
Electrical Engineering Fundamentals: *Motors, Generators & Power Distribution*

Course No: E08-003

Credit: 8 PDH

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**Electrical Engineering Fundamentals:
Electrical Equipment, Electric Motors,
Generators, Power Quality and Power
Distribution ©**

By

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**Electrical Engineering for Non-Electrical Engineers
Series**

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Preface

Many Non-engineering professionals as well as engineers who are not electrical engineers tend to have a phobia related to electrical engineering. One reason for this apprehensiveness about electrical engineering is due to the fact that electrical engineering is premised concepts, methods and mathematical techniques that are somewhat more abstract than those employed in other disciplines, such as civil, mechanical, environmental and industrial engineering. Yet, because of the prevalence and ubiquitous nature of the electrical equipment, appliances, and the role electricity plays in our daily lives, the non-electrical professionals find themselves interfacing with systems and dealing with matters that broach into the electrical realm. Therein rests the purpose and objective of this text.

This text is designed to serve as a resource for exploring and understanding basic electrical engineering concepts, principles, analytical strategies and mathematical strategies.

If your objective as a reader is limited to the acquisition of basic knowledge in electrical engineering, then the material in this text should suffice. If, however, the reader wishes to progress their electrical engineering knowledge to intermediate or advanced level, this text could serve as a useful platform.

As the adage goes, “a picture is worth a thousand words;” this text maximizes the utilization of diagram, graphs, pictures and flow charts to facilitate quick and effective comprehension of the concepts of electrical engineering.

In this text, the study of electrical engineering concepts, principles and analysis techniques is made relatively easy for the reader by inclusion of most of the reference data, in form of excerpts from different parts of the text, within the discussion of each case study, exercise and self-assessment problem solutions. This is in an effort to facilitate quick study and comprehension of the material without repetitive search for reference data in other parts of the text.

Due to the level of explanation and detail included for most electrical engineering concepts, principles, computational techniques and analyses methods, this text is a tool for those engineers and non-engineers, who are not current on the subject of electrical engineering.

The solutions for end of the segment self-assessment problems are explained in just as much detail as the case studies and sample problem in the pertaining segments. This approach has been adopted so that this text can serve as an electrical engineering skill building resource for engineers of all disciplines. Since all segments and topics begin with the introduction of important fundamental concepts and principles, this text can serve as a “brush-up,” refresher or review tool for even electrical engineers whose current area of engineering specialty does not afford them the opportunity to keep their electrical engineering knowledge current.

In an effort to clarify some of the electrical engineering concepts effectively for energy engineers whose engineering education focus does not include electrical engineering, analogies are drawn from non-electrical engineering realms, on certain complex topics, to facilitate comprehension of the relatively abstract electrical engineering concepts and principles.

Each segment in this text concludes with a list of questions or problems, for self-assessment, skill building and knowledge affirmation purposes. The reader is encouraged to attempt these problems and questions. The answers and solutions, for the questions and problems, are included under Appendix A of this text.

Most engineers understand the role units play in definition and verification of the engineering concepts, principles, equations, and analytical techniques. Therefore, most electrical engineering concepts, principles and computational procedures covered in this text are punctuated with proper units. In addition, for the reader’s convenience, units for commonly used electrical engineering entities, and some conversion factors are listed under Appendix C.

Most electrical engineering concepts, principles, tables, graphs, and computational procedures covered in this text are premised on SI/Metric Units. However, US/Imperial Units are utilized where appropriate and conventional. When the problems or numerical analysis are based on only one of the two unit systems, the given data and the final results can – in most cases

- be transformed into the desired unit system through the use of unit conversion factors in Appendix B.

Some of the Greek symbols, used in the realm of electrical engineering, are listed in Appendix C, for reference.

What readers can gain from this text:

- Better understanding of electrical engineering terms, concepts, principles, laws, analysis methods, solution strategies and computational techniques.
- Greater confidence in interactions with electrical engineering design engineers, electricians, controls engineers and electrical engineering experts.
- A number of skills necessary for succeeding in electrical engineering portion of various certification and licensure exams, i.e. CEM, Certified Energy Manager, FE, Fundamentals of Engineering (also known as EIT, or Engineer in Training), PE, Professional Engineering and many other trade certification tests.
- A better understanding of the many electrical engineering components of energy projects.
- Better understanding of illumination principles and concepts, and an appreciation of efficient lighting/illumination design

An epistemic advice to the reader: if you don't understand some of the abstract concepts the first time, don't give up. Read it again! Such is the nature, intrigue and challenge of engineering, physics, science and other subjects that require thinking, reflection and rumination.

Segment 1

Load factor, service factor and voltage regulation

Introduction to the concept of load factor, its role in power quality considerations and electrical energy cost reduction through peak shaving. Significance of electrical equipment service factor and voltage regulation of power distribution systems. Electric power bill calculation in residential, commercial and industrial arena.

Segment 2

Electric motors and generators

Introduction to DC and AC motors and generators. Basic principles and equations governing the operation and performance of electric motors. Common calculations involving electric motors. Concept of induction motor slip. Roles that slip and frequency play in determination of the motor shaft speed. Motor classifications.

Segment 3

Power distribution equipment, instrumentation and electronic safety devices

An exploratory tour of power distribution and safety equipment is conducted through the review of motor control center (MCC), power switchgear, electronic safety devices and variable frequency drives (VFD). Pictures and diagrams are used in this discussion to give the reader a “hands- on” feel of common electrical and electronic equipment.

Appendix A

Solutions for self-assessment problems

Appendix B

Common units and unit conversion factors

Appendix C

Greek symbols commonly used in electrical engineering

Segment 1

Demand, Load Factor, Service Factor and Electrical Power Bill Computation

Introduction

In this short segment we will begin with the discussion on fundamental concepts of electrical demand and peak demand. Introduction to the concepts of demand and peak demand should poise us well for investigation of the concept of load factor, its role in power quality considerations and electrical energy cost reduction through peak shaving. Later in the segment, we will explain the concept of service factor as it applies to electrical equipment. This segment concludes with discussion and analysis of large industrial power bill computation. The bill calculation examples are designed to help the reader develop skills and acumen to analyze and understand important components of large power bills, in their efforts to identify cost reduction opportunities. As with other electrical concepts presented in this text, we will substantiate our discussion with analogies, mathematical and analytical models, as applicable.

Demand

In the electrical power distribution and energy realms, generally, the term “demand” implies electrical power demanded by electrical loads. The term “power” could be construed as *apparent power*, **S**, measured in VA, kVA, MVA, etc., or it could be interpreted as real power, **P**, measured in W, kW, MW, etc. Many electrical power utilities tend to apply the term *demand* in the context of *real power*, **P**, demanded from the grid. However, some electrical power utilities use the term demand to signify *apparent power* demanded from the grid, measured in kVA. When demand is known to represent real power in kW’s or MW’s, average demand is computed in accordance with Eq. 1.1.

Average Demand, in kW

$$= \frac{\text{Energy (kWh or MWh) consumed during the billing Month}}{\text{Total number of hours in the month}}$$

Eq. 1.1

Peak demand

The term peak demand has two common or mainstream interpretations. The first interpretation is associated, mostly, with electrical power load profiling, such as the real power, P (kW), load profile or graph included among the various power monitoring screens available through EMS, Energy Monitoring Systems¹, or BMS, Building Management Systems. The graph in Figure 1.1 is a screen capture of load profile screen in an EMS system. The graph depicts a plot of real power load (in kW's) plotted as a function of time. The darker line spanning from the left to right in the graph represents the ***actual power demand (in kW)***, recorded by the hour, over a 24 hour period. The lighter line in the graph represents ***demand forecasted*** on the basis of the actual load profile measured and recorded by the EMS system, over the long term. The forecasted demand plays an essential role in energy conservation related peak shaving programs¹. As obvious, demand forecast premised on actual, measured, load profile - for a specific facility - would tend to be more reliable than general load profiles based on theoretical models. This constitutes an important justification for EMS systems.

The second interpretation of the term peak demand is associated more directly with the computation of electrical power bills for large industrial and commercial consumers of electricity. The peak demand, in the billing context, is computed by most power companies on the basis of demand intervals.

Some utilities (power companies) base their peak demand computation on the basis of 30 minute intervals and others base the demand computation on the basis of 15 minute intervals. We will limit our consideration of the peak demand interval to 30 minute intervals.

Under one of the more common large power consumer contract rate schedules, referred to as the OPT, Time of the Day, or Time of Use Rate Schedule, the power company captures and records the energy consumed by the consumer, in kWh, over half hour intervals. Each energy data point thus captured is converted to the corresponding demand value, in kW, as stated under Eq. 1.2.

¹ Finance and Accounting for Energy Engineers by S. Bobby Rauf

$$\text{Demand} = \text{Power in kW} = \frac{\text{Energy in kWh}}{\text{Time in Hours}} = \frac{\text{Energy in kWh}}{\frac{1}{2} \text{ Hour}}$$

Eq. 1.2

This could amount to, approximately, 1440 data points for a 30 day billing month, with each data point representing the demand (kW) for a specific 30 minute interval during the billing month.

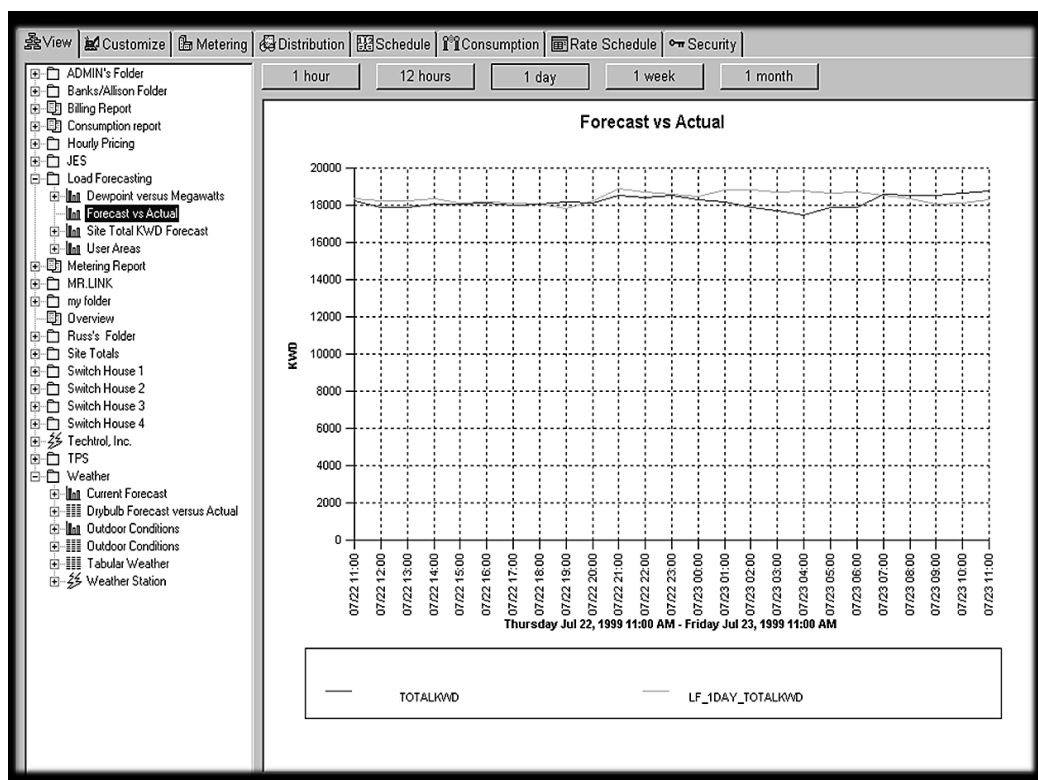


Figure 1.1: Actual vs. forecasted power demand (kW)

The utility provider (power company) selects the highest demand data point, during the declared “on-peak” periods and labels it **Peak Demand** for the month. See additional information on peak demand under the bill calculation section.

Load factor

The most common and general definition of load factor is that it is the ratio of *average power* to *peak demand*. This definition of load factor can be translated into the Eq. 1.3.

$$\text{Load Factor} = \frac{\text{Average Demand for the Month, in kW or MW}}{\text{Peak Demand for the Billing Month, in kW or MW}}$$

Eq. 1.3

Equation 1.3 can be modified to define load factor (LF) in terms of **Energy Usage (in kWh)** and **Demand (in kW)**.

$$\text{Load Factor} = \frac{(\text{kWh Used in the Billing Period})/(\text{Hrs in Billing Period})}{\text{Peak Demand in kW}}$$

Eq. 1.4

A closer look at Eq. 1.3 and Eq. 1.4 highlights the following facts:

- 1) High peak demands (large denominator) result in low load factors. Low load factors result in higher energy cost due to high peak demand and, often, due to low load factor triggered penalties.
- 2) Higher load factors signify better power management, better power quality, higher energy productivity and lower energy cost.
- 3) High load factor implies relatively leveled and controlled demand (kW), short peaks with low amplitude, accomplished in some cases through “peak shaving” and targeted peak avoidance.

A Load Factor of unity or “1” indicates that demand peaks are negligible resulting in steady and relatively leveled power (kW) demand. Since most facilities don't operate 24 hours a day, and since the demand (kW) varies during a 24 hour period and the billing month, load factor, similar to power factor, in most practical applications is usually less than one “1.”

Low load factor is a good indicator of the cost savings potential in shifting some electric loads to off-peak hours, thus reducing on-peak demand.

In a utopian situation, theoretically, if the load factor of a facility is already almost unity, further demand reduction can be accomplished through replacement of existing *low efficiency* equipment with *higher efficiency* equipment

Example 1.1

The EMS System at an automotive plastic component manufacturing plant that operates around the clock, 365 days a year, is displaying following electrical power data:

Billing Days in the Current Month: 30

On Peak Energy Consumption: 4,320,000 kWh

Off Peak Energy Consumption: 17,280,000 kWh

Highest 30 Minute Energy Recorded: 17,500 kWh

Calculate the following assuming that this facility is on OPT, Time of Use contract with a 30 minute demand interval:

- (a) Average demand.
- (b) Peak demand.
- (c) The load factor for the current month.

