of the gas remains low. With the gas at atmospheric pressure, the circuit breaker still retains dielectric properties and current interrupting capacity adequate to allow its operation in perfect safety.

5. ADVANCED MOTOR SYSTEMS

During the past 15 years, motor control systems have undergone a great change-traditional relay control systems have been replaced by electronic, digital, and microprocessor control systems. Three of the advanced motor systems are discussed below:

5.1 Brushless Excitation for Synchronous Motors

Brushless excitation and field control units are used for synchronous motors. Connection and disconnection of field excitation is automatic and without moving parts. Brushes, commutator, collector rings and conventional field controls are eliminated and replaced by a static semiconductor circuit mounted on the rotor of the machine.

Figure 15 shows the brushless excitation system for fixed speed synchronous motors. This system consists of a field discharge resistor (starting resistor), diodes, SCR's, and a field control unit (a gating module and a synchronizing module).

5.1.1 The Principles of Field Control

When alternating current is applied to the stator windings of a synchronous motor, the circulating electrical field (magnetic flux) set up in the stator winding acts on the windings of the rotor causing the rotor to turn. The rotor accelerates to near synchronous speed. It does not attain the speed of the rotating electrical field because of the slip characteristic that is similar to the induction type, or squirrel cage, motor.

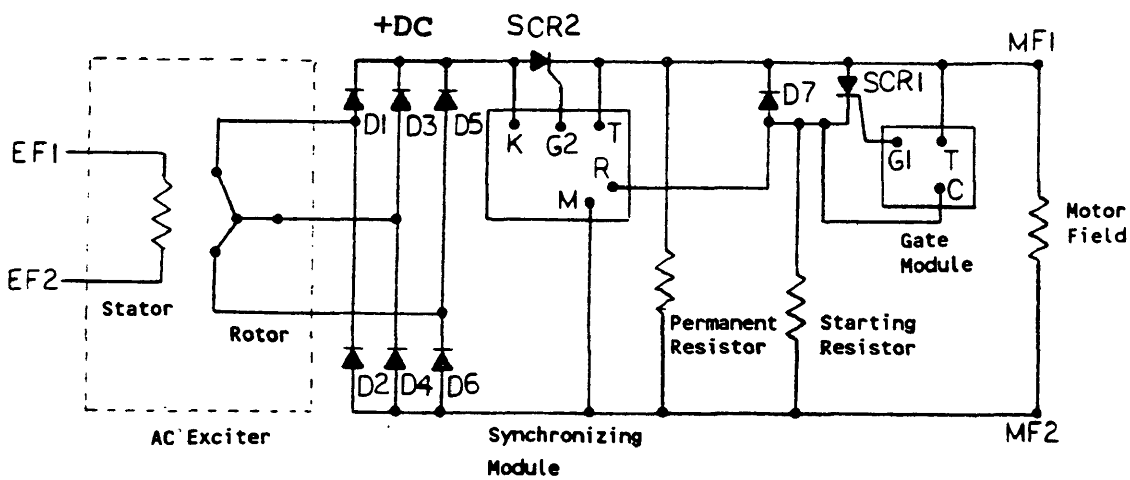


Figure 15. Schematic Field Circuit for Synchronous Motor.

During the acceleration period, the voltage induced in the motor field is such that MF2 is positive with respect to MF1, and diode D7 conducts at a very low voltage and short circuits the motor field through the starting resistor. When the polarity is reversed on the next half-cycle so that MF1 is positive with respect to MF2, the induced voltage ramps rapidly toward an open circuit high peak voltage possibly in the vicinity of 30 to 40KV, depending on the motor design. At some low voltage point, however, SCR1 will be fired at a predetermined voltage (somewhere between 300 and 500 volts depending on motor design) and conduct the discharge current through the discharge resistor (starting resistor).

Thus, there will be an alternating voltage across the starting resistor and control circuit. The frequency of this wave starts out at line frequency when the motor is at a standstill and decreases to zero at the time the motor is synchronized. Since the frequency of the voltage induced in the rotor field is:

$$f_r = sf \qquad (1)$$

where: s = slip

f = power line frequency

At standstill, $s = 1$

Hence, $f_r = 1$

At synchronizing, $s = 0$

Hence, $f_r = 0$

The purposes of the "Synchronizing Module" (Figure 15) are to:

1. Keep SCR2 from firing until the frequency is very low, representing a close approach (95 to 99.5% speed) to synchronous speed.

2. Fire SCR2 at near synchronous speed and thus apply excitation to the field of the synchronous motor.

Fortunately, the best point in the slip cycle to apply excitation, from a torque standpoint, occurs during a period when SCR1 is not conducting and so there is positive interlocking between SCR1 and SCR2.

Hence, the synchronizing module monitors rotor speed (by the frequency of induced field voltage) and rotor phase angle (by phase angle of induced voltage). When the speed and phase angle are such as to cause minimum disturbance to the supply system, the field voltage is applied, and the motor "pulls-in" to synchronization. (i.e. At that proper slip and phase angle time, the starting resistor is removed automatically from the field circuit, and DC current is applied to the field to pull the motor into synchronism.)

To discuss out-of-step operation, refer to Figure 15 once again. On the first half cycle after pull-out, when MF2 is positive with respect to MF1, the field current will build up. As soon as the voltage reverses and MF1 becomes more positive than the exciter voltage (making the potential across SCR2 reverse), SCR2 shuts off and automatically removes the excitation from the synchronous motor field. Thus, removal of field excitation is positively achieved in the first cycle of out-of-step operation.

5.1.2 The Advantages of Brushless Excitation

The following items are the advantages of a synchronous motor with brushless excitation and field auto-control:

1. Field excitation is applied with high accuracy and torque efficiency to meet the most severe applications.

2. The synchronizing point can be precisely adjusted to provide most effective pull-in (as Section 5.1.1).

3. Field excitation is automatically removed whenever the motor is out of step. This removal induces automatic resynchronizing.

4. Field control and excitation are static and thus relatively maintenance free.

5. Brush sparking is eliminated, thus enhancing safety of operation in hazardous areas, and reduction of electromagnetic interference.

5.2 Integrated Protection Systems

Large motor protection requires a number of distinct functions which are typically provided by up to 9 separate relays. Some manufacturers have combined the experience gained in applying and manufacturing these separate relays with the flexibility of a microprocessor to provide a single multi-function relay for total integrated motor protection.

The protective functions are based on motor currents and/or RTD inputs. These inputs are scanned continually by a microprocessor-controlled circuit and provide the digital equivalent to continuous protection.