Solution:

(a) Average demand can be calculated by applying Eq. 1.1 as follows:

Average Demand, in kW

$$\begin{aligned} &= \frac{\text{Energy (kWh or MWh) consumed during the billing Month}}{\text{Total number of hours in the billing month}} \\ &= \frac{\text{On Peak Energy} + \text{Off Peak Energy Consumption}}{\text{Total number of hours in the billing month}} \\ &= \frac{4,320,000 \text{ kWh} + 17,280,000 \text{ kWh}}{(24 \text{ hrs/Day}) \cdot (30 \text{ Days/Month})} \\ &= 30,000 \text{ kW or } 30 \text{ MW} \end{aligned}$$

(b) Peak Demand can be calculated by applying Eq. 1.2 to the 30 minute interval during which the highest energy consumption is recorded:

$$\begin{aligned}\text{Demand} = \text{Power in kW} &= \frac{\text{Energy in kWh}}{\text{Time in hours}} = \frac{\text{Energy in kWh}}{\frac{1}{2} \text{ hour}} \\ &= \frac{17,500 \text{ kWh}}{0.5 \text{ h}} = 35,000 \text{ kW or } 35 \text{ MW}\end{aligned}$$

(c) Load factor can be calculated by applying Eq. 1.3 as follows:

$$\text{Load Factor} = \frac{\text{Average Demand for the Month, in kW or MW}}{\text{Peak Demand for the Billing Month, in kW or MW}}$$

Using the Average Demand, calculated in part (a) as 30 MW, and the Peak Demand calculated in part (b) as 35 MW:

$$\text{Load Factor} = \frac{30 \text{ MW}}{35 \text{ MW}} = 0.8571 \text{ or } 85.71\%$$

Service Factor

Service factor of electrical equipment such as motors, transformers, switchgear, etc. can be defined as the ratio of load the equipment can sustain continuously and the load rating of that equipment. Another way to view service factor is that it is a ratio of “safe” operating load to standard (nameplate) load. The service factor is typically expressed as a decimal. Occasionally, the decimal value of the load factor is presented in a percentage form. The formula for the service factor is stated as Eq. 1.5 below.

$$\text{Service Factor} = \frac{\text{Safe or Continuous Load, in kW, kVA or hp}}{\text{Nameplate rating of equipment, in kW, kVA or hp}}$$

Eq. 1.5

Example 1.2

A 20hp motor has been tested by a motor manufacturer to safely and continuously sustain a load of 25hp. What service factor should the manufacturer include on the nameplate of the motor?

$$\begin{aligned} \text{Service Factor} &= \frac{\text{Safe or Continuous Load, in kW, kVA or hp}}{\text{Nameplate rating of equipment, in kW, kVA or hp}} \\ &= \frac{\text{Safe Operating Load}}{\text{Full Load Rating of the Motor}} = \frac{25 \text{ hp}}{20 \text{ hp}} = 1.25 \end{aligned}$$

Electrical bill calculation for large electrical power consumers is different and more complex than the assessment of monthly residential bills. As supported by the electric bill shown in Figure 1.2, residential electrical bill of an average size American home in the Southeast can be calculated using Eq. 1.6.

Service From: FEB 26 to MAR 26 (28 Days)			Your next scheduled meter reading will occur between APR 26 and MAY 01		
PREVIOUS BILL AMOUNT	PAYMENTS (-)	NEW CHARGES (+)	ADJUSTMENTS (+ OR -)	AMOUNT DUE (=)	
\$51.94	\$51.94	\$47.35	\$0.00	\$47.35	
METER NUMBER	METER READINGS: PREVIOUS PRESENT	MULTI- PLIER	TOTAL USAGE	RATE SCHEDULE DESCRIPTION	AMOUNT
431400	84552 84938	1	386 KWH	RS - Residential Service Renewable Energy Rider Sales Tax	45.75 .22 1.38
Amount Due					47.35
To be drafted on or after					Apr 06 , 2013

$$\text{Baseline Charge} = (\text{Present Reading} - \text{Prev. Reading}).(\text{Rate in \$/kWh})$$

Eq. 1.6

$$\text{Total Bill} = \text{Baseline Charge} + \text{Special Riders} + \text{Taxes} \quad \text{Eq. 1.7}$$

Example 1.3

If the “present reading” in the residential bill depicted in Figure 1.2 was 85,552, what would be the baseline bill for the month? The energy cost rate for this property remains unchanged at ¢11.9/kWh. (**Hint:** The baseline charge does not include riders or taxes.)

Solution:

According to Eq. 1.6,

$$\begin{aligned}\text{Baseline Charge} &= (85552 - 84552) \cdot (\$0.119 / \text{kWh}) \\ &= (1000) \cdot (\$0.119 / \text{kWh}) = \$119\end{aligned}$$

Case Study 1.1: EMS Based Electrical Power Bill - Large Industrial Power Consumer¹

This case study is modeled on a scenario with large industrial customer in the southeastern region of the United States. The rates in \$/kW or \$/kWh and the fixed charges are assumed to represent that time frame, during non-summer months. This consumer is assumed to have a 45 MW (megawatt) contract with the power company. This facility is a 24/7,365 day operation and a significant portion of its load can be shifted from on-peak periods to off-peak periods, during its daily operations. This overall service contract of 45 MW is split into the following two components:

- A. A 30 MW, uninterruptible, power service, on OPT, Time of Use Schedule.
- B. A 15 MW, HP, Hourly Pricing Schedule. This schedule applies to incremental, interruptible, load and was offered to this customer as a part of DSM (Demand Side Management) program.

The monthly electrical bill computation for this facility is performed automatically by an existing EMS, Energy Monitoring System. A screen print of one such bill is shown in Figure 1.3.

The calculation methods associated with the various line items in this bill are explained through a specific bill calculation scenario described and analyzed in Case Study 1.2.

- HMLS - playground - HOURLY PRICING - SITE TOTALS - UTILITIES - CHILLERS - COMPRESSORS - GRU - PNG - POWER BILL - Power Bill HP - Power Bill OPT - WTP - WEATHER	
BASELINE BILLING DETERMINANTS	
BILLING DEMAND	25,994 KW
ON-PEAK BILLING DEMAND	25,994 KW
ON-PEAK ENERGY	3,696,021 KWH
OFF-PEAK ENERGY	15,138,552 KWH
BASELINE CHARGES	
BASIC FACILITIES CHARGE	\$36.07
ON-PEAK BILLING DEMAND CHARGE	
FOR THE FIRST 2,000 KW	2,000 X (\$7.64 per KW) =
FOR THE NEXT 3,000 KW	3,000 X (\$6.54 per KW) =
FOR ALL OVER 5,000 KW	20,994 X (\$5.43 per KW) =
	\$15,280.00
	\$19,620.00
	\$113,997.42
ECONOMY DEMAND CHARGE	0 X (\$1.030000 per KW) =
ON-PEAK ENERGY CHARGE	3,696,021 X (\$0.042393 per KWH) =
OFF-PEAK ENERGY CHARGE	15,138,552 X (\$0.021039 per KWH) =
TOTAL BASELINE CHARGE	(\$0.033135 per KWH)
	\$624,082.83
HP BILLING DETERMINANTS	
ACTUAL DEMAND	39,132 KW
HP CHARGES	
INCREMENTAL DEMAND CHARGE	13,138 X (\$0.260000 per KW) =
NEW LOAD X AVG HOURLY PRICE	7,845,899 X (\$0.021672 per KWH) =
TOTAL HP CHARGE	(\$0.022107 per KWH)
	\$173,448.60
TOTAL CHARGE	(\$0.029892 per KWH)
	\$797,531.44

Figure 1.3: Industrial electrical power bill – EMS system based.

Case Study 1.2 - Electrical Power Baseline Parameters and Bill Calculation - Large Industrial Power Consumer¹

In an effort to illustrate the interpretation and arithmetic behind the various components of an OPT based electrical power bill, let us consider data from a specific billing period, recorded and processed in Spreadsheet 1.1. This spreadsheet shows all of the pertinent measured data, derived billing parameters, standard charges, tiered demand charge rates, energy charge rates, and computed line item charges for the billing month. In the following sections we will highlight the arithmetic behind the derived or extended line item charges.

Baseline Billing Determinants: The on peak billing demand and the billing demand are typically the same. This segment of the bill represents derived and measured data. The measured portion is in the form of the energy consumption (kWh) measured in 15 or 30 minute intervals; which are then divided by 0.25 hour or 0.5 hour, respectively. This yields demand (kW) for each of the intervals for the entire billing month. The utility company then selects the highest of these demands – registered during the On-Peak periods - as the peak demand or billing demand for the month. The other billing determinants consist of the total energy usage during on-peak and off periods. The consumed energy data is in measured and recorded for the billing month, in kWh.

Basic Facilities Charge: This charge could be considered to represent administrative cost associated with the generation and processing of the bill. This charge stays relatively constant over time.

Extra Facilities Charge: This charge is a means for the utility to recoup its cost embedded in providing “extra facilities” to the customer. In this case study, the extra facilities consisted of a set of redundant transmission lines installed by the power company to enhance reliability of the power service to this customer. In some cases, this type of charge is associated with the upgrade of main switch yard step down transformers, regulators, separate metering, etc.

On-Peak Billing Demand Charge: The overall billing demand of 26,000 kW is tiered into three segments: first 2,000 kW, next 3,000 kW and the remaining

¹Finance and accounting for energy engineers, by S. Bobby Rauf
 21,000 kW. Each of these demand tiers are applied respective charges, in \$/kW, as shown in Spreadsheet 1.1, to yield tiered line item demand charges. These tiered line item demand charges are later added to other billing line item charges.

Economy Demand Charge: This charge is triggered when the highest integrated demand during off-peak periods exceeds the highest integrated demand recorded during the on-peak periods. The latter also serving as the peak demand for the billing month. When economy demand charge is triggered on the premise described above, the difference between the two demands is labeled as the economy demand. The economy demand figure thus derived is multiplied with the stated \$1.03 rate multiplier to compute the economy demand charge for the month. Since, in this case study, the peak demand is assumed to be greater than the demands set during the off-peak periods, economy demand is *not* triggered and, therefore, the economy demand charge is zero.

Description	Demand and Energy Parameters	Rates	Line Item Charge
Baseline Billing Determinants			
Billing Demand	26,000 kW		
On-Peak Billing Demand	26,000 kW		
On-Peak Energy Usage	4,334,573 kWh		
Off-Peak Energy Usage	14,500,000 kWh		
Baseline Charges			
Basic Facilities Charge		\$36.07	\$36.07

Extra Facilities Charge		\$13,000	\$13,000
On-Peak Billing Demand Charge			
For the First 2,000 kW	2,000 x	\$7.64 per kW =	\$15,280.00
For the Next 3,000 kW	3,000 x	\$6.54 per kW =	\$19,620.00
For Dem. Over 5,000 kW	21,000 x	\$5.43 per kW =	\$114,030
Economy Demand Charge	0 x	\$1.03 per kW =	\$0
On-Peak Energy Usage	4,334,573 x	\$0.042393 Per kWh =	\$183,755.55
Off-Peak Energy Usage	14,500,000 x	\$0.021039 Per kWh =	\$305,065.50
Total Baseline Charge		\$0.033135 Per kWh	\$650,787.12
HP Billing Determinants			
Actual Demand	40,000 kW		
HP Charges			
Incremental Demand Charge	14,000 kW x	\$0.26 / kW =	\$3,640.00
New Load x Avg. Hourly Price	8,805,800 x	\$0.021672 Per kWh =	\$190,839.30
HP Subtotal			\$194,479.3
Total Bill for the Month			\$845,266.42

Spreadsheet 1.1 – Large industrial electric bill calculation

Energy Charge: This charge accounts for the actual (measured) energy consumed during the billing month. This charge comprises of two components as shown in Spreadsheet 1.1: the on-peak energy charge and the off-peak energy charge. As apparent from examination of the spreadsheet, the on-peak rate (\$0.042/kWh) is almost twice the magnitude of the off-peak rate (\$0.021/kWh).

Total Baseline Charge: The total baseline charge is simply the sum of all line items calculated or identified to that point; \$650,787.12, in this case.

HP, Hourly Pricing and Billing Determinants: This portion of the bill represents the demand and energy charges associated with the load that fall under the Hourly Pricing contract. The hourly pricing demand was measured and billed at 14,000 kW, in this case. The energy consumed under the hourly pricing contract was 8,805,800 kWh.

HP Charges: Special HP rates are applied to the recorded demand and energy under HP contract, yielding respective line item charges as shown on Spreadsheet 1.1.

Total Bill for the Month: The last line of the bill represents the sum of Total Baseline Charge and the HP Charge, amounting to the total bill of **\$845,266.42** for the month.

Self-assessment Problems & Questions - Segment 1

1. The BMS System at a truck assembly plant, that operates 365 days a year, is displaying following electrical power and energy consumption data:

Billing Days in the Current Month: 30

On Peak Energy Consumption: 2,880,000 kWh

Off Peak Energy Consumption: 11,520,000 kWh

The three highest 30 minute energy usages for the billing month are:

- (i) 12,500 kWh
- (ii) 12,300 kWh
- (iii) 12,290 kWh

Assuming this facility is on OPT, Time of Use contract with a 30 minute demand interval, determine the following:

- (a) Average demand
- (b) Peak demand
- (c) The load factor for the current month
- (d) Average annual demand

2. A 200 kVA transformer has been tested by the manufacturer to safely and continuously sustain a load of 230 kVA. What service factor should the manufacturer include on the nameplate of this transformer?

3. A 5 hp single phase AC motor, rated at a service factor of 1.10, is being tested at maximum safe load, powered by 230 V_{AC} source. Determine the amount of current drawn by this motor from the power source if the motor efficiency is 90% and the power factor is 0.85.

4. Consecutive electrical power meter readings at a home in Hawaii are listed below:

- (a) Previous reading: 45,000

(b) Current or present reading: 46,000

Determine the total electrical power bill for the month of this residence if the flat \$/kWh cost rate is ¢ 21/kWh. The renewable energy rider is \$15 and the energy sales tax rate is 4%.

5. If the peak demand in Case Study 1.2 is reduced by 10% through the implementation of peak shaving measures, what would be the baseline cost for the demand portion of the bill?

Segment 2

Electric motors and generators

Introduction

Generators and motors are primarily rotating machines. The rotating machines are called ***motors*** when they ***consume*** electrical energy, and are referred to as ***generators*** when they ***produce*** electrical energy. In practical applications, while DC machines are almost always single phase, AC machines can be single phase or three phase. In this segment we will explore fundamental operating principles and concepts associated with DC and AC motors and generators. The electromagnetics principles behind the operation of generators and motors will be illustrated through simplified electrical diagrams. Basic principles and equations, governing important and practical functions and operational parameters of motors and generators, will be introduced. Common calculations involving electric motors will be illustrated. The concept of induction motor slip is explained and associated calculations are covered. Roles that slip and frequency play in determination of the motor shaft speed are illustrated through example problems. Significance of certain common classifications of motors is explained. Interpretation of a common motor nameplate is discussed.

DC Generator

A direct current generator, also referred to as a ***dynamo***, is an electromagnetic device designed to convert mechanical energy or mechanical power, namely brake horsepower, to electrical energy or electrical power. The electrical energy and power developed in DC dynamos consists of DC current and DC voltage. A DC generator is fundamentally an AC generator. The feature that differentiates a DC generator's function and output from an AC generator is a "commutator." A common commutator consists of two rings as shown in Figure 2.1. As depicted in Figure 2.1, the current, ***I*** and associated voltage are generated in the dynamo by virtue of the motion, movement or rotation of the coil windings within a magnetic field set up by permanent magnets or in some cases by "field windings." Of course, the rotation of the winding coils is caused by force, torque, work producing system or energy

source such as steam turbines, hydroelectric turbines, hydraulic pumps, etc. The end result is conversion of mechanical energy into electrical energy.

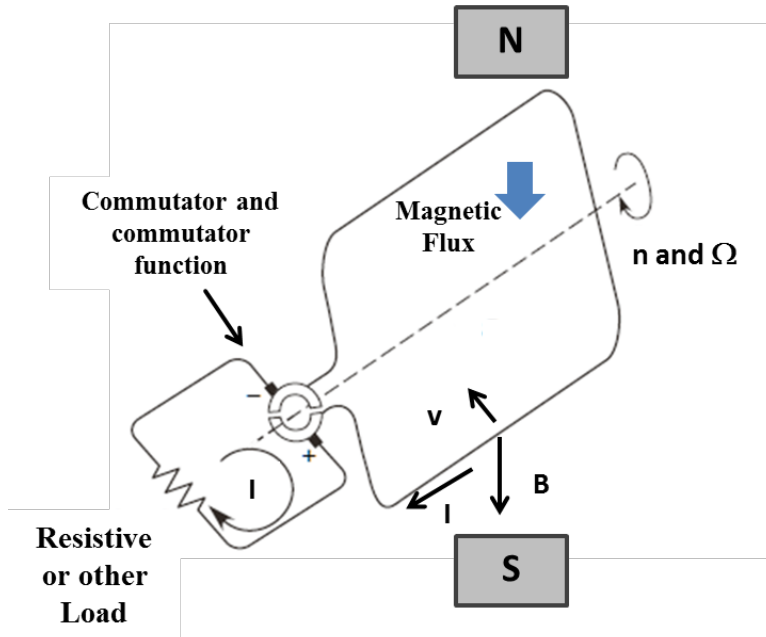


Figure 2.1: A DC Generator or Dynamo.

As shown in Figure 2.1 and as stipulated by Eq. 2.1, Eq. 2.2 and Eq. 2.3, key variables, the interaction of which, result in the production of voltage across the windings are:

- Magnetic flux density, **B**
- Number of turns, **N**, the coil consists of
- The area of cross-section, **A**
- The electrical frequency, **ω** , at which the armature is rotated by external work producing force
- Rotational speed of the armature, **Ω**
- The number of poles, **p**

$$V(t) = V_m \sin \omega t = \omega N A B \sin \omega t \quad \text{Eq. 2.1}$$

Voltage generated by the dynamo, or DC generator, can be expressed in terms of the rotational speed of the armature, Ω (in rads/sec), by applying the ω to Ω conversion formula expressed as Eq. 2.2.

$$\omega = \frac{p}{2} \Omega \quad \text{Eq. 2.2}$$

$$V(t) = \frac{p}{2} \Omega NAB \sin\left(\frac{p}{2} \Omega t\right) \quad \text{Eq. 2.3}$$

Since Ω (in rads/sec) is related to the RPM of the DC generator as stated in Eq. 2.4, Eq. 2.3 can be expanded in form of Eq. 2.5.

$$\Omega = \frac{2\pi n}{60} \quad \text{Eq. 2.4}$$

$$V(t) = \pi n \frac{p}{60} NAB \sin\left(\frac{p}{2} \Omega t\right) \quad \text{Eq. 2.5}$$

Since $V(t)$ represents the sinusoidal form of the voltage generated by the dynamo, to derive the magnitude of DC, work producing, effective or RMS portion of this voltage, we can equate the coefficient of the sinusoidal term in Eq. 2.5 to V_{peak} , V_{max} or, simply, V_p or V_m , and apply the “peak” to “RMS” conversion equation ($V_{\text{RMS}} = V_p/\sqrt{2}$). This yields Eq. 2.6 for computation of the DC voltage produced by a dynamo or DC generator.

$$V_{\text{DC}} = V_{\text{RMS}} = V_{\text{eff}} = \frac{V_p}{\sqrt{2}} = \left(\frac{\pi}{2}\right) \cdot \left(\frac{n}{30}\right) \cdot \frac{pNAB}{(\sqrt{2})} = \frac{\pi npNAB}{(60) \cdot (\sqrt{2})} \quad \text{Eq. 2.6}$$

Where,

$$V_m = V_p = \left(\frac{\pi}{2}\right) \cdot \left(\frac{n}{30}\right) \cdot pNAB = \frac{\pi npNAB}{60} \quad \text{Eq. 2.7}$$

And,

n = Rotational speed of the dynamo, in rpm

p = Number of poles in the design and construction of the armature. For instance, one coil or set of winding with N turns, consist of two (2) poles.

N = number of turns constituting an armature coil.

A = Cross-sectional area portended by the coil in m².

B = Magnet field intensity, in Tesla, or T.

Graphical depiction of the DC voltage computed through Eq. 2.7 is shown in Figure 2.2.

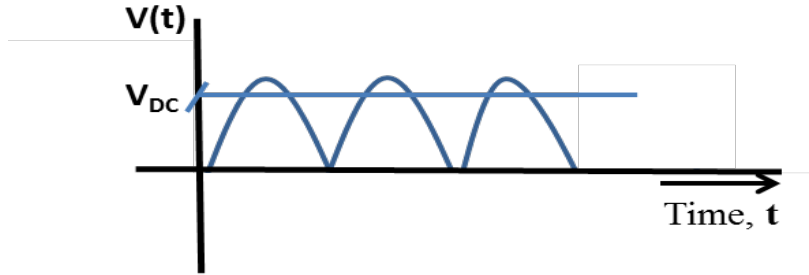


Figure 2.2: DC voltage output of a DC generator or dynamo

The relationship between the rotational speed of the generator, n_s , number of poles, p , the electrical frequency, f , and the angular speed, ω , corresponding to the electrical frequency, is given by Eq. 2.8 and Eq. 2.9.

$$n_s = \text{Synchronous speed} = \text{Rotational speed} = \frac{120f}{p} \quad \text{Eq. 2.8}$$

$$\omega = 2\pi f \quad \text{Eq. 2.9}$$

Example 2.1

The rotor of a single phase alternator is rotating at an actual mechanical rotational speed of 2400 rpm. The alternator consists of four pole construction. The effective diameter of the coil is 0.13m and the length of the coil loop is 0.22m. The coil consists of 20 turns. The magnetic flux density has been measured to be 1.15T. Calculate the RMS, effective, or V_{DC} produced by this generator.

Solution:

The RMS, effective or DC voltage produced through an alternator or generator can be computed by applying Eq. 2.6:

$$V_{DC} = V_{RMS} = V_{eff} = \frac{V_P}{\sqrt{2}} = \frac{\pi n p N A B}{(60) \cdot (\sqrt{2})}$$

Given:

$$n = 2400 \text{ rpm}$$

$$p = 4$$

$$N = 20$$

$$B = 1.15 \text{ T}$$

$$A = (\text{Eff. diameter of the coil conductor}) \times (\text{Eff. length of the coil}) \\ = (0.22\text{m}) \times (0.13\text{m}) = 0.0286\text{m}^2$$

$$V_{\text{DC}} = V_{\text{RMS}} = \frac{\pi n p N A B}{(60) \cdot (\sqrt{2})} \\ = \frac{(3.14)(2400\text{rpm})(4)(20)(0.0286\text{m}^2)(1.15\text{T})}{(60) \cdot (\sqrt{2})} = 233.7\text{V}$$

Example 2.2

A two pole alternator/generator is producing electrical power at an electrical frequency of 60 Hz. (a) Determine the angular speed corresponding to the generated electrical frequency. (b) Determine the rotational (synchronous) speed of the armature/rotor. (c) Determine the angular velocity of the armature/rotor, assuming slip = 0.

Solution:

(a) Angular speed, ω , corresponding to the generated electrical frequency, f , can be calculated using Eq. 2.9:

$$\omega = 2\pi f = (2) \cdot (3.14) \cdot (60\text{Hz}) = 377 \text{ rad/s}$$

(b) The rotational or synchronous speed of the armature/rotor is given by Eq. 2.8:

$$n_s = \frac{120f}{p} = \frac{(120)(60 \text{ Hz})}{2} = 3600 \text{ rpm}$$

(c) Angular velocity of the armature/rotor is simply the rotational speed, in rpm, converted into rad/s. Since there are 2π radians per revolution:

$$\omega_s = 3600 \text{ rev./min} = \left(\frac{3600 \text{ rev.}}{\text{min}} \right) \cdot \left(\frac{2\pi \text{ rad.}}{\text{rev.}(60\text{sec/min})} \right) = 377 \text{ rad/sec}$$

DC Motor

A DC motor can be perceived as a DC generator or dynamo operating in reverse. As in the case of a dynamo, a magnet - serving as a stator -

provides the magnetic field (**B** and **H**) that interacts with the DC current flowing through the rotor. The DC current flowing through the rotor windings is supplied from an external DC voltage or current source, via the commutator rings that are stationary. Basic construction of a DC motor is illustrated in Figure 2.3.

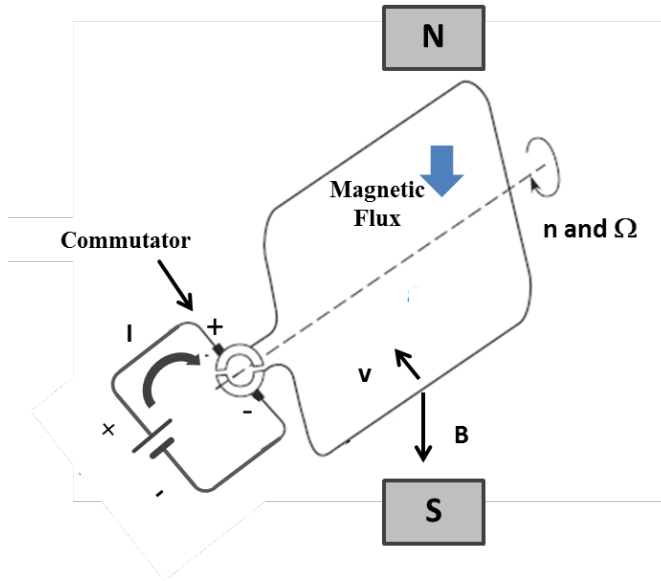


Figure 2.3: DC motor

In other words, a DC motor is a mechanically commutated electric motor powered from direct current (DC). The current in the rotor is switched by the commutator. The relative angle between the stator and rotor magnetic flux is maintained near 90 degrees, which generates the maximum torque.

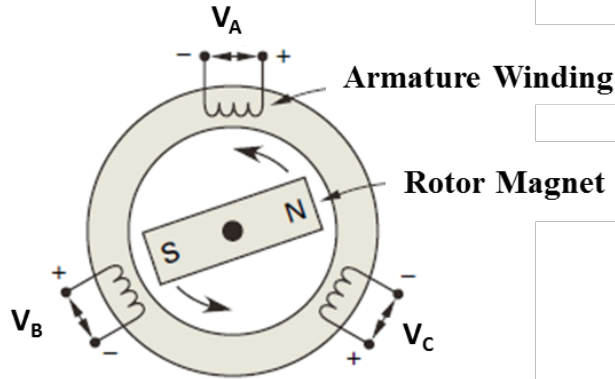
In DC motors, different connections of the field and armature winding provide different inherent speed/torque regulation characteristics. In so far as the control of the *speed of a DC motor* is concerned, it can be controlled by changing either the *voltage applied* to the armature or by changing the *field current*. Since voltage is related to current by Ohm's law, $V = I.R$, speed control can be accomplished through introduction of variable resistance in the armature circuit or field circuit. However, modern DC motors are often controlled by power electronics systems called DC drives.

Historically, the introduction of DC motors to run machinery eliminated the need for steam or internal combustion engines. Case in point, the application of DC motors as the motive power in locomotives. An advantage of DC motors is that they can be operated *directly* from DC power supply, with variable voltage, without the need for an inverter. This positions DC motors well for electric vehicles application. Despite the dominance of AC induction motors in myriad applications, DC motors continue to play an important role in providing motive power in small toys and disk drives. Overall, DC motors continue to provide an alternative to inverter driven AC motors where motor speed variation is needed.

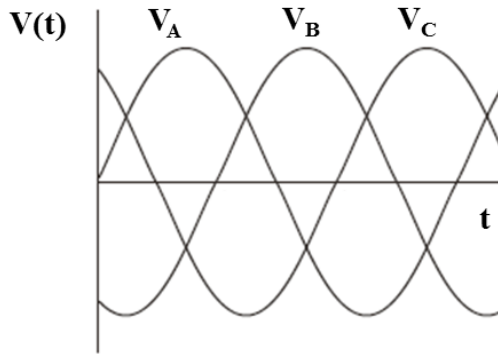
AC Alternator

The basic construction and premise of operation is similar to a dynamo with the exception of the fact that the commutator is *unnecessary* and therefore absent. Another salient difference between a dynamo and an AC alternator is that the roles and the properties of the stator and rotor are reversed. In an AC alternator, as shown in Figure 2.4 (a), the magnetic field is produced by the *rotating rotor* and the *stator serves as an armature*. The key reason for the armature – the segment of the generator where the generated current and EMF(voltage) are harnessed – to serve as a stationary “exoskeleton” is that large induced currents require robust insulation of the armature windings. In addition, with large currents, larger magnetic forces and torques are in play, which makes it important to secure or anchor the windings in a rugged structure. As with a DC generator, the power in AC alternators is fundamentally produced in *sinusoidal form*. Since the output of an AC alternator does not need to be rectified to DC form, commutator function is not needed. Construction of a basic AC alternator or generator is shown in Figure 2.4 (a). The output of a typical AC alternator is depicted in Figure 2.4 (b).

As observable in Figure 2.4 (a), the magnetized rotor is being rotated counter-clockwise by external means. As the magnetized rotor rotates, the magnetic field emanating from the north pole and terminating into the south pole cuts through the three phase coils in the armature. Movement of the magnetic field through the coils initiates current flow and potentials in the three coils. As noted in Figure 2.4 (a), the voltage thus developed across coil A is V_A , voltage developed across coil B is V_B , and the voltage developed across coil C is V_C .



(a) Generator/Alternator Construction



(b) Generator/Alternator Construction

Figure 2.4: AC alternator construction and output waveform.

The overall principle of operation and construction of a *single phase AC alternator/generator* is similar to a *three phase AC alternator/generator*, with the exception of the fact that the armature windings consist of one set of windings for the harnessing of single phase AC.