Although there are many kinds of integrated protection relays, their features and functions are almost equivalent. These features are discussed below:

5.2.1 Features of The Integrated Protection Relay

The following constitute the features of a general integrated protection relay:

1. Trip indication and reset
2. Alarm indication and reset
3. Field settable:
   - RTD type and quantity
   - Alarm levels
   - Trip levels and time delays
   - Trip mode
   - Motor constants
4. Selective digital display:
   - Setting values
   - Alarm values
   - Relay trip currents
5. Monitoring data:
   - Phase currents
   - RTD temperature
   - Ground current
   - Differential current
   - Settings
6. Self diagnostic display

5.2.2 Functions of The Integrated Protection Relay

The following are the functions of a general integrated protection relay:

1. Trip indication:

When the trip relay is energized, a trip indication LED will turn ON. Trip indication will remain on until manually reset by an operator. This reset is accomplished by pressing a reset button.

2. Alarm indication:

In case of an alarm an LED will FLASH corresponding to the condition in the alarm.

3. Display of motor operating parameters:

The motor operating parameters that can be viewed are given in Table 9. Each parameter is identified by a function number. Hence, one can select the function number to get the VALUE display to read the current operating value of a given function.

If a trip indication is present, the operating values displayed are the values at the time the trip occurred. An operator can press the reset button to return the relay to display the present operating values.

Table 9. Motor Operating Parameters.

Function No.	Value Display	Units
1	Load current	% FLC
2	Phase A current	AMPS
3	Phase B current	AMPS
4	Phase C current	AMPS
5	Max. RTD temperature	°C
6	RTD 1 winding temperature	°C
7	RTD 2 winding temperature	°C
8	RTD 3 motor bearing temp.	°C
9	RTD 4 load bearing temp.	°C
10	Ground fault current	% TRIP
11	Phase A diff. current	% TRIP
12	Phase B diff. current	% TRIP
13	Phase C diff. current	% TRIP

Notes: 1. Source: Westinghouse Electric Corporation product bulletin 41-155 "Type MPR Motor Protective Relay"
2. Diff. = Differential
3. FLC = Full load current
4. RTD = Resistance temperature detector

4. Trip values setting:

Table 10 lists the various trip values and trip time delays which determine the trip and alarm operating modes of the relay. An operator can set the trip values and trip time delays in accordance with the trip requirements. Any of these may be displayed using the function number given in the table.

5. Winding overtemperature protection with RTD's

Temperature conditions may be examined in a more refined way when RTD's are available. The RTD is located between windings in the motor stator slot, and is therefore subjected to all of the same influences of heating as the stator insulation, including ambient and ventilation.

Excessive temperature of the RTD will cause tripping without additional time delay. Time delay is inherent in the increase in temperature of the motor itself.

Table 10. Trip Values and Time Delay Settings.

Function No.	Trips and Time Delays	Set Point	Units
14	Lock rotor current trip	3 - 12	x FLC
15	Lock rotor time delay	1 - 99	sec
16	Inst. overcurrent trip	3 - 15	x FLC
17	Inst. overcurrent delay	0.04 - 0.2	sec
18	Overload trip	100 - 190	% FLC
19	RTD winding temp. trip	10 - 190	°C
20	RTD motor brg. temp. trip	10 - 190	°C
21	RTD load brg. temp. trip	10 - 190	°C
22	Phase reversal trip	1	-
23	Ground fault trip	0.1 - 1.0	Amps
24	Ground fault delay	0.1 - 1.0	sec
25	Load loss trip	20 - 95	% FLC
26	Load loss delay	1 - 16	Sec
27	Phase diff. trip	0.1 - 1.0	Amps
28	Phase diff. delay	0.04 - 0.2	sec
29	Load jam trip	0.7 - 12.0	x FLC
30	Load jam delay	1 - 10	sec

Notes:
1. Source: Westinghouse Electric Corporation product bulletin 41-155 "Type MPR Motor Protective Relay"
2. FLC = Full load current
3. Inst = Instantaneous
4. Brg = Bearing
5. Diff = Differential
6. RTD = Resistance temperature detector

Table 10. (Continued)

Alarms			
Function No.	Alarms and Time Delays	Set Point	Units
31	Winding temp.	2 - 20	°C below trip
32	Motor brg. temp.	2 - 20	°C below trip
33	Load bearing temp.	2 - 20	°C below trip
34	Phase unbalance	5 - 30	12 % of I_1
35	Ground fault	30 - 100	% Trip
36	Load loss	20 - 95	% FLC
37	Load loss alarm delay	1 - 16	sec
38	Phase diff.	30 - 100	% Trip

Note: I_1 is the positive sequence component of the three phase input currents.

6. Thermal overload protection (49)

Measurement of overload where RTD's are not available is accomplished by using the expression

$$(I_H)^2 = (I_1)^2 + K(I_2)^2 \qquad (2)$$

Where I_H is the current from an appropriate function of I_1 and I_2. I_1 is the positive sequence component of the three phase input currents; I_2 is the negative sequence component, and K is a weighting factor to accommodate the increased influence of heating produced by the negative sequence current. The combined measure of current (I_H) makes the overload protection more sensitive under unbalanced conditions.

The integrated protection relay is given a locked rotor (full voltage) current setting and a "cold" permissible locked rotor time setting. This protection has a memory to monitor the motor current, and it continuously compares the data to the known thermal record of the motor. When the thermal limit of the motor is exceeded, the relay operates.

7. Long start and locked rotor protection

As well as being covered by the thermal protection relay, each starting sequence is individually monitored in order to check that the heating effect is not significantly above that defined by the parameters of function number 14 and 15 on the relay.

8. Instantaneous overcurrent (short circuit) protection

Detection of faults is achieved by the measurement of individual phase current levels. When the highest phase current magnitude exceeds the instantaneous overcurrent trip level setting for a period of time in excess of the instantaneous overcurrent delay setting, immediate tripping and indication will occur.

9. Ground fault protection

Motors are generally ungrounded. By using the integrated protection relay a "through-type" ZCT (such as the BYZ-S 50:5) with all three phase conductors routed through it, sensitive detection of ground faults in the motor or motor supply cables can be obtained by measuring the ZCT secondary current. The ground fault trip (function number 23) can be set between 0.1 and 1.0 amperes. Ground fault trip delay tripping may be selected from 0.1 to 1.0 seconds (function number 24). This delay is necessary to override phenomenon such as discharge and energization of surge protective capacitors that are often connected from phase-to-ground at the motor terminals.

10. Jam protection

A sudden large increase in current after the motor is running is indicative of a jam condition on the motor. A jam is sensed when the magnitude of I_H (equation 2) is above the load jam trip (function number 29) and delay setting (function number 30).

11. Load loss protection

A sudden decrease in current is indicative of a loss of load (shaft breakage or a driven load problem). If the motor is running, load loss is sensed by a dropping in the magnitude of I_H below the load loss trip setting (function number 25) and remaining there for a period greater than the load loss delay setting (function number 26). After this delay, a trip signal is generated and load loss is indicated. Reduction of current to zero is recognized as removal of the motor from the line, and no tripping or indication function will occur.

12. Phase differential protection

Additional protection for motor windings is provided by sensing the current from 3 CT's connected (such as Figure 8) to measure the differential current in each winding. A phase differential trip may be set between 0.1 and 1.0 amps (function number 27). Trip may be delayed from 0.04 to 0.2 seconds with the phase differential delay setting (function number 28).

13. Phase reverse protection

The phase sequence of the input currents is sensed if two sequential checks indicate an ACB sequence instead of ABC, and an immediate trip is generated. This protection function (function number 22) can be disabled if the motor is to be run with phases reversed.

14. Bearing overtemperature protection

This function senses bearing temperature, as measured by bearing RTD's. A trip output is provided when the measured resistance of any one of the active RTD's indicates that its temperature has reached or exceeds the trip setting.

5.3 Energy Management

To fluid pumps and fan drives, the relationship of their power, flow, and speed can be expressed by the equation (3).

$$\frac{P_1}{P_2} = \left(\frac{Q_1}{Q_2}\right)^3 = \left(\frac{N_1}{N_2}\right)^3 \qquad (3)$$

Where P = Electrical power

Q = Flow

N = Speed (RPM of motor)

Hence, the electrical power will be reduced dramatically if the speed of the motor can be controlled according to the decrease of the load. Theoretically, the power is only one-eighth of the original if the speed is reduced to a half. It is for this reason the speed controllers (up to 500HP) are often used for saving energy. There are two major methods used for adjusting the motor speed: the frequency controllers and the pole-changing motors.

5.3.1 Frequency Controllers

There are two basic types of inverters for use with variable-frequency and variable-voltage speed control systems for three-phase a.c. motors, namely the current-source type and the voltage-source type.

1. The current-source inverter

A block diagram of a current-source inverter is shown in Figure 16. It consists of either a phase-controlled rectifier circuit, or rectifier-chopper circuit, followed by a choke to provide a constant-current source for the inverter. The inverter thyristors are force-commutated to transfer the current between phases. Since the inverter is supplied from a current source, it is protected from transient current surges arising from rapid load variations.

In theory, the current-source inverter provides an economical inverter design in which the thyristors are fully utilized during normal operation. However, it cannot be used for the control of two or more motors in parallel, and motors exhibit pulsating torques at low frequencies. Because of these restrictions, current-source inverters are therefore only of limited utility.

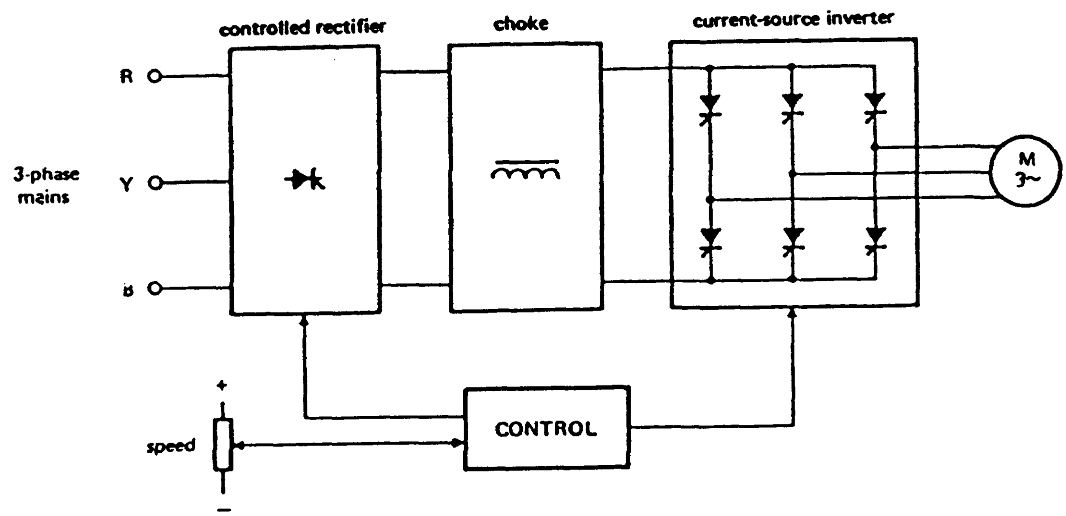


Figure 16. Variable-Frequency Current-Source Inverter System.

2. The voltage-source inverter

Because of the limitations of the current-source inverter, the voltage-source inverter is the most commonly used type. The simplest form of this is the "quasi-square-wave" inverter, or "six-pulse" inverter. In the quasi-square-wave inverter system, each of the three inverter outputs is switched every half-period between the positive and negative terminal of the fixed d.c. supply source as shown in Figure 17. This produces the output waveforms of Figure 18.

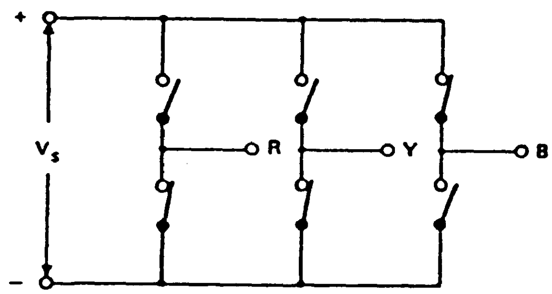


Figure 17. Voltage-Source Inverter.

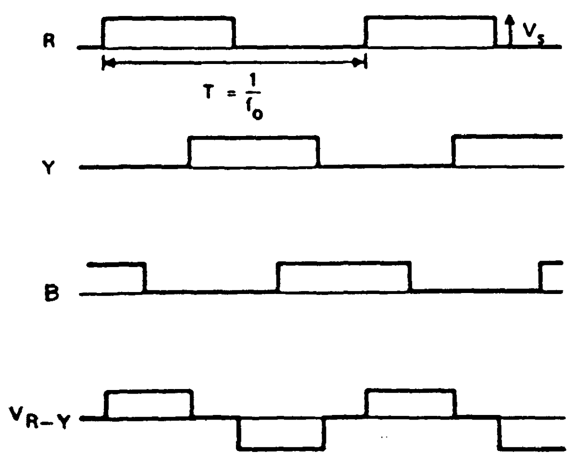


Figure 18. Quasi-Square Waveforms.

The half-period average line output voltage is given by

$$V_{(R-Y)av} = V_s \times 2/3 \tag{4}$$

Where V_s is the d.c. supply voltage. However, the a.c. motor requires an average voltage proportional to frequency, and this variation of the output voltage with frequency requires the use of an additional chopper circuit. The need for this extra circuitry can be overcome by the pulsed quasi-square-wave system. The output of this system is shown in Figure 19. Each of the three inverter outputs supply the motor with :

n output pulses ,

amplitude V_s ,

pulse-width T_δ ,

during each half-period.

The average line output voltage for half a period is given by:

$$\begin{aligned} V_{(R-Y)av} &= V_s \times n \times \frac{2}{3} \times T_\delta \times \frac{2}{T}, \\ &= V_s \times \frac{4n}{3} \times T_\delta \times f_o. \end{aligned} \tag{5}$$

The output voltage $V_{(R-Y)av}$ is therefore proportional to the motor drive frequency f_o, assuming V_s, n, and T are fixed, and so the induction over the whole speed range is constant.