While the complete representation of the AC sinusoidal voltage generated by single phase AC generator is given by Eq. 2.5 (angle of the voltage is assumed to be “0”), the RMS and peak voltages would be stipulated by Eq. 2.6 and Eq. 2.7, respectively. For the sake of reader’s convenience, these equations are restated below:

$$V(t) = \pi n \frac{p}{60} NAB \sin\left(\frac{p}{2} \Omega t\right) \quad \text{Eq. 2.5}$$

$$V_{DC} = V_{\text{eff}} = \frac{V_P}{\sqrt{2}} = \left(\frac{\pi}{2}\right) \cdot \left(\frac{n}{30}\right) \cdot \frac{pNAB}{(\sqrt{2})} = \frac{\pi npNAB}{(60) \cdot (\sqrt{2})} \quad \text{Eq. 2.6}$$

$$V_m = V_P = \left(\frac{\pi}{2}\right) \cdot \left(\frac{n}{30}\right) \cdot pNAB = \frac{\pi npNAB}{60} \quad \text{Eq. 2.7}$$

Example 2.3

A four pole single phase AC generator consists of windings constituting 90 series paths and is driven by a propane prime mover (engine). The effective or mean length of the armature is 20 cm and the cross-sectional radius of the armature is 5 cm. The armature is rotating at 2000 rpm. Each armature pole is exposed to a magnetic flux of 1.5 T. The efficiency of this generator is 92% and it is rated 1.5kW. Determine the following:

- (a) The maximum voltage generated
- (b) The RMS voltage generated
- (c) The horsepower rating of the generator
- (d) The horse power output of the prime mover

Solution:

The maximum voltage, V_m , generated by this alternator is given by Eq. 2.7.

$$V_m = V_P = \left(\frac{\pi}{2}\right) \cdot \left(\frac{n}{30}\right) \cdot pNAB = \frac{\pi npNAB}{60} \quad \text{Eq. 2.7}$$

Given:

$n = 2000$ rpm

$p = 4$

$N = \text{Number of series paths} = 90$

$B = 1.5$ T

$$\begin{aligned} \mathbf{A} &= (\text{Eff. diameter of the coil conductor}) \times (\text{Eff. length of the coil}) \\ &= (2 \times 5\text{cm}) \times (20\text{cm}) = (0.1\text{m}) \times (0.2\text{m}) = 0.02\text{m}^2 \end{aligned}$$

(a)

$$\begin{aligned} V_m &= \frac{\pi n p N A B}{60} = \frac{(3.14) \cdot (2000 \text{rpm}) (4) (90) (0.02\text{m}^2) (1.5\text{T})}{60} \\ &= 1130\text{V} \end{aligned}$$

(b) The RMS voltage could be calculated by using Eq. 2.6, or simply by dividing V_m , from part (a), by the square root of 2 as follows:

$$V_{\text{RMS}} = V_{\text{eff}} = \frac{V_m}{\sqrt{2}} = \frac{1130}{\sqrt{2}} = 799 \text{ V}$$

(c) The horsepower rating of this generator is the power **output** rating specified in hp, premised on the stated **output capacity** of 1.5kW. Therefore, application of the 0.746 kW/hp conversion factor yields:

$$P_{\text{hp}} = \frac{P_{\text{kW}}}{0.746\text{kW/hp}} = \frac{1.5\text{kW}}{0.746\text{kW/hp}} = 2.01\text{hp} \cong 2 \text{ hp}$$

(d) The horsepower rating of the prime mover, or the propane fired engine, would need to offset the inefficiency of the AC generator. Therefore, based on the given 92% efficiency rating of the generator:

$$P_{\text{hp - Prime Mover}} = \frac{P_{\text{hp - Gen.}}}{\text{Eff.}_{\text{Gen}}} = \frac{2.01 \text{ hp}}{0.92} = 2.19 \text{ hp}$$

AC Induction Motor

An induction motor is also referred to as an asynchronous motor; primarily, because a typical AC induction motor has a certain amount of “slip” (discussed in detail in the next section) and the shaft speed is less than the motor’s synchronous speed. An AC induction motor can be considered as a special case of a transformer with a rotating secondary (rotor) and a stationary primary (stator). The electromagnetic field in the primary (stator) rotates at synchronous speed, n_s , as given by Eq. 2.9. The stator magnetic field, rotating at the synchronous speed, cuts through the rotor windings. This rotating or moving magnetic field in accordance with the Faradays law induces EMF and current through the rotor windings. Due to the fact that the rotor windings are inductive and possess inductive reactance, X_L , the current induced in the rotor windings lags behind the induced voltage, resulting in a definite amount of slip.

$$n_s = \text{Synchronous speed} = \frac{120f}{p} = \frac{60\omega}{\pi p} \quad \text{Eq. 2.8}$$

In essence induction motors allow the transfer of electrical energy from the primary (stator) windings to the secondary (rotor) windings. The primary or secondary windings, or the stator and the rotor, are separated by an air gap. In a wound rotor the wire wound construction is similar to the rotor construction of AC alternators. However, with AC motors, a more common alternative to a wound rotor is a **squirrel cage rotor**, which consists of copper or aluminum bars – in lieu of insulated wire – embedded in slots of the cylindrical iron core of the rotor. See Figure 2.5. Construction of a common, TEFC, Totally Enclosed Fan Cooled, motor is illustrated in Figure 2.5. Major components of an AC induction motor, i.e. squirrel cage rotor, motor shaft, armature windings, cooling fan and bearings, are labeled and highlighted in Figure 2.5.

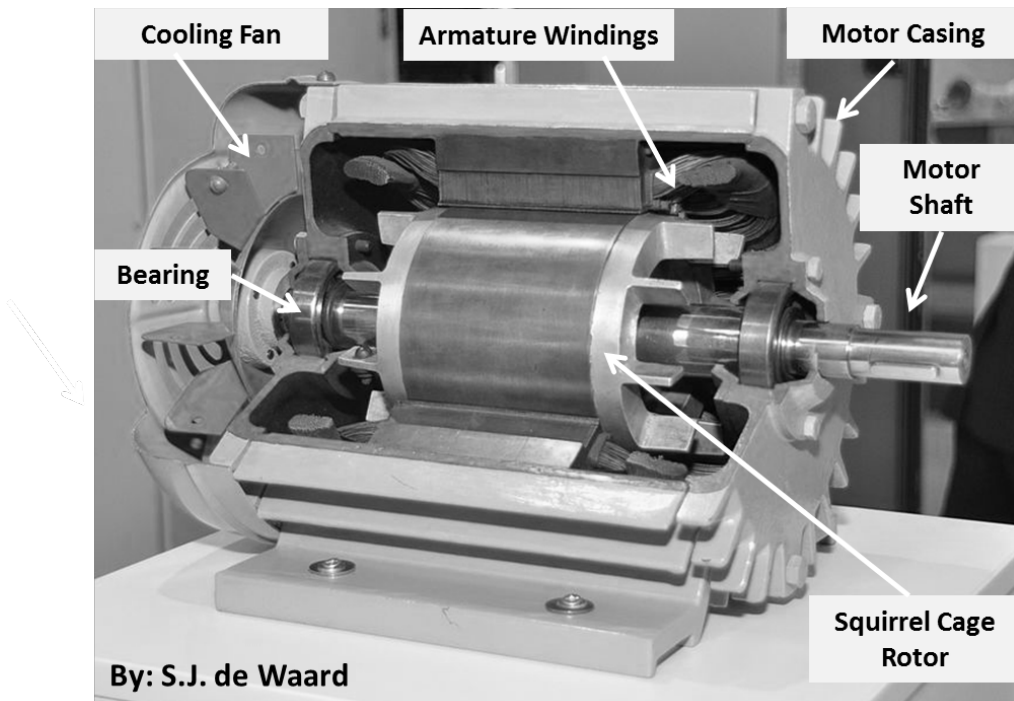


Figure 2.5: AC induction motor construction.

Motor Slip

The rotational speed of rotor (secondary) of an induction motor – rotational speed of the rotor is the also the actual speed of the motor shaft - lags behind the synchronous speed, n_s . This difference in rotational speeds can range between 2% to 5% and is called **slip**. Slip can also be defined as the difference between synchronous speed and operating speed, at the same frequency, expressed in rpm or in percent or ratio of synchronous speed. Slip can be defined mathematically as represented by Eq. 2.10 and Eq. 2.11.

$$\text{Slip} = \left(\frac{n_s - n}{n_s} \right) = \left(\frac{\Omega_s - \Omega}{\Omega_s} \right) \quad \text{Eq. 2.10}$$

$$\% \text{ Slip} = \left(\frac{n_s - n}{n_s} \right) \cdot (100)\% = \left(\frac{\Omega_s - \Omega}{\Omega_s} \right) \cdot (100)\% \quad \text{Eq. 2.11}$$

Where,

n_s = Synchronous speed of the AC induction motor, in rpm.

= Rotational speed of the armature AC induction EMF, in rpm.

n = Actual speed of the AC induction motor shaft, in rpm.

= Rotational speed of the EMF in the rotor, expressed in rpm.

Ω_s = Rotational speed of the armature AC induction EMF, in rad/sec.

= Synchronous speed of the AC induction motor, rad/sec.

Ω = Rotational speed of the rotor EMF, in rad/sec.

= Actual speed of the rotor, in rad/sec.

Induction motors are made with slip ranging from less than 5% up to 20%. A motor with a slip of 5% or less is known as a **normal-slip motor**. A normal-slip motor is sometimes referred to as a **constant speed motor** because the speed changes very little from no-load to full-load conditions. Higher slip characteristics of motors are not always “undesirable.” Since low slip is often accompanied by instantaneous imparting of a large amount of torque – which can be detrimental to the material and mechanical integrity of the shaft - to the motor shaft, motors with slip over 5% are often used for hard-to-start applications.

Typically, at the rated full load, slip ranges from more than 5% for small or special purpose motors to less than 1% for large motors. Speed variations due to slip can cause load-sharing problems when differently sized

motors are mechanically connected. Slip can be reduced through various means. Due to the progressive decline in the cost and continuous technological improvements in the VFD (Variable Frequency Drive) technology, they offer the most optimal solution for mitigating undesirable effects associated with slip.

A common four-pole motor with a synchronous speed of 1,800 rpm may have a no-load speed of 1,795 rpm and a full-load speed of 1,750 rpm. The rate-of-change of slip is approximately linear from 10% to 110% load, when all other factors such as temperature and voltage are held constant.

Motor Torque and Power

Torque generated or produced by a motor is equivalent to the amount of *external work* performed *by* the motor. In the absence of transactions involving other forms of energy, such as heat, the amount of work performed or torque applied by a motor is equal to the energy stored in the external system in the form of potential energy or kinetic energy. Therefore, torque, work and energy are equivalent entities. This is further corroborated by the fact that torque, work and energy can be quantified or measured in terms of equivalent units, i.e. ft-lbf, BTU, calories, therms, N-m, joules, kWh, etc.

On the other hand, power, as explained earlier in this text, is the rate of performance of work, rate of delivery of energy rate of application of torque, etc. In order to illustrate the difference between torque and power let's consider the example of a crank wheel that is being turned at a certain rate. Suppose the wheel has a one-foot long crank arm takes a force of one pound (lbf) to turn at steady rate. The torque required would be one pound times one foot or one foot-pound, 1 ft-lbf. If we were to apply this torque for two seconds, the power delivered would be $\frac{1}{2}$ ft-lbf/sec. Now let's assume that we continue to apply the same amount of torque, i.e. 1 ft-lbf, but twice as fast, or for 1 second. Then we would have a case where the torque remains the same, or 1 ft-lbf, but the rate of delivery of torque would double to 1 ft-lbf/sec.

Application of motors in mechanical or electromechanical systems often challenges engineers to assess the *amount* of torque involved. However, unlike power output or input of a motor which can be assessed through simple and safe measurement of voltage and current, with the help of hand-held instruments such as the handheld voltmeter or clamp-on ammeter,

measurement of torques produced by large motors requires large, stationary and rather unwieldy systems called dynamometers. See Figure 2.6. Therefore, if the motor power is known in, hp or kW, and if the actual shaft speed, n (rpm), is available, the torque can be calculated by using Eq. 2.12 and Eq. 2.13.

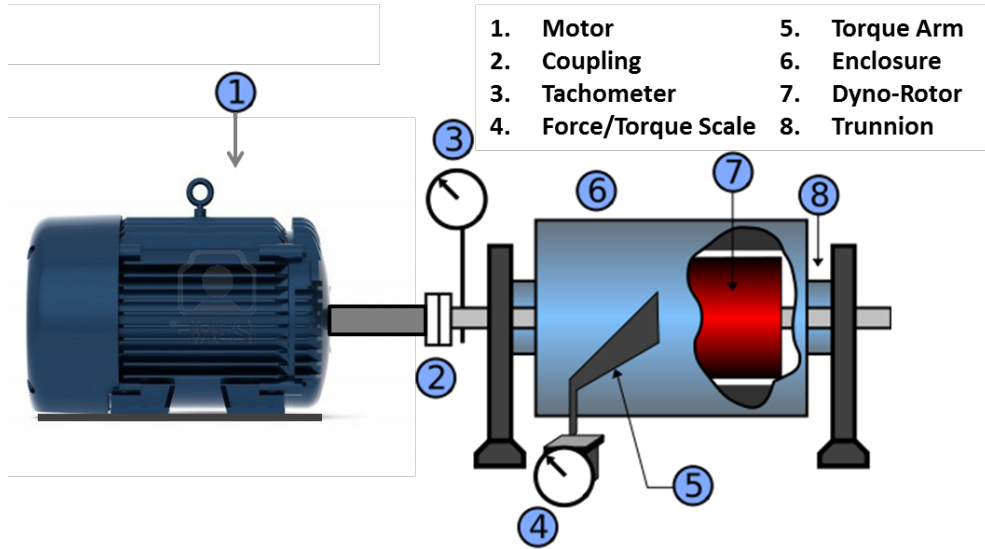


Figure 2.6: Motor dynamometer

$$\text{Torque}_{(\text{ft-lbf})} = \frac{5250 \times P_{(\text{horsepower})}}{n_{(\text{rpm})}} \quad \text{Eq. 2.12}$$

$$\text{Torque}_{(\text{N-m})} = \frac{9549 \times P_{(\text{kW})}}{n_{(\text{rpm})}} \quad \text{Eq. 2.13}$$

The torque computation equations stated above are derived from the basic torque, angular speed and power equation stated as Eq. 2.14.

$$P = T \cdot \omega \quad \text{or,} \quad T = \frac{P}{\omega} \quad \text{Eq. 2.14}$$

Where,

P = Power delivered by the motor, in hp or watts.

T = Torque delivered by the motor, in ft-lbf or N-m or Joules.

ω = Actual rotational speed of the motor shaft, in rad/sec.

Single Phase and Three Phase Motor Line Current Computation

While copious tables, charts, handbooks and pocket cards include full load current information for various (standard) motor sizes, at standard voltages, when accuracy is of the essence, one must **compute** correct current values pertaining to specific voltage, efficiency, power factor and actual load. Therein rests the value of line current calculation equations for single phase and three phase motors. Those equations and their derivation are summarized below.

Single Phase AC Induction Motor Current:

$$\begin{aligned} S_{L,1-\phi} &= \text{Full load apparent power on the line side of single phase motor} \\ &= \frac{\text{Full Load Rating of Motor (in Watts)}}{(\text{Pf}).(\text{Eff.})} \end{aligned}$$

Eq. 2.15

Or,

$$\begin{aligned} |S_{L,1-\phi}| &= \text{Magnitude of apparent power (drawn) on the line side of a single} \\ \text{phase motor} &= \frac{P_{1-\phi} \text{ (in Watts)}}{(\text{Pf}).(\text{Eff.})} \end{aligned}$$

Eq. 2.16

Since the magnitude of single phase apparent power, $|S_{L,1-\phi}| = |V_L| \cdot |I_L|$,

$$\text{then } |I_L| = \frac{|S_{L,1-\phi}|}{|V_L|}$$

Eq. 2.17

Therefore,

$$\text{Single Phase AC Line Current drawn, } |I_L| = \frac{|S_{L,1-\phi}|}{|V_L|} = \frac{P_{L,1-\phi} \text{ (in Watts)}}{|V_L|(Pf).(Eff.)}$$

Eq. 2.18

Three Phase AC Induction Motor Current:

$$\begin{aligned} S_{L,3-\phi} &= \text{Full Load Apparent (3-}\phi\text{) Power on the Line Side} \\ &= \frac{\text{Full Load (3-}\phi\text{) Rating of Motor (in Watts)}}{(Pf).(Eff.)} \end{aligned}$$

Eq. 2.19

Or,

$$\begin{aligned} |S_{L,3-\phi}| &= \text{Magnitude of Full Load Apparent Power on the Line Side of} \\ \text{a 3-phase motor} &= \frac{P_{3-\phi} \text{ (in Watts)}}{(Pf).(Eff.)} \end{aligned}$$

Eq. 2.20

Since the magnitude of 3- ϕ (three phase) apparent power is given as:

$$|S_{L,3-\phi}| = \sqrt{3} (|V_L|) \cdot (|I_L|),$$

$$\text{by rearranging this equation, the 3-}\phi \text{ phase line current, } |I_L| = \frac{|S_{L,3-\phi}|}{\sqrt{3} (|V_L|)}$$

Eq. 2.21

Therefore,

$$\text{The 3-}\phi \text{ phase line current, } |I_L| = \frac{|S_{L,3-\phi}|}{\sqrt{3} (|V_L|)} = \frac{P_{L,3-\phi} \text{ (in Watts)}}{\sqrt{3} (|V_L|)(Pf).(Eff.)}$$

Eq. 2.22

Where,

$|I_L|_{1-\phi}$ = Single phase RMS line current, measured in amps.