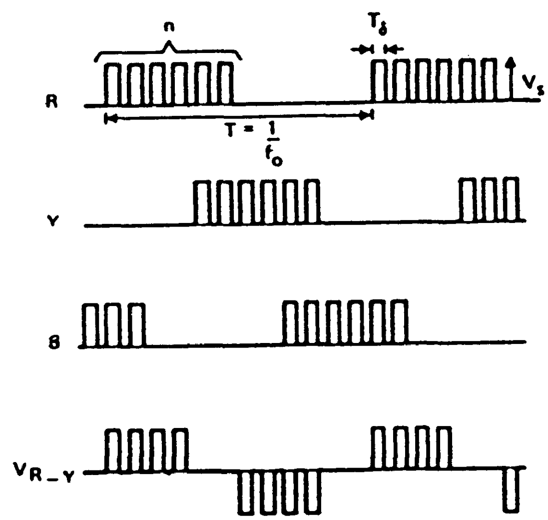


Figure 19. Pulsed Quasi-Square Waveforms.

The motor performance obtained using the quasi-square inverter system can be improved by using the technique of sinewave-modulated pulse-width modulation (PWM). Many types of sinusoidal PWM systems have had their own shortcomings such as circuit complexity, cost, and output variation with temperature. A block diagram of the system is shown in Figure 20.

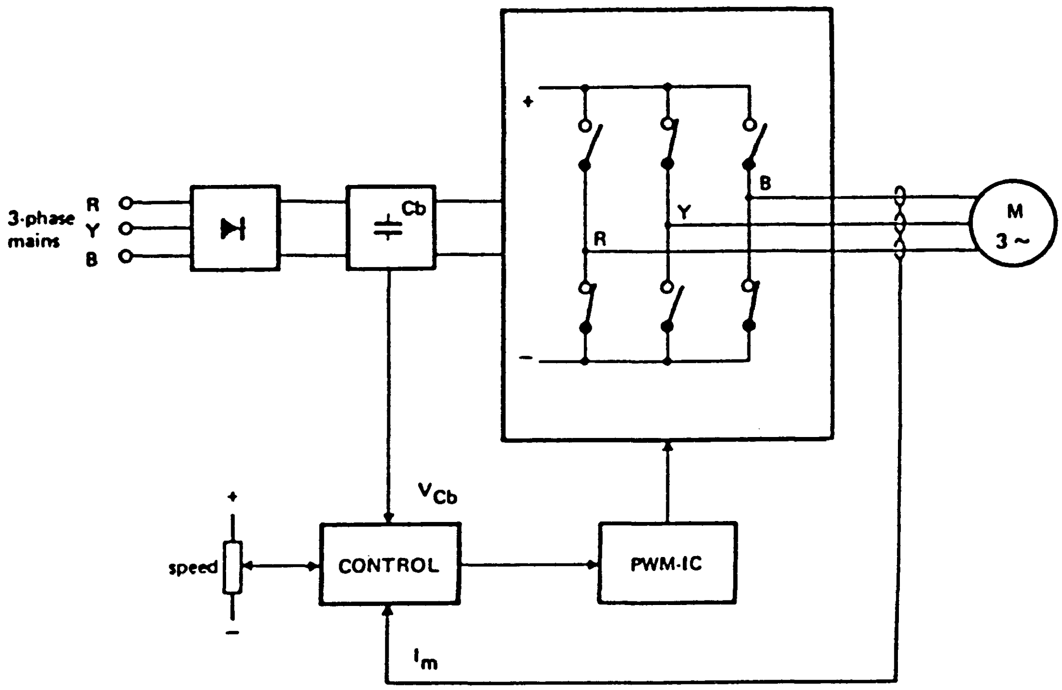


Figure 20. Voltage-Source PWM Inverter System.

The PWM-IC provides three complementary pairs of output drive waveforms which, when applied to a three-phase bridge inverter, produce a symmetrical three-phase (120°) output. Data inputs for reversing, start/stop, and interlock delay selection are provided.

The relationship between the motor drive voltage and frequency is inherently linear, but separate control of voltage and frequency is possible if required.

5.3.2 Pole-Changing Motors

The stator winding can be designed so that by simple changes in coil connections the number of poles can be changed in the ratio 2 to 1. Either of two synchronous speeds can be selected. The rotor is almost always of the squirrel-cage type. A cage winding always reacts by producing a rotor field having the same number of poles as the inducing stator field.

There are three kinds of pole-changing motors: the variable torque, the constant torque, and the constant horsepower.

1. The variable torque pole-changing motors

Load requires much lower torque at low speed than at high speed. Horsepower varies approximately as the cube of the speed, and the torque varies approximately as the square of the speed. This type is used in applications such as centrifugal fans, pumps, and blowers.

Figure 21 shows the variable torque 3-phase 4P/8P motor internal connection diagram. Figure 22 shows the external connection of the motor.

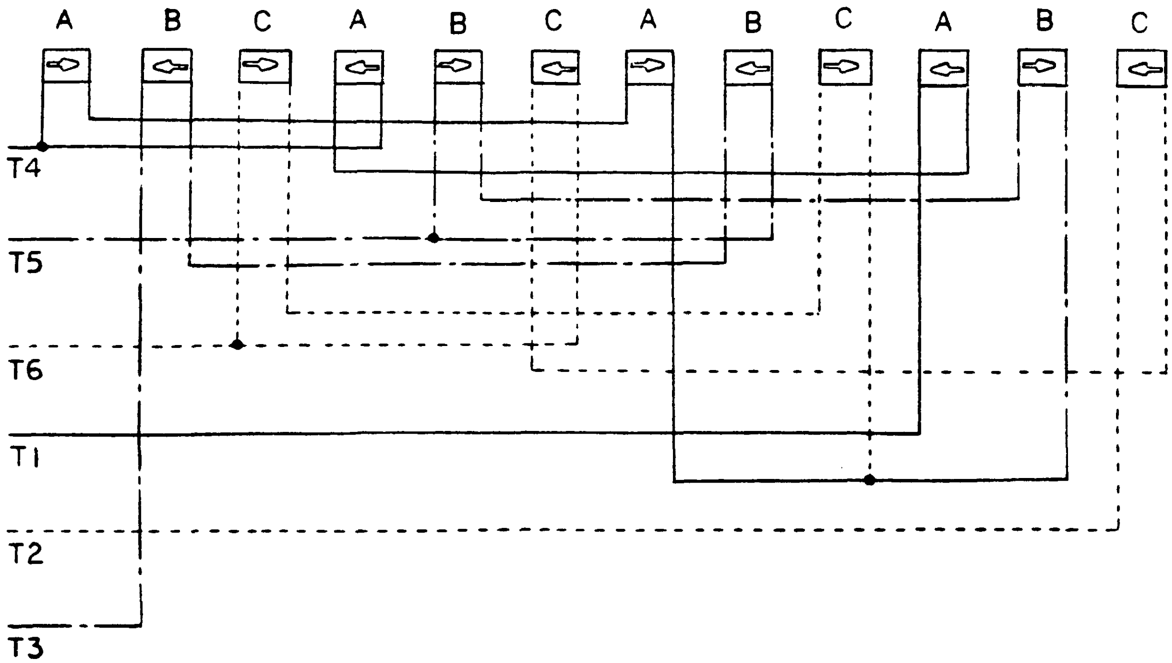


Figure 21. Internal Connection Diagram for Variable Torque Motor.

Speeds	Power Line			Connections	
	L1	L2	L3		
Low (8P)	T1	T2	T3	T4,T5,T6 Open	1Y
High (4P)	T4	T5	T6	T1-T2-T3 Conn.	2Y

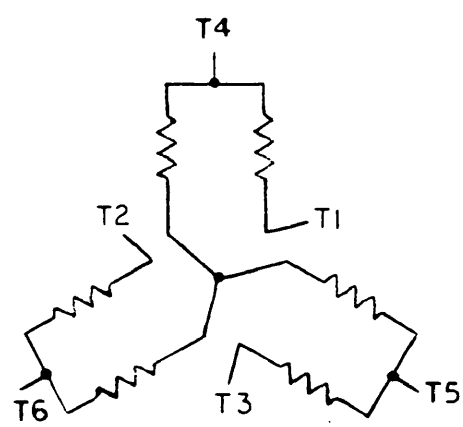


Figure 22. External Connection for Variable Torque Motor.

2. The constant torque pole-changing motors

The load requires the same amount of torque at low speed as at high speed. Torque remains constant at both the low and the high speed, and the horsepower increases and decreases in direct proportion to the speed. This type is used in applications such as conveyors, and when shock loads, overloads or high inertia loads are encountered.

The Figure 23 shows the constant torque 3-phase 4P/8P motor internal connection diagram. Figure 24 shows the external connection of the motor.

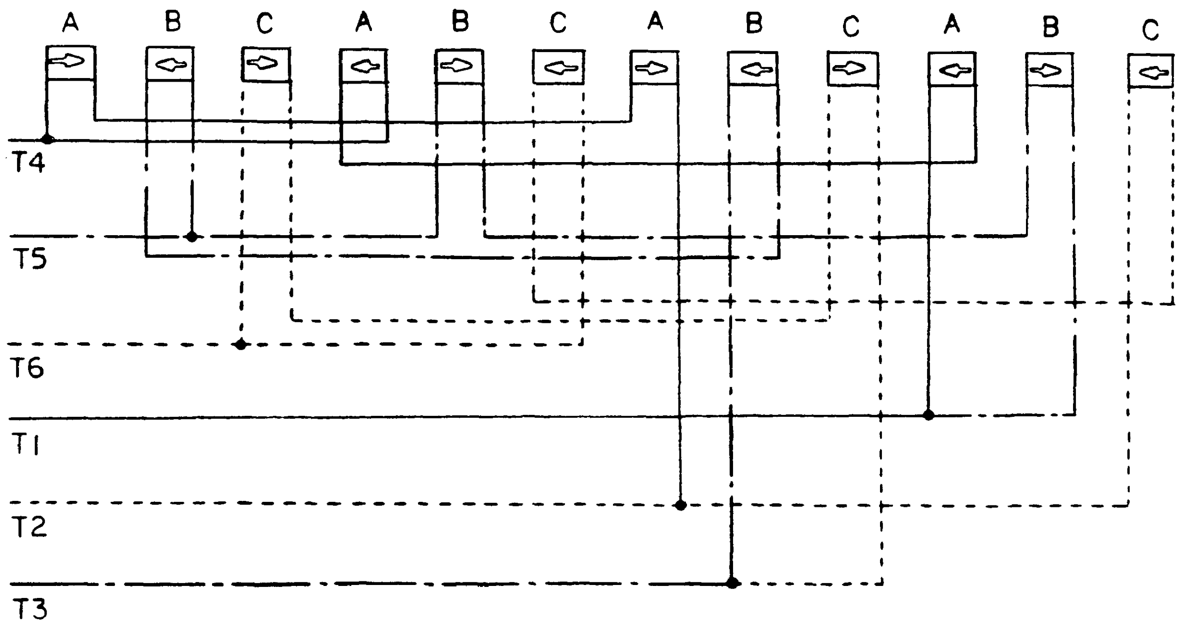


Figure 23. Internal Connection Diagram for Constant Torque Motor.

Speeds	Power Line			Connections	
	L1	L2	L3		
Low (8P)	T1	T2	T3	T4,T5,T6 Open	1Δ
High (4P)	T4	T5	T6	T1-T2-T3 Conn.	2Y

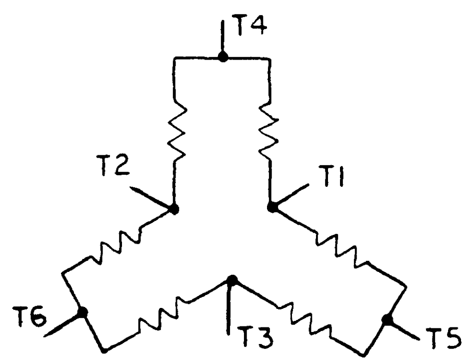


Figure 24. External Connection for Constant Torque Motor.

3. The constant horsepower pole-changing motors

Load requires high torque at low speed, low torque at high speed, and thus constant horsepower at both low and high speed. This type is used in applications such as lathes requiring low speed for deep cuts and high speed for finishing. Usually very high starting torques are required.

The Figure 25 shows the constant horsepower 3-phase 4P/8P motor internal connection diagram. Figure 26 shows the external connection of the motor.