$|I_L|_{3-\phi}$ = Three phase RMS line current, measured in amps.

$|V_L|$ = RMS line to line, or phase to phase, voltage, measured in volts.

$|S_L|_{1-\phi}$ = Apparent power drawn by a single phase motor, in VA or kVA,
etc.

$|S_L|_{3-\phi}$ = Apparent power drawn by three phase motor, in VA or kVA, etc.

$P_{1-\phi}$ = Real power demanded by a single phase motor load, in W, or kW, etc.

$P_{3-\phi}$ = Real power demanded by a three phase motor load, in W, or kW, etc.

Pf = Power factor of the motor, as specified on motor nameplate.

Eff. = Motor efficiency, as specified on motor nameplate.

Example 2.4

A three phase, four pole, AC induction motor, rated 150 hp, is operating at full load, 50 Hz, 480 V_{rms}, efficiency of 86%, power factor of 95%, and a slip of 2%. Determine the following:

- (a) Motor shaft speed, in rpm,
- (b) Torque developed, in ft-lbf.
- (c) Line current drawn by the motor, and
- (d) The amount of reactive power, Q, sequestered in the motor under the described operating conditions.

Solution

Given:

$P_{L,3-\phi}$ = Real power or rate of work performed by the motor = 150 hp
= (150 hp).(746 W/hp) = 111,900 W

p = 4 poles

V_L = 480 V_{RMS}

Pf = 95% or 0.95

Eff. = 86% or 0.86

n_s = Synchronous speed, in rpm = ?

Slip, s = 2%

f = Frequency of operation = 50 Hz

(a) **Shaft or motor speed:** Rearrange and apply Eq. 2.10:

$$\text{Slip} = s = \left(\frac{n_s - n}{n_s} \right)$$

And, by rearrangement: $n = n_s (1 - s)$

Next, we must determine the synchronous speed of the motor by applying Eq. 2.8:

$$n_s = \text{Synchronous speed} = \frac{120f}{p} = \frac{(120).(50)}{4} = 1500 \text{ rpm}$$

$$\therefore n = (1500 \text{ rpm})(1 - 0.02) = 1470 \text{ rpm}$$

(b) **Torque developed, in ft-lbf:** There are multiple methods at our disposal for determining the torque developed. Formulas associated with two common methods are represented by Eq. 2.12, Eq. 2.13 and Eq. 2.14. Since the power is available in hp and the rotational speed in rpm, apply Eq. 2.12:

$$\text{Torque}_{(\text{ft-lbf})} = \frac{5250 \times P_{(\text{horsepower})}}{n_{(\text{rpm})}} = \frac{5250 \times 150 \text{ hp}}{1470 \text{ rpm}} = 536 \text{ ft-lbf}$$

Note: The reader is encouraged to prove this result through application of Eq. 2.14.

(c) **Line current drawn by the motor:** Full load line current is the current the motor draws from the power source, or utility, in order to sustain the full load. Therefore, the determination of line current at full load requires that the full load output of 150 hp be escalated in accordance with motor efficiency and power factor to compute the line current. Application of Eq. 2.22 takes this into account in the computation of 3-phase motor line current, after the motor hp rating (or actual load) is converted into watts:

Therefore,

$$\text{The 3-}\phi \text{ phase line current, } |I_L| = \frac{|S_{L,3-\phi}|}{\sqrt{3}(|V_L|)} = \frac{P_{L,3-\phi} \text{ (in Watts)}}{\sqrt{3}(|V_L|)(\text{Pf})(\text{Eff.})}$$

Three phase (total) real power was converted into watts under “Given” as $P_{L,3-\phi} = 111,900 \text{ W}$

Therefore,

$$\text{The 3-}\phi \text{ phase line current, } |I_L| = \frac{111,900 \text{ Watts}}{\sqrt{3}(480 \text{ V}_{\text{RMS}})(0.95).(0.86)} = 165 \text{ A}$$

(d) **Reactive power, Q:** There are multiple approaches available to us for determination of reactive power Q for this motor application. We will utilize the power triangle or apparent power component vector method:

$$S = P + jQ, \text{ and } S^2 = P^2 + Q^2, \text{ or, } Q^2 = S^2 - P^2 \text{ and } Q = \sqrt{S^2 - P^2}$$

Real power “P” was computed earlier as 111,900 W, and apparent power S can be assessed using Eq. 2.20

$$|S_{L,3-\phi}| = \frac{P_{3-\phi} \text{ (in Watts)}}{(\text{Pf}).(\text{Eff.})} = \frac{111,900\text{W}}{(0.95).(0.86)} = 136,965 \text{ VA}$$

Therefore,

$$Q = \sqrt{S^2 - P^2} = \sqrt{136,965^2 - 111,900^2} = \sqrt{6,237,665,433} \\ = 78,979 \text{ VAR}$$

Example 2.5

A four-pole induction motor operates on a three-phase, 240 V_{rms} line-to-line supply. The slip is 5%. The operating (shaft) speed is 1600 rpm. What is most nearly the operating frequency?

Solution:

Given:

p = 4 poles

n = Shaft or motor speed = 1600 rpm

n_s = Synchronous speed, in rpm = ?

Slip, s = 5% or 0.05

f = Frequency of operation = ?

Since this case involves synchronous speed and slip, it requires the application of Eq. 2.8 and 2.10. As apparent from examination of Eq. 2.8, the operating frequency can be determined by rearranging the equation if the synchronous speed **n_s** was known.

$$\text{Slip} = s = \left(\frac{n_s - n}{n_s} \right) \text{ or, } n_s = \left(\frac{n}{1 - s} \right) = \left(\frac{1600}{1 - 0.05} \right) = 1684 \text{ rpm}$$

Eq. 210

$$n_s = \text{Synchronous speed} = \frac{120f}{p} \text{ or, } f = \frac{(p).(n_s)}{120} = \frac{(4).(1684)}{120} = 56 \text{ Hz}$$

Eq. 2.8

Synchronous Motors

Synchronous motors are AC induction motors that have no slip. In other words, in synchronous motors, the speed of rotor or motor shaft is the same as the rotational speed of the stator winding magnetic field. This is accomplished through the excitation of the rotor through the field windings such that the rotor is able to “*catch up*” to the rotational speed of the stator. This characteristic permits synchronous motors to induce *leading currents* in the branch circuit. Therefore, synchronous motors can serve as alternative means for power factor correction; albeit, application of power factor correcting capacitors is more economical and effective in most lagging power factor situations.

Example 2.6

A three phase induction motor delivers 550 kW at a power factor of 82%. Determine the size of synchronous motor, in kVA, that should be installed to carry a load of 250 hp load and, at the same time, raise the (combined) power factor to 95%.

Solution:

Given

P_I = Real power delivered by the 3- ϕ induction motor = 550 kW

P_S = Real power contributed by the synchronous motors = 250 hp =
(250 hp) x (0.746 kW/hp) = 186.5 kW

Pf_i = Initial Power Factor = 82% = 0.82

Pf_f = Final Power Factor = 95% = 0.95

To solve this problem, as in many others, we will begin with the final state and work our way upstream. With the final combined power factor of 95% in mind, we will work our way back to the required synchronous motor specifications. The apparent power rating, S , of the synchronous motor that must be installed to achieve the combined “system” power factor of 95% (0.95), while contributing 250 hp toward the system’s real power, P_T ,

requirement, can be determined if we could assess the Q_T (kVAR) contributed by the synchronous motor in an effort to raise the combined power factor of the two motor system to 95% (0.95). This can be accomplished through the assessment of final (combined) S_T and P_T values and application of the power triangle equation:

$$S_T = P_T + jQ_T, \text{ and } S_T^2 = P_T^2 + Q_T^2, \text{ or, } Q_T^2 = S_T^2 - P_T^2 \text{ and,}$$

$$Q_T = \sqrt{S_T^2 - P_T^2}$$

The combined real power of the induction motor and the synchronous motor is:

$$P_T = 550 \text{ kW} + 186.5 \text{ kW} = 736.5 \text{ kW}$$

$$\text{Since } S_T \cos \theta = P_T, \quad S_T = \frac{P_T}{\cos \theta},$$

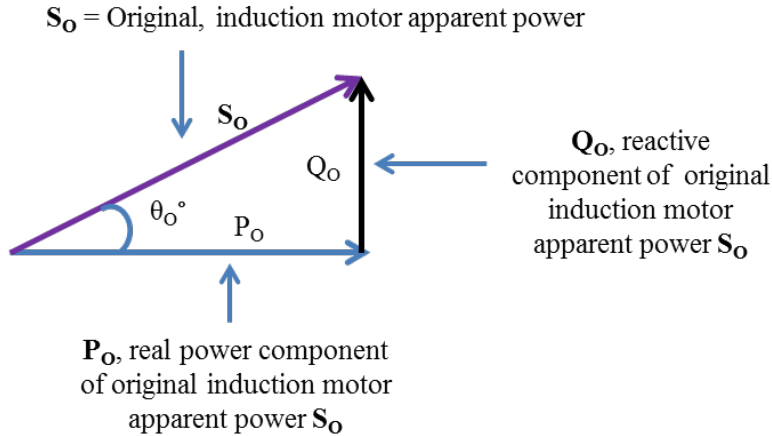
And since θ_T , the final power factor angle = $\cos^{-1}(0.95) = 18.19^\circ$,

$$S_T = \frac{P_T}{\cos \theta_T} = \frac{736.5 \text{ kW}}{\cos(18.19^\circ)} = 775.26 \text{ kVA}$$

Therefore,

$$Q_T = \sqrt{S_T^2 - P_T^2} = \sqrt{775^2 - 736^2} = \sqrt{59,337} = 244 \text{ kVAR}$$

Now, in order to determine Q_S , the reactive power contributed by the synchronous motor, we must subtract the original reactive power, Q_O , from the final, total, reactive power, Q_T . However, Q_O is unknown and can be determined through the power triangle as follows:



Since $\tan(\theta_o) = \frac{Q_o}{P_o}$, or, $Q_o = P_o \tan(\theta_o) = 550 \text{ kW} \tan(\theta_o)$

And, $\theta_o = \cos^{-1}(\text{Pf}_o) = \cos^{-1}(0.82) = 34.92^\circ$

Therefore,

$Q_o = 550 \text{ kW} \tan(34.92^\circ) = 550 \text{ kW}(0.698) = 384 \text{ kVAR}$

And, reactive power contributed by the synchronous motor would be:

$Q_s = Q_o - Q_T = 384 \text{ kVAR} - 244 \text{ kVAR} = 140 \text{ kVAR}$

Therefore,

$S_s = P_s + jQ_s$, and $S_s^2 = P_s^2 + Q_s^2$, or, $S_s = \sqrt{P_s^2 + Q_s^2}$

Or, $S_s = \sqrt{(186.5 \text{ kW})^2 + (140 \text{ kW})^2} = 233 \text{ kVA}$

Motor starting methods for induction motors

Often, the starting method for an induction motor depends on the type of motor. The five basic types of small induction motors are as follows:

- 1) Single-phase capacitor-start
- 2) Capacitor-run
- 3) Split-phase
- 4) Shaded-pole
- 5) Small polyphase induction motors

Because of the absence of a rotating EMF field in the armature, a single-phase induction motor requires separate starting circuitry to provide a rotating field to the motor. A starting circuit is needed to determine and “set” the direction of rotation due to the fact that the regular armature windings of a single-phase motor can cause the rotor to turn in either direction. Therefore, rotation direction is initiated in certain smaller single-phase motors by means of a “**shaded pole**” with a copper wire “**turn**” around a section of the pole. Then, the current induced in the shaded pole turn lags behind the supply current, creating a delayed magnetic field around the shaded part of the pole face. This imparts sufficient rotational field energy to start the motor in a specific direction. The shaded pole starting method is often employed in motors installed in applications such as small fans and pumps.

A common approach for starting larger single phase motors is to incorporate a second stator (armature) winding that is fed with an “out-of-phase” current. The out-of-phase current may be created by feeding the winding through a *capacitor* or through an *impedance* that is different from the main winding. Often, the second “starting” winding is disconnected once the motor has accelerated up to normal steady state speed. This is accomplished, commonly, through either by a *centrifugal switch* or a *thermistor* – the thermistor heats up and increases its resistance, thereby reducing the current through the starting winding to a negligible level. Some designs maintain the starting winding in the circuit to supplement the regular motor torque.

Since three phase, or polyphase, motors possess a rotating armature emf, the direction of rotation is determined by phase sequence, ABC versus ACB. Hence, during start-up or commission of three phase motors, if the motor rotation is incorrect, two of the three phase conductors are “swapped” to reverse the direction of rotation. This reversing starter design – in *FVR*, *Full Voltage Reversing starters* - is premised on the “phase-swapping” principle to reverse the direction of rotation of motors, such as in conveyor or fan applications where direction reversal is required. Self-starting polyphase induction motors produce torque even when stationary. Common starting methods for larger polyphase induction motors are as follows:

- 1) Direct-on-line starting

- 2) Reduced-voltage reactor or auto-transformer starting
- 3) Star-delta starting
- 4) Application of solid-state soft starting systems
- 5) Use of VFDs for electronically controlled starting and normal motor operation through variation of frequency and voltage.

In squirrel cage polyphase motors, the rotor bars are designed and shaped according to the desired speed-torque characteristics. The current distribution within the rotor bars varies as a function of the frequency of the induced current. In locked rotor scenarios, or when the rotor is stationary, the rotor current has the same frequency as the stator current, and the current tends to travel at the outermost parts of the cage rotor bars due to the “*skin effect*.” The squirrel cage rotor bars are designed to meet the required speed-torque characteristics and to limit the inrush current.