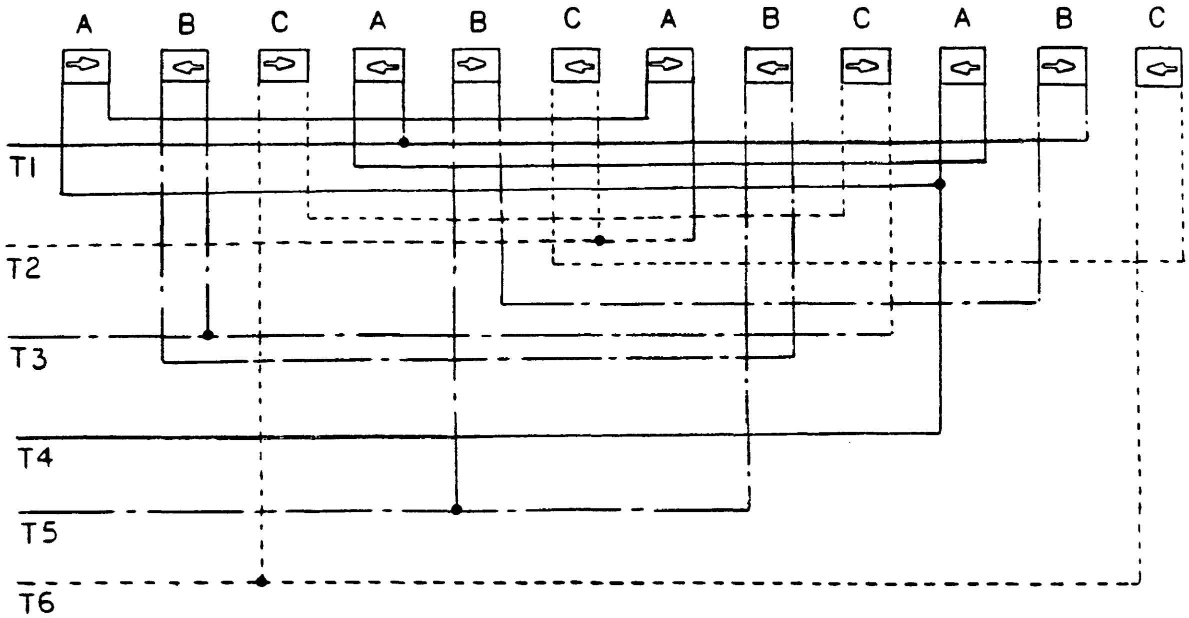


Figure 25. Internal Connection Diagram for Constant Horsepower Motor.

Speeds	Power Line			Connections	
	L1	L2	L3		
Low (8P)	T4	T5	T6	T1-T2-T3 Conn.	2Y
High (4P)	T1	T2	T3	T4,T5,T6 Open.	1△

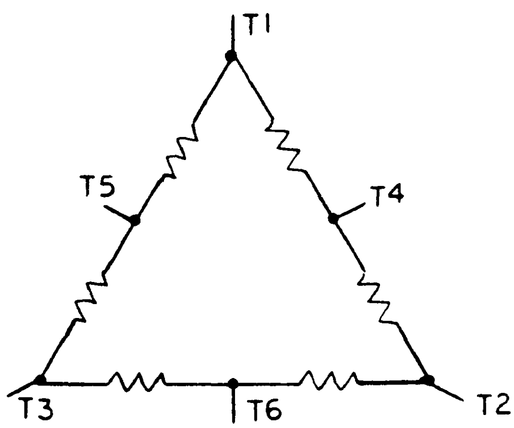


Figure 26. External Connection for Constant Horsepower Motor.

Figure 27 shows the control diagram of the variable torque pole-changing motor used in air cooler fan. In summer the temperature of cooling water is high, and one can select fast speed (4P-200HP). In winter the temperature of cooling water is low, and one can select low speed (8P-50HP). The pole-changing motor presents one way of saving energy.

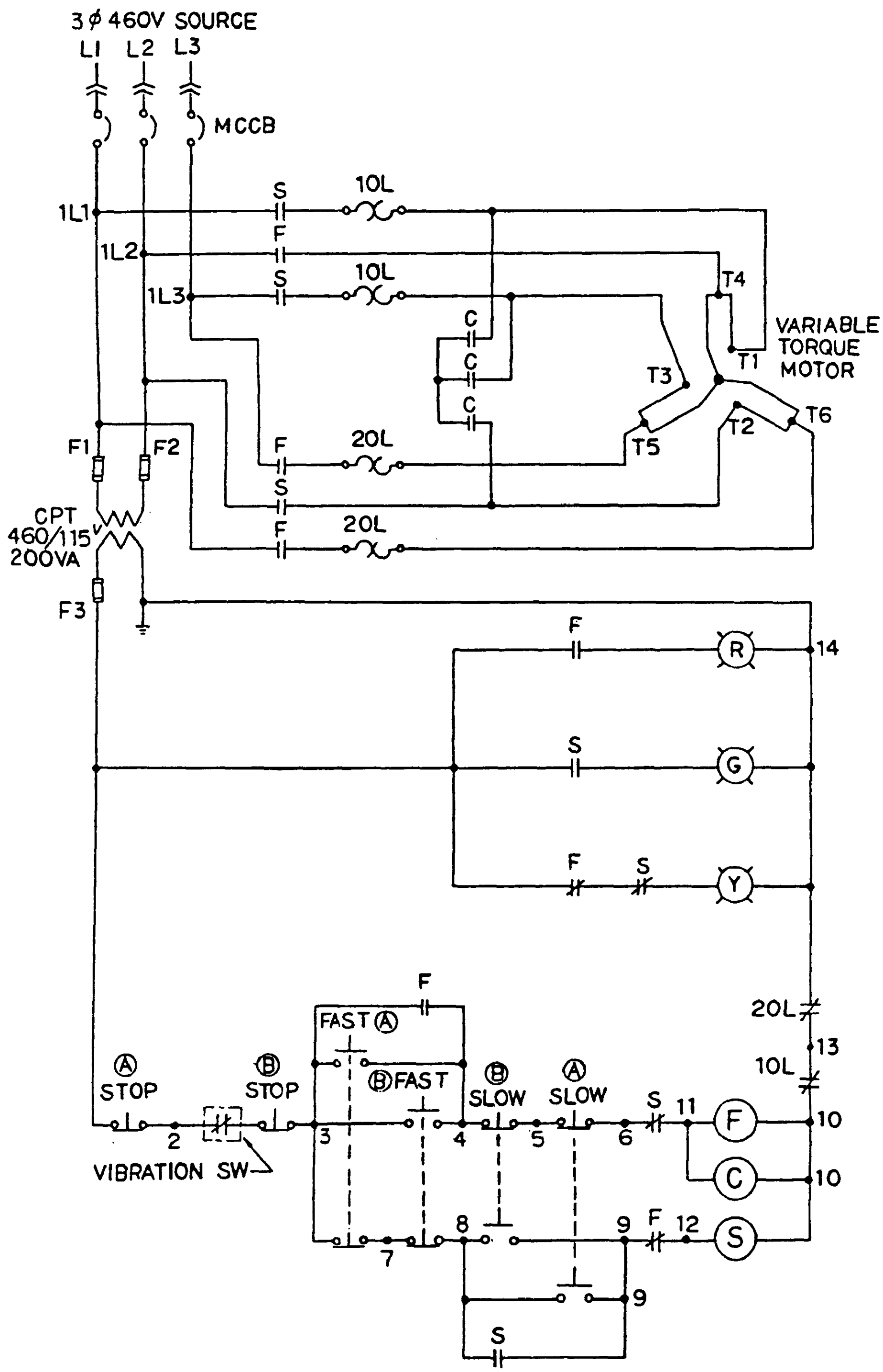


Figure 27. Control Diagram for Pole-Changing Motor.