DC Motor Speed control

While DC motor speed control through armature or field windings was briefly discussed earlier in this segment, specific approaches to DC motor shaft speed control can be categorized as follows:

- 1) **Armature Control:** The armature based speed control technique involves changing the voltage across the armature through variation of parallel or series resistance, while holding the field voltage constant.
- 2) **Field Control:** The field control approach involves variation of the field voltage while holding the armature voltage constant. The field voltage is varied through the variation of series or shunt resistance.
- 3) **Electronic Control:** This approach involves the use of electronic controls for the variation of armature and/or the field voltage and current. Due to the fact that features like programmability, closed loop control and automation are inherently available with electronic controls, this approach tends to provide better control over a wide range of speeds and torques.
- 3) **Combination of basic approaches:** In certain applications, combination of the three approaches described above is more suitable.

AC Motor Speed Control

A common and efficient means for controlling speed of AC motors is through the application of AC inverters, VFD (Variable Frequency Drives) or ASD (Adjustable Speed Drives). The premise of AC motor speed control is the ability to vary the frequency of AC power being supplied to the motor through a variable frequency drive. The shaft speed in such cases can be determined through the application of Eq. 2.8 and Eq. 2.23.

$$n_s = \text{Synchronous speed} = \frac{120f}{p} = \frac{60\omega}{\pi p} \quad \text{Eq. 2.8}$$

$$\text{Motor Shaft Speed, } n = (1 - s) \cdot (n_s) = (1 - s) \cdot \left(\frac{120f}{p} \right) \quad \text{Eq. 2.23}$$

Where,

n_s = Synchronous speed of the AC induction motor, in rpm, or rotational speed of the armature AC induction EMF, in rpm.

n = Actual speed of the AC induction motor shaft, in rpm.

s = Rotational speed of the EMF in the rotor, expressed in rpm.

s = Motor slip.

f = Frequency of the AC power source feeding the motor, in Hz.

p = Number of poles, as stated on the motor nameplate.

Motor Classifications

There are numerous motor classifications and these classifications tend to change and evolve over time as new applications for AC and DC motors emerge. Discussion and listing of all possible classifications and categories of AC and DC motors are beyond the scope of this text. However, some of the more common categories and classifications are stated below for reference.

- a. Self-commutated motors
- b. AC Asynchronous motors (i.e. typical induction motor)
- c. AC Synchronous motor
- d. Constant speed motors
- e. Adjustable speed motor
- f. General duty
- g. Special purpose

Classification based on the winding insulation type: Motor insulation class rating is determined by the *maximum allowable operating temperature* of the motor, which subsequently depends on the type or grade of insulation used in the motor. Seven mainstream insulation classifications and associated maximum allowable temperatures are listed below:

- I.** Class A: **105° C**
- II.** Class B: **130° C**
- III.** Class F: **155° C**
- IV.** Class H: **180° C**
- V.** Class N: **200° C**
- VI.** Class R: **220° C**
- VII.** Class S: **240° C**

Aside from exercising proper care in specifying the correct insulation type for a motor when installing new motors (based on the operating environment of a motor) one must ensure that if a motor is rewound or repaired, the windings are replaced with the *original classification of insulation*. For example, if the windings of a 100 hp **Class H** motor are replaced with **Class B** insulation windings, the motor will lose its capacity to operate in a higher temperature environment.

Typical Motor Nameplate Information for Large Three Phase Induction Motor

Electric motors are typically labeled with a nameplate that displays pertinent specifications of that motor. While there are a myriad of possible specifications, ratings and characteristics of motors, some of the more common ones are described and illustrated through a motor nameplate example in Figure 2.7.

Model No.	B200		Marine Duty, IEEE 45				
		TYPE:					
HP:	200	kW	150	RPM:	1760		
Volt	460	AMP	233	PH.	3	MAX.	40°C

						AMB:	
Hz	60	S.F.	1.15	P.F.	84.5	Code: G	
NEMA NOM EFF:	96.2			DUTY:	CONT.	WT: 1052 kg	2314 lbs
FRAME:	447T	ENCL. Type: TEFC		Motor Type: TKKH		Insul. Type: NEMA: B	IP: 56

Figure: 2.7: Motor nameplate example,

Interpretation of this nameplate information would be as follows:

Model No: B200

Type: Marine Duty, IEEE-45

Power Rating: 200 hp

Standard Operating Voltage: 460 V_{RMS}.

Standard Frequency of operation: 60 Hz

NEMA based efficiency of the motor: 96.2%

Motor frame size: 447T. This NEMA designated frame classification often signifies the mechanical construction, mounting or installation of a motor.

Power rating of the motor, in kW = 150 kW

AMP or Full Load Current rating of the motor: 233 Amp

Service factor of the motor: 1.15 or 115%

ENCL. or NEMA rating of the motor enclosure: TEFC; or, Totally Enclosed Fan Cooled.

RPM: Full load shaft or rotor speed: 1760 rpm.

PH. Or number of phases: 3

PF, or Power Factor of the motor: 84.5%

Duty, or duration of operation: Continuous.

TYPE: TTKH, High Efficiency Motor

NEMA – B: Class B winding insulation

IP56: European enclosure rating, comparable to NEMA 4.

Maximum Allowable Ambient Temperature: 40°C

Weight of the motor: 1052 kG or 2413 lb.

Self-assessment Problems & Questions – Segment 2

1. A gas powered prime mover is rotating the rotor of a single phase alternator at a speed of 1200 rpm. The alternator consists of six pole construction. The effective diameter of the coil is 0.15m and the length of the coil loop is 0.24m. The coil consists of 20 turns. The magnetic flux density has been measured to be 1.2T. Calculate the power delivered by this generator across a resistive load of 10Ω .

2. A four pole alternator/generator is producing electrical power at an electrical frequency of 50 Hz.

(a) Determine the angular speed corresponding to the generated electrical frequency.

(b) Determine the rotational (synchronous) speed of the armature/rotor.

(c) Determine the angular velocity of the armature/rotor (rad/sec).

3. A four pole single phase AC generator consists of windings constituting 80 series paths and is driven by a diesel engine. The effective or mean length of the armature is 18 cm and the cross-sectional radius of the armature is 5 cm. The armature is rotating at 1800 rpm. Each armature pole is exposed to a

magnetic flux of 1.0 T. The efficiency of this generator is 90% and it is rated 2 kW. Determine the following:

- (a) The maximum voltage generated.
- (b) The RMS voltage generated.
- (c) The horsepower rating of the generator.
- (d) The horse power output of the prime mover.

4. A three phase, four pole, AC induction motor is rated 170 hp, is operating at full load, 60 Hz, 460 V_{rms}, efficiency of 90%, power factor of 80%, and a slip of 4%. Determine the following:

- (a) motor shaft speed, in rpm
- (b) torque developed, in ft-lbf
- (c) line current drawn by the motor and
- (d) the amount of reactive power, Q, sequestered in the motor under the described operating conditions.

5. A three phase, four pole, AC induction motor is tested to deliver 200 hp, at 900 rpm. Determine the frequency at which this motor should be operated for the stated shaft speed. Assume the slip to be negligible.

6. A three phase induction motor delivers 600 kW at a power factor of 80%. In lieu of installing power factor correction capacitors, a synchronous motor is being considered as a power fact correction measure. Determine the apparent power size of the synchronous motor, in kVA, that should be installed to carry a load of 300 hp and raise the (combined) power factor to 93%. The source voltage is 230 V_{rms}.

Segment 3

Power distribution equipment, instrumentation and electronic safety devices

Introduction

In this segment will take an exploratory tour of power distribution equipment through the review of motor control center (MCC), disconnect switches, motor starters, breakers, power switchgear, variable frequency drives (VFD), etc. Pictures and diagrams are used in this discussion to give the reader a “hands- on” feel of common electrical and electronic equipment. Of course, as with the rest of this text, the reader will have an opportunity to test their knowledge through self-assessment problems at the end of the segment.

Voltage Categories in Power Distribution Systems

Before we delve into the specific voltage categories of electrical systems, let’s examine the flow of power from the point of generation to the point of consumption through Figure 3.1.

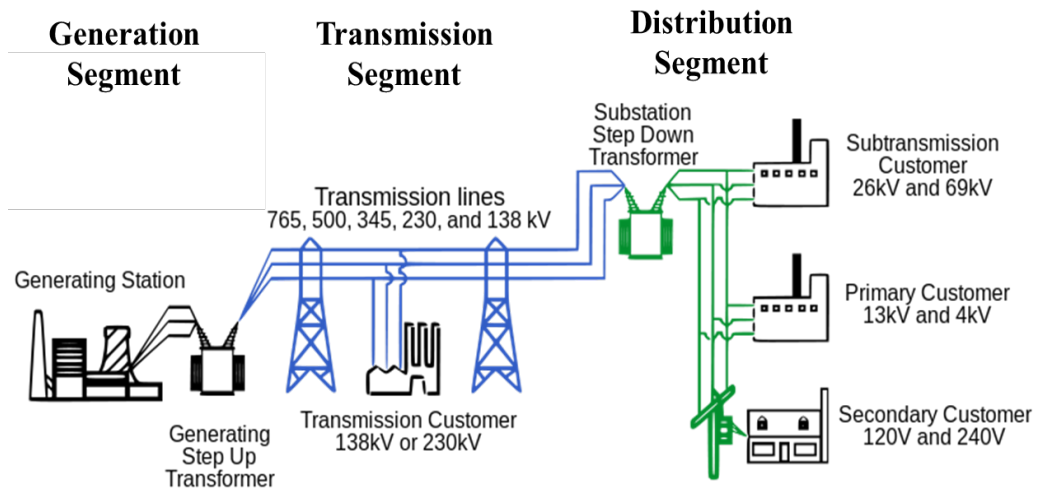


Figure 3.1: Electric power distribution and voltage levels. US DOE.

As shown in Figure 3.1, after AC power is generated at a typical power plant in the US, it is “stepped up” for transmission, to voltages ranging from 138 kV to 765 kV. As explained earlier in this text, the higher the transmission voltage, the lower the current required to deliver a certain amount of power to the consumers. As shown in Figure 3.1, once the power arrives within reasonable proximity of the consumers, it is stepped down to lower voltages suitable for use by the consumers. As we describe the major categories of voltage systems in the sections below, the reader is cautioned against interpreting these categories in an absolute fashion. As explained below, the boundaries between the various categories vary to some degree depending on the entity or organization performing the interpretation.

Low Voltage Systems

The low voltage category includes systems with voltages that **range 50 to 1000 V_{RMS} AC or 120 to 1500 Volts DC**. This category has the following subcategories:

Extra low voltage: The voltage in this category is typically below 50V_{RMS} AC or below 120 Volts DC. The extra low voltage category is associated voltage, which typically can't harm humans, due to the low magnitude of

potential difference. This category applies to equipment and wiring widely used in bathrooms, showers, swimming pools, toys and other electric devices, which might be in open contact with human.

Low voltage in power supplies for fluorescent lamps: This low voltage category pertains to fluorescent lamp power supplies that use low DC voltage as source.

Low-voltage connectors: This low voltage category is associated with low voltage connectors and low voltage plugs. Common examples include cigarette lighter 12V plugs, low voltage power adapters such as those used for charging rechargeable domestic and office cordless electronic, DC, equipment

Low-voltage overhead power lines: This low voltage category pertains to power lines that bring low voltage, 110 – 240VAC power, to most homes and small commercial establishments.

LVDS voltage level: This low voltage category pertains to LVDS systems. The term LVDS stands for Low Voltage Differential Signaling. LVDS represents electrical digital signaling standard that pertains to high speed digital communications. It specifies the electrical-level details for interface between inputs and outputs on integrated circuit chips. Some common applications of low voltage LVDS standards are high-speed video, graphics, video camera data transfers, and general purpose computer buses.

Microphone preamp voltage level: This category pertains to microphone preamplifiers used to amplify a microphone's low output voltage to a higher, more usable level.

Medium Voltage Systems

Medium voltage is typically the voltage going from the substations to the service drops. The medium voltage **category ranges from 1 kV up to 15 kV, or, 35 kV**, by some standards. According to ANSI/IEEE 1585-2002 medium voltage ranges from 1000V to 35 kV_{RMS}. NEMA 600-2003, on the other hand, refers to medium voltage cables as "medium voltage cables rated from 600 volts to 69,000 volts AC."

High Voltage Systems

The High Voltage category, by most standards, ranges from 15,000 V (35 kV, by some standards) up to 230 KV. High voltage is typically the voltage going from substation to substation or, as shown in Figure 3.1, the voltage level at which power is typically transmitted in the US from the point of generation to the point of consumption. Transmission-level voltages are usually considered to be 110 kV and above. Lower voltages such as 66 kV and 33 kV are usually considered sub-transmission voltages.

Extra High Voltage (EHV) Systems

There is a general consensus among power experts that voltage ranging between **230 kV to 600 kV** could be aptly termed as extra high voltage, or **EHV**. However, some standards refer to voltages ranging from 230 kV to 600 kV as simply “High Voltage.”

Ultra-High Voltage Systems

There is a general consensus that **voltages exceeding 600 kV** could be referred to as Ultra-high voltage, or **UHV**. Ultrahigh voltage (UHV) transmission lines are rare, however. There are a very few of these in the world. A 1.20 MV (1,200,000 V) Ultra High Voltage line, spanning from eastern to western part of India, when commissioned into operation, it is expected to be the highest voltage commercial power transmission line in the world.

Power Equipment Measurement Categories

The measurement category system pertains to the classification of live electric circuits used in measurement and testing of installations and equipment.

There are four measurement categories that take into account the total continuous energy available at the given point of circuit, and the occurrence of impulse voltages. Of course, this energy can be limited by circuit breakers or fuses, and the impulse voltages by the nominal level of voltage. Figure 3.2 shows the four categories in relation to the typical power distribution components.

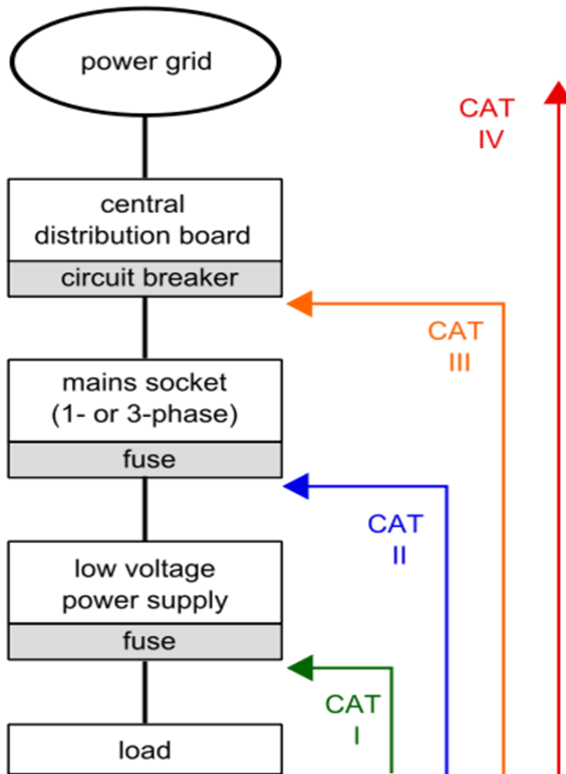


Figure 3.2: Power measurement categories.

There are four categories, which are always stated with the designated voltage, for instance "CAT III, 150 V" or "CAT IV, 1000 V". This has important safety implications for impulse voltages and insulation clearances.

CAT I: This category is applicable to instruments and equipment, which are not intended to be connected to the main supply. Because the available energy is very limited, this category is typically not labeled on the equipment. Examples: Low voltage electronic circuits, load circuits of typical test bench power supplies, etc.

CAT II: This category defines circuits which are intended for direct connection into mains sockets. The energy in such installations is typically limited to below 100 A continuous. In CAT II systems, maximum available continuous power must be limited to 22k VA or less through fuses or circuit breakers.

CAT III: This category pertains to circuits which can be connected to the main feeders. The energy in CAT III systems is limited by circuit breakers to less than 110kVA with the current not exceeding 11kA.

CAT IV: CAT IV systems include circuits which are connected directly to the source of power, or utility, for a given building. The level of energy in CAT IV systems is high, limited to an extent by the power transformer impedance. CAT IV systems, typically, carry higher arc flash hazard during energized work.

MCC's or Motor Control Centers

The term motor control center can be somewhat misleading. The application of MCC's is not typically limited to the "control of motors." While majority of power controls housed in most MCC's are motor starters, often controls for lighting and other types of loads are included, as well. While our examination of MCC's will be limited to Allen-Bradley/Rockwell brand of MCC's and associated components, there are many other world class brands available, i.e. Square-D, ABB and Siemens.

As you tour an industrial or commercial facility, gray or blue cabinets such as the one depicted in Figure 3.3 can hardly escape notice. Those who are not engineers or technicians are likely to walk by one of these cabinets unaware of the electromechanical equipment performing critical functions behind the doors of those individual cubicles. Through examination of a series of MCC pictures and components, thereof, we will explore vital specifications of MCC's, the devices behind those MCC cubicle doors, how they function and what they consist of.

- 20" (508mm) wide standard
- 15" (381mm) or 20" (508mm) deep
- 90" (2286mm) high standard,
 - 71" (1790mm) high available
- Front mounted or back-to-back



Figure 3.3: Physical size specifications of a typical MCC.

An Allen-Bradley CENTERLINE Motor Control Center, pictured in Figure 3.3, is made up of one or more vertical sections. A standard section is 90" (2286mm) high, 20" (508mm) wide, and either 15" (381mm) or 20" (508mm) deep for front mounted configurations. Greater widths are sometimes supplied when larger equipment is required. Back-to-back configured MCCs are also available in 30" (762mm) and 40" (1016mm) designs.

NEMA Enclosure Types

Rockwell Automation offers a variety of NEMA type enclosures to meet specific requirements. The standard enclosure is NEMA Type 1. This compares to the IEC enclosure IP40. NEMA Type 1 with gaskets, which is unique to MCCs, provides gasketing for unit doors. This compares to the IEC enclosure IP41. NEMA Type 12 provides gasketing for unit doors, bottom plates, and all cover plates.



- Type 1
- Type 1 with gaskets
- Type 12 (also in stainless steel)
- Type 3R
- Type 4 stainless steel

Figure 3.4: MCC enclosure NEMA specifications.

MCC's in stainless steel NEMA Type 12 enclosures are also available for corrosive environment applications. This is comparable to the IEC enclosure IP54. For outdoor use, manufacturers offer NEMA Type 3R enclosures. This enclosure is essentially a metal shell around a NEMA Type 1 inner enclosure. This is comparable to the IEC enclosure IP44. For indoor or outdoor use, the manufacturers offer a NEMA Type 4 enclosure. This enclosure is essentially a stainless steel shell around a NEMA Type 1 inner enclosure. This is comparable to the IEC enclosure IP65. All metallic parts (except stainless steel) are painted or plated before assembly, providing protection on all mating surfaces.

MCC Bus bars and bus connections

The motor starters, contactors, VFD's and other devices housed in MCC's are mounted on draw out rack assemblies. These devices or systems can be "drawn out" and removed for replacement or service, after their disconnect switches have been turned off. This does not imply that the main power disconnect switch for power fed *into* the MCC must be disconnected or turned off while removing starters/cubicles for service.

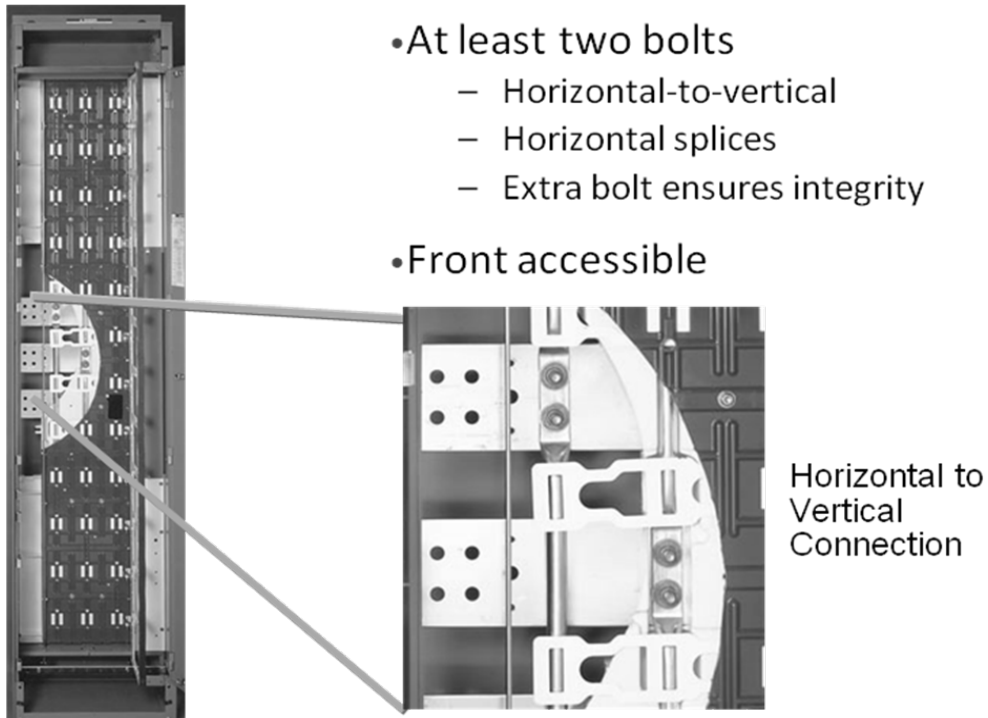


Figure 3.5: MCC bus bar network.

If all cubicle assemblies were removed, the view would be similar to what is depicted in Figure 3.5. As apparent in Figure 3.5, behind the Micarta insulating panel, or equivalent, an array of bus bars are visible. Three visible bus bars are shown magnified on the right side of Figure 3.5. The three bus bars represent phases A, B and C of three phase AC. These bus bars are essentially *silver plated copper conductors* forming a network of conductors carrying three phase 480 VAC (or other specified/rated voltage) to all MCC cubicles. Power bus connections are typically made with at least two bolts. The vertical-to-horizontal bus connection is made with two bolts, as pictured in Figure 3.5. The horizontal bus splice connections are made with at least two bolts on each side of the splice (depending on bus size). The two-bolt connection requires less maintenance and the extra bolt guards against the occurrence of “hot spots” (a result of loose connections) and arcing faults (a result of an open connection).

Horizontal Ground Bus

A 1/4" x 1" (6.4mm x 25.4mm) horizontal ground bus, rated 500A, is supplied, as standard, with each vertical section. A 1/4" x 2" (6.4mm x

50.8mm) horizontal ground bus, rated 900A, is optional. The bus can be unplated or supplied with optional tin plating. The horizontal ground bus can be mounted in the top or bottom horizontal wireway, or top and bottom horizontal wireways of the MCC. See Figure 3.6.

Vertical Ground Bus

Proper grounding is critical for safety of personnel and property. A substantial part of the NEC ®, National Electrical Code, is dedicated safe grounding design, grounding equipment, and grounding methods. Hence, it is no surprise that grounding of MCC's and the connected equipment is facilitated through a network of ground buses in various segments of MCC's. Figure 3.6 and 3.7, for instance, show vertical and horizontal ground bus bars located inside the MCC cabinet in.

- Plug-in ground bus
 - Steel (standard)
 - Copper (optional)
- Unit load ground bus optional
 - Copper
 - For easier termination of ground wires

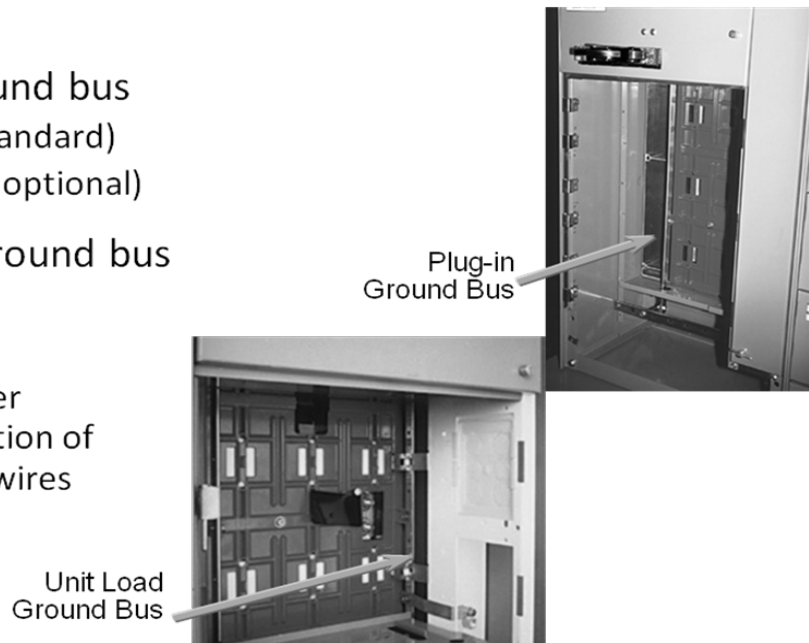
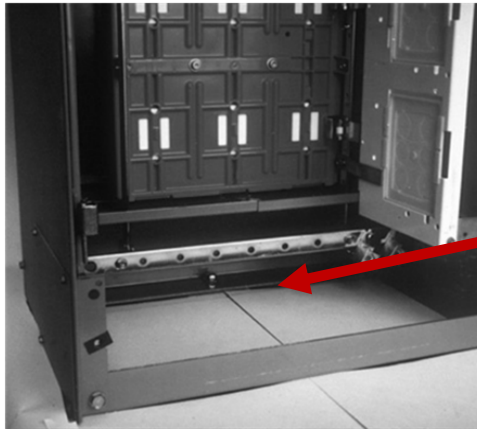


Figure 3.6: Vertical and horizontal ground bus bars in a typical MCC.



- 1/4" x 1" (6.4mm x 25.4mm)
or
1/4" x 2" (6.4mm x 50.8mm)
- Unplated or
tin-plated copper
- Located in wireway
 - Top or bottom
 - Top and bottom

Figure 3.7: Horizontal ground bus bars in an MCC.

Each standard vertical section is supplied with a steel vertical “plug-in ground bus” on the left side of the section. The vertical ground bus is bolted to the horizontal ground bus, providing positive grounding for all plug-in units. The load ground wires, from various field locations, can be brought directly to the MCC.

Incoming Lug Compartment

Power must be brought into the MCC. Therefore, the MCC needs to have some type of incoming compartment. There are 3 ways to accommodate the incoming power: incoming lug compartment, main fusible disconnect, and main circuit breaker.



- Top or bottom
- Straight pull for
cables

Figure 3.8: Physical size specifications of a typical MCC.

Typically, an incoming lug compartment is used when the main disconnecting means for the MCC is located in switchgear near the MCC. See Figure 3.8. Incoming lug compartments are available for top or bottom entry of the power cables. The incoming lug compartment is designed so the cables are brought straight into the compartment. There is no power bus in the way and therefore, there is no need for sharp cable bends. This configuration is available sizes range from 600A to 3000A.

Main Fusible Disconnect Switch

- Top or bottom
- Frame mounted
- 600A-2000A utilize “Bolted Pressure Switch”
- Visible blade

Bolted
Pressure
Switch

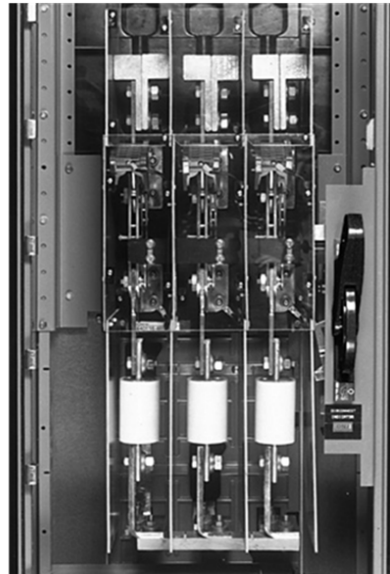
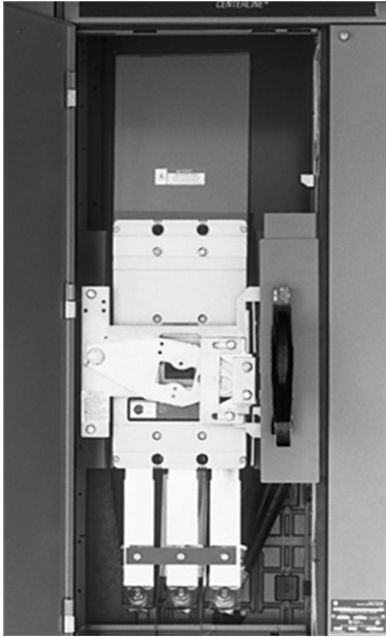


Figure 3.9: Physical size specifications of a typical MCC.

Another way to accommodate the incoming cables is with a main fusible disconnect switch. See Figure 3.9. Main fusible disconnect switches are available for top or bottom entry of power cables. They are frame-mounted (non plug-in), and hard-wired to the horizontal bus. For 600A to 2000A applications, a “Bolted Pressure Switch” is used. The bolted pressure switch features a contact system that tightly holds the blades during closure to provide a reliable current path and high withstand. All main disconnect switches provide visible blade indication.

Main Circuit Breaker



- Top or bottom
- Frame mounted
- Ground fault protection available

Figure 3.10: Physical size specifications of a typical MCC.

A main circuit breaker is another way that the incoming power cables can be accommodated. See Figure 3.10. Main circuit breakers are available for top or bottom entry of power cables and, are frame-mounted (non plug-in) and hard-wired to the horizontal bus. They are available in sizes up to 2000A. Ground fault protection is available for 600A to 2000A main circuit breakers.

There are pros and cons associated with fusible disconnect switches and breakers. When fuses clear (or “blow”), they must be replaced with exact equivalents. Incidents have been reported where improper fuse substitution has resulted in catastrophic failure of fuses, resulting in arc flash incidents. If breakers are applied as disconnecting and over current protection means in a power distribution system, they simply need to be reset when they trip in response to over-current conditions. One possible disadvantage associated with breakers is that they don’t offer as much flexibility in terms of current limiting and fast action as compared with some of the current limiting and fast acting fuses, i.e. Ferraz Shawmut class J and RK.

Stab Assembly

The stab assembly housing isolates each phase at the rear of the unit. See Figure 3.11. Since the power wires are isolated within the stab assembly, a fault barrier is effectively formed between the units and the vertical bus.