6. FUTURE DEVELOPMENTS AND RECOMMENDATIONS

How to keep the motors in good operating condition is one of the operator's main tasks. What operators can do now is to enhance walk-through check (items listed below). In the future, technology developments will enable operators to monitor the currents, vibrations, temperatures, and noise levels of motors in the control room. This data will be displayed on a computer screen. Meanwhile, one kind of monitor called MOTOR MONITOR will be installed in the control room. This monitor will continually check the motors while they are operating. The monitor will alarm the operator when one of the operating parameters exceeds its preset value. Hence, the status of the motor's operating conditions will be monitored and can be read any time.

For motor control systems, programmable logic controllers will be used widely. Dual redundancy and triple modular redundancy systems will keep the critical control systems from mistripping.

6.1 <u>Preventive Maintenance for Motor Equipment</u>

Preventive maintenances for motor equipment are very important in refineries. The motor equipment includes motors, MCC's, power cables, and control cables. Recommended preventive maintenance schemes are discussed below:

a. PLC auto-control of the operating hours

The operating hours of the motors can be calculated by Programmable Logic Controllers (PLC) through the auxiliary contact of a magnetic switch in the MCC. The PLC computer prompts preventive maintenance items when the operating hours exceed preset levels. For example, lubrication level is 2160 hours and renew bearings is 4320 hours for the 100HP 2-pole motor.

b. Items for routine check - once for every half year.

1. Internal cleaning and visual inspection.
2. Electrical connections and terminal inspection.
3. Indication lamps verification.
4. Insulation test for each motor, power cable, and control cable.

c. Items for walk through check - once for every two hours.

1. Oil level for lubrication:

   Oil for 2P motors - R32 (SAE 10)

   Oil for 4P motors - R68 (SAE 20)

2. Temperature inspection:

   Maximum temperature rises of the motors are according to the insulation class of the motors.

   E class - 70°C, B class - 75°C

   F class - 100°C, H class - 125°C

3. Vibration analysis:

   Measure the vibration velocity and displacement with a vibration instrument. The tolerances of the vibration velocity and displacement are as follows:

   Vibration velocity - below 8 mm/sec

   Vibration displacement:

   2P motors - below 25 μm (10^{-6} m)

   4P motors - below 38 μm (10^{-6} m)

   others - below 50 μm (10^{-6} m)

4. Bearing noise assessment:

   If some noise is heard and different from usual smooth sound. Maybe, the bearing is short of lube grease or the bearing is going to damage.

5. Test running, once a week, for stand-by motors to ensure that they are operating satisfactorily.

6.2 Power Disturbance Detector

An electrical disturbance leading to a power outage can be costly and disruptive to all refinery operations. Information is needed to restore power as quickly as possible to minimize revenue losses, damage to equipment, and possible injury to personnel or the public. For these reasons many industrial companies and refineries utilize modern transient fault recorders to monitor their systems.

Transient recorders continuously gather data on the electrical power system. They monitor the voltage and current on main power lines, along with the status of relays and breakers. When a fault occurs, the transient recorder triggers and records the disturbance and a specified amount of prefault data into memory. The data can be printed out automatically and/or transferred to a computer to identify how lines and breakers performed during the fault. A variety of different menu-drive software packages display the fault on the computer screen and display instantaneous voltage, current, MWatts and MVars, power factor, harmonics and other key parameters.

Time is critical during an outage. A transient recorder permits a quick determination of what caused the event and what specific equipment (circuit breaker, relay) may have failed. Fault analysis provides data on the performance of protective relays, saving valuable time physically searching for damaged equipment. The fault current magnitude and duration through breakers and power transformers is readily available.

Transient recorders prove to be even more valuable when a power outage is caused by equipment malfunction or human error and not by actual fault conditions. Analysis of the fault data can verify that a real fault did not occur, permitting power to be restored promptly. Without such transient recorder fault data, it may take hours or days of physical inspection to determine the exact cause and restore power with full confidence that another more serious fault will not result.

6.3 Uninterruptible Power Supply (UPS)

Uninterruptible power supplies (UPS) provide high quality power that is free from disturbances. In general, the UPS consists of five modular power sub-assemblies:

- 1 rectifier/charger,
- 1 battery bank,
- 1 three-phase inverter,
- 1 static switch,
- 1 mechanical maintenance by-pass.

The operating principle of UPS is discussed below:

a. Mains available

Figure 28 shows the one-line diagram when the mains power is available. The load is supplied by the inverter via rectifier/charger without direct connection to mains. The battery bank is in a charging (floating) condition.

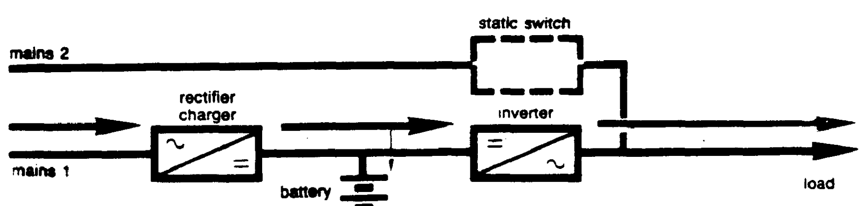


Figure 28. One-Line Diagram for UPS (Mains Available).

b. Mains down

Figure 29 shows the one-line diagram when the mains power is down. The load is supplied by the inverter from the battery power. The battery is in a discharging condition.

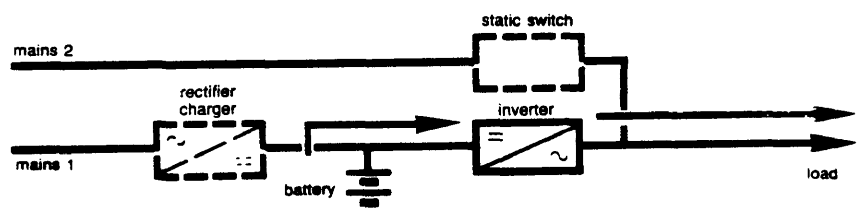


Figure 29. One-Line Diagram for UPS (Mains Down).

c. Major overload

Figure 30 shows the one-line diagram when there is a major overload. The overload is supplied by mains power via the static switch. The transfer speed is within 0.5 milliseconds and without disturbance to the load. The inverter is in an off condition. The inverter will restart automatically as soon as the overload regresses. A similar operating condition prevails when the inverter malfunctions.

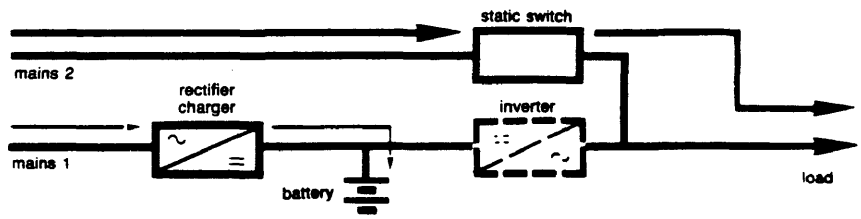


Figure 30. One-Line Diagram for UPS (Major Overload).

d. Maintenance

Figure 31 shows the one-line diagram when the UPS is in maintenance. The load is supplied by mains power via maintenance the by-pass. The rectifier/charger and inverter are off and isolated.

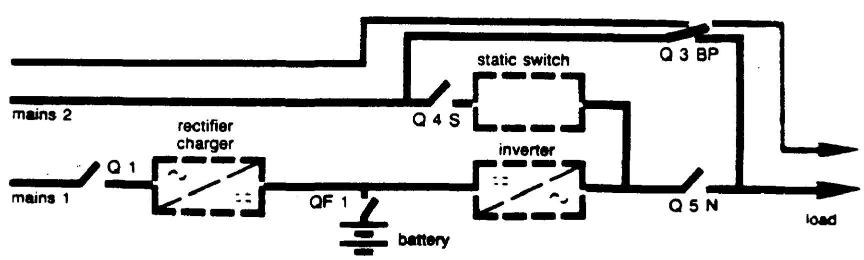


Figure 31. One-Line Diagram for UPS (Maintenance).

7. CONCLUSIONS

7.1 Critique of The State-of-Art

Progress in high technologies is yielding high quality materials and electronic auto-control devices. For example, the new technologies of vacuum pressure impregnation (VPI) and thermalastic epoxy insulation are now used for motor windings. Also, an integrated protection relay provides multifunction protection of 3 phase AC motors. The electronic devices are compact, precise, and save much space, but they are so sensitive that they must be installed in an air condition room with humidity control and must have good air quality to keep them from being contaminated.
For example, in the Kaohsiung Refinery, the electronic protection and control systems are installed in the control room. Due to the bad air quality, high humidity and high percentage of SO_2, the printed circuit boards are contaminated and cause mistripping. Each mistripping may cost 400,000 dollars. Hence, the air purity devices and humidity controllers must be installed to ensure good air quality. The associated costs for air purity devices and humidity controllers are about 50,000 dollars.

7.2 Speculation on Future System

7.2.1 Smart Motor Controller

Smart motor controllers provide microcomputer controlled starting for standard three-phase squirrel cage induction motors. The following operating functions are available for these kinds of controllers.

a. Soft start

The motor voltage is gradually increased during the acceleration ramp period, which can be adjusted from 2 to 30 seconds. To ensure the best starting performance, we can adjust the settings over the required load range.

b. Soft stop

This function can be used on applications which require an extended coast to rest. The voltage ramp down time can be set from 2 to 60 seconds. The load will stop when the motor voltage drops to a point where the load torque is greater than the motor torque.

c. Pump control

This function is used to reduce surges in a pumping system during starting and stopping of a centrifugal pump by smoothly accelerating and decelerating the motor at a selectable rate. The microcomputer analyzes the motor variables and generates commands which control the motor to reduce the possibility of surges occurring in the system.

The starting time is adjustable from 2 to 30 seconds and the stopping time is adjustable from 2 to 120 seconds.

7.2.2 On-Line Insulation Monitors

It is now possible to have real time warning of deteriorating insulation because on-line insulation monitors can continually check the circuits while they are in operation. Hence, advanced warning of deteriorating electrical insulation without shutdown can be detected with no compromise of personnel or equipment safety.

On-line insulation monitors continually measure the leakage to ground of a known DC signal carried on the electrical circuit to be monitored. The less than one joule energy level of the signal is low enough not to be a threat to system wiring or personnel. This kind of monitoring technique allows detection of much smaller faults than possible by conventional means.

On-line insulation monitors have the following advantages:

1. Reduce unscheduled downtime.

2. Reduce risk of electrical failure, shock, and fire.

REFERENCES

1. A. E. Fitzgerald, Charles Kingsley, Jr. Stephen D. Umans "Electric Machinery" McGraw-Hill Book Company Inc. 1983.

2. Charles S. Siskind "Induction Motors" McGraw-Hill Book Company Inc. 1958.

3. C. Russell Mason "The Art and Science of Protective Relaying". John Wiley & Sons, New York 1956.

4. Irving L. Kosow "Control of Electric Machines" Prentice-Hall, Inc. 1973.

5. Richard A. Pearman "Power Electronics Solid State Motor Control". Reston Publishing Company, Inc. 1980.

6. JIS C-4003 & C-4004. "Classification of Materials for Insulation of Electrical Machinery and Apparatus" & "Limits of Temperature Rise".

7. NEC 500-3, 500-5, 500-6, 500-7. "Classification of Hazardous Atmospheres" & "Definition of Hazardous Locations".

8. NEMA Standard "According to Electrical Type, Mechanical Protection, and Method of Cooling" & "Classification of Insulation systems".

9. Limitorque Inc. Instructions for "Motor Operated Valve Control".

10. OMRON Catalog "Fundamentals of Stationery Type Motor Relay" & "Motor Protective Relay".

11. General Electric Company Instructions "Equipment Protection for AC Rotating Machines".

12. Westinghouse Electric Corporation Instructions "Type COV Voltage Controlled Overcurrent Relay".

13. Mitsubishi Electric Corporation Instruction "Type CV-8 Overvoltage Relay".

14. General Electric Instruction (GEI-70540B) "Rotating Brushless Exciters for Synchronous Machines".

15. Westinghouse Motor Company Catalog "Synchronous Motors" Round Rock, Texas.

16. STROMBERG Catalog "SPEM Motor Protection Relay".

17. Westinghouse Electric Corporation Product Bulletin 41-155. "Type MPR Motor Protective Relay" August 1985.

18. Compagnie Continentale d'Equipements Electriques Instruction "Serie IMM7900 Digital Multi-function Motor Protection Relays".

19. Emerson Industrial Controls Catalog "Accuspede-5100 Adjustable Frequency AC Drive Controller".

20. Rochester Instrument System Application Bulletin "Improved Electric Power Reliability for Industrial Facilities".

21. Merlin Gerin Catalog "EPS-2000 Three-Phase UPS From 10 to 80KVA".

22. Rochester Instrument System Catalog "New FM-100 Fault Monitor".

23. Allen-Bradley Product Data Bulletin 150 "SMC Plus Smart Motor Controller".

24. Allen-Bradley Bulletin 1334 "Industrial AC Drives".

25. AEG Modicon Catalog "Redundancy Systems for Critical Applications". Modicon, Inc., Industrial Automation Systems. One High Street, North Andover, MA 01845.

26. Rochester Instrument System (RIS) Application Bulletin "Machine Monitors".

27. Alsthom Delle-Alsthom Catalog "SF_6 Circuit Breakers Types FP61 &FP62".

28. Toshiba Catalog "SF_6 Gas Insulated Switchgear".

29. Yaskwa Catalog "Magnetic Contactors, SF_6 Gas Fluopac Series".

30. RIS Product Data Bulletin "Temperature/Process Monitors".

31. RIS Catalog "RIS Series VT-2490 Machine Monitoring".