- Housing

- Isolates incoming phases acting as a fault barrier

- Stabs

- Tin-plated
- Rated 240A
- Directly crimped
- Steel spring backed
- Free-floating and self-aligning

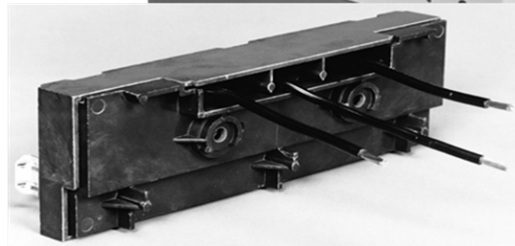
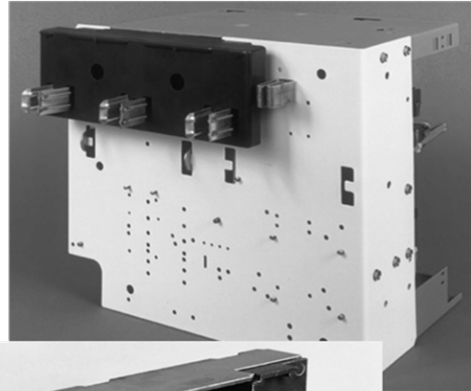


Figure 3.11: Stab assembly behind a typical MCC cubicle.

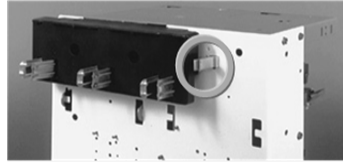
The tin-plated stabs, rated 240 amperes, are directly crimped to the power wires, minimizing any chance for a loose connection. The steel spring that backs the stab ensures a reliable high-pressure four-point connection on the vertical bus. The stabs are also free-floating and self-aligning, meaning they will position themselves for easy unit insertion.

Unit Grounding Provisions

A unit ground stab is provided on the back of each plug-in unit. See Figure 3.12. The ground stab engages the ground bus before the power stabs contact the vertical bus, and disengages after the power stabs are withdrawn from the vertical bus. The standard unit ground stab is made of a copper alloy. An unplated or tin-plated solid copper unit ground stab is also available.

- Unit ground stab

- Used with unit plug-in ground bus
- Copper alloy (standard)
- Solid copper (optional)



Standard
Plug-in
Ground
Stab

- Unit load ground connector

- Used with unit load ground bus
- Solid copper
- For easier termination of load ground wire



Optional
Plug-in
Ground
Stab

Unit Load
Ground
Connector



Figure 3.12: Ground system bus stabs in a typical MCC.

Unit Handle

The unit handle is flange mounted, and therefore stays in control of the disconnecting means at all times, whether the door is opened or closed.

The unit handle has positive status indication:

- Color-coded: **red** for **ON**, **green** for **OFF**.
- Labeled: ON and OFF (international symbols – **I** is used for **ON** and **O** for **OFF**).

Unit Handle



- Remains in control of disconnecting means
- Positive status identification
- Interlocked with door
- Padlockable

Figure 3.13: LOTO feature in the incoming power disconnect switch in a typical MCC.

The handle position is depicted in the ON and OFF positions (and TRIPPED position for circuit breakers). See Figure 3.13. The unit door is interlocked to the unit handle. The door cannot be opened when the handle is in the ON position unless the operator “defeats” the mechanism using a screwdriver. The unit handle can be locked in the OFF position with up to 3 padlocks for LOTO, Lock-Out/Tag-Out, purposes.

Unit Interlock

Plug-in units are supplied with a “unit interlock” that prevents the unit from being inserted into or withdrawn from the section while the handle is in the ON position. See Figure 3.14. When the handle is in ON position, the interlock mechanism moves upward engaging the unit support pan above the unit. The unit interlock can also be used to secure the unit in a service position to guard against accidental unit insertion. This is shown in the picture on the left.



- Prevents inserting or withdrawing unit with handle in ON position
- Padlockable

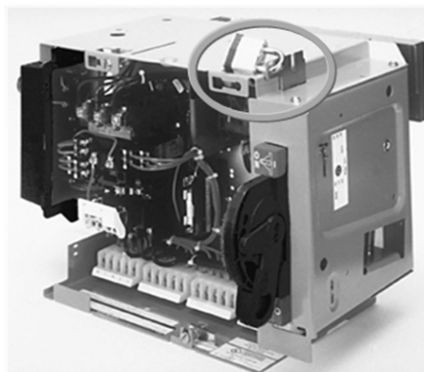


Figure 3.14: Physical size specifications of a typical MCC.

Lastly, the interlock can be padlocked during servicing to prevent unit insertion, shown in the photo on the right, even with the handle OFF.

Motor Starter – A-B Bulletin 2100

A motor starter is designed to control the flow of power to a motor, while, simultaneously, protecting the motor branch circuit against over-current conditions. Motor starters assemblies, such as the A-B Bulletin 500, are designed for up to 10 million operations. See Figure 3.15. Additional information on the design, specifications and operation of some of the motor starter components will be discussed in greater detail in Segment 10.

We will use the picture of a Bulletin 500 A-B starter, as captured in Figure 3.15, to examine the design and operation of a typical FVNR, Full Voltage Non-Reversing motor starter. Beginning at about 3 o'clock, in the motor starter picture below, we notice the handle of disconnect switch. The handle of the disconnect switch is mechanically linked to the mechanism labeled as the “Fusible Disconnect or Circuit Breaker.” The three knife switches visible in the picture, at about 12 o'clock, allow the three phase AC voltage to be applied to the fuse holder segment below. The three over current protection fuses are not shown installed in the starter assembly. The three terminals, with three emerging black wires, provide the continuity of the three phase voltage to the top of the contactor; labeled Bulletin 500 NEMA

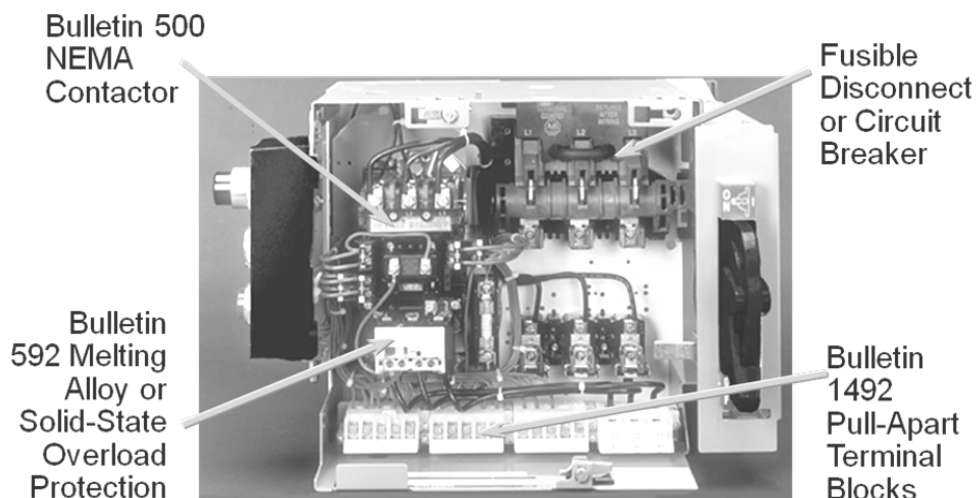


Figure 3.15: Physical size specifications of a typical MCC.

Contactor. A contactor, similar to a typical electrical relay, is simply an electromechanically controlled device that closes or opens contacts, to apply

or disengage AC voltage from the load, respectively. The load, in this case, is an electric motor.

The two wires visible directly in front of the contactor are ***control wires*** that energize the solenoid of the contactor. When the solenoid coil is energized, the core rod or plunger pushes the contact of the contactor shut and allows the flow of current and power downstream toward the motor, via the solid state overload protection device shown at about 8 o'clock. The solid state overload device is labeled as "Bulletin 592 Melting Alloy or Solid State Overload Protection" in Figure 3.15.

Notice the white terminal strips or terminal blocks visible along the bottom of the starter unit depicted in Figure 3.15. These terminal strips are called the "pull-apart terminal blocks." These pull apart terminal blocks are, typically, used in plug-in units and they represent a significant improvement in wire termination method. Prior to the advent of pull-apart terminal blocks, replacement, removal and re-installation of electrical required meticulous and arduous effort on the part of technicians to correctly terminate wires. The tedious task of disconnecting and connecting wires often resulted in miswiring and workmanship defects. The pull-apart terminal blocks have a front half and a rear half that detach for easy unit removal. The back half of the terminal block is factory wired, and the front half is where the contactor terminates field wires.

Pilot Devices

Pilot devices are shown mounted on the left side of the starter chassis as depicted in Figure 3.15 and shown again in the top left corner of Figure 3.16, labeled as "Bulletin 800T." Typical set of pilot devices include indicating lamps and control switches. The pilot device set shown in Figure 3.16 consists of one motor/load status indicating light at the top (typically, red or green). The two push buttons located below the indicating light are momentary (spring loaded) push button type switches. The middle switch, typically green in color, is the "START" switch, and the bottom switch, typically red in color, functions as a "STOP switch.

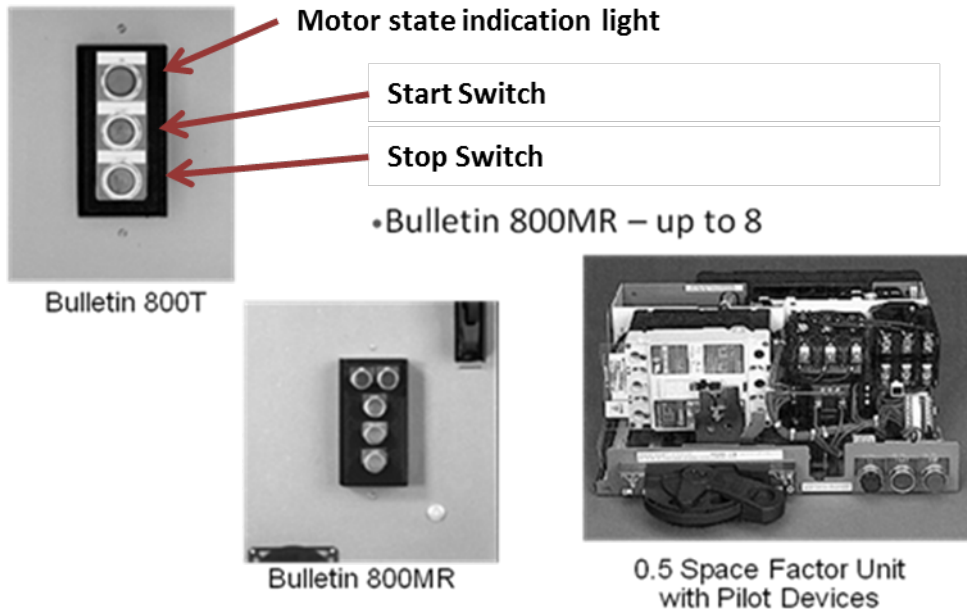


Figure 3.16: Motor starter pilot devices.

FVR, Full Voltage Reversing Starter and variety of other power control devices

As discussed earlier, when “on the fly,” instantaneous, reversal of a three phase AC motor is desired, a second contactor is incorporated into the motor starter cubicle to reverse the three phase AC sequence from ABC to ACB, and vice and versa. Of course, the two starters in such cases are interlocked to ensure that simultaneous connection of the two opposite phase sequences is avoided.

An FVR starter is pictured on the top right side of Figure 3.17. See labels “Contactor No. 1” and “Contactor No. 2” in Figure 3.17. An FVNR starter, with a single contactor, is depicted to the left of the FVR starter in Figure 3.17 for contrast. The bottom half of the picture in Figure 3.17 shows two other power control devices: (1) A soft start or two-speed starter unit, and (2) A full voltage lighting contactor unit.

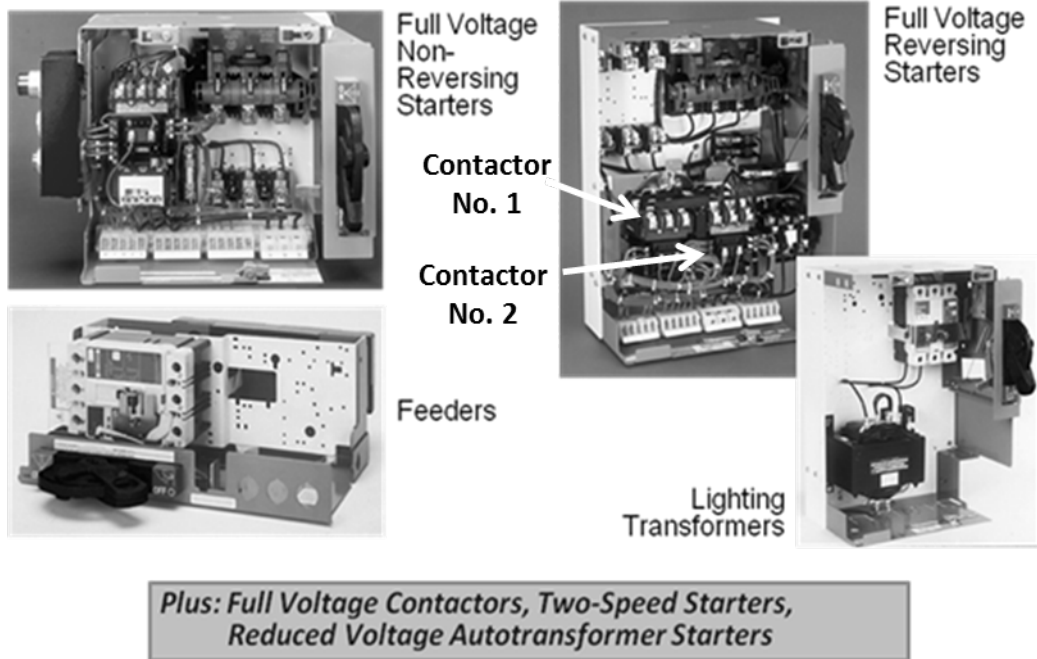


Figure 3.17: Motor starter pilot devices.

Variable Frequency Drives - Up to 250HP:

In addition to the power control devices discussed above, engineers can design or specify the integration of VFD's, or variable frequency drives, into MCC systems. When VFD's are housed into an MCC cabinet, it is advisable to maintain **electrical shielding** and adequate physical separation between power control components and more sensitive electronic systems like the VFD's and PLC's, Programmable Logic Controllers. In the absence of such caution, **electromagnetic interference**, or **EMI**, can adversely affect the operation of sensitive electronic systems.

Smaller variable frequency drives are often, specifically, designed to fit into plug-in units, or "**rack-out assemblies**." The VFD pictured on the left side of Figure 3.18, is a smaller, Bulletin 1305 drive. The smaller drives range from 3 hp at 240V to 5 hp at 480V. The VFD pictured on the right side of Figure 3.18, is a larger, Bulletin 1336 PLUS, drive. Some of the larger VFD's, such as the A-B 1336, fall in the following size categories:

- 1/2 – 30HP at 480V, plug-in design
- 40 – 125HP at 480V, frame-mounted design

- 150 – 250HP at 480V, roll-out design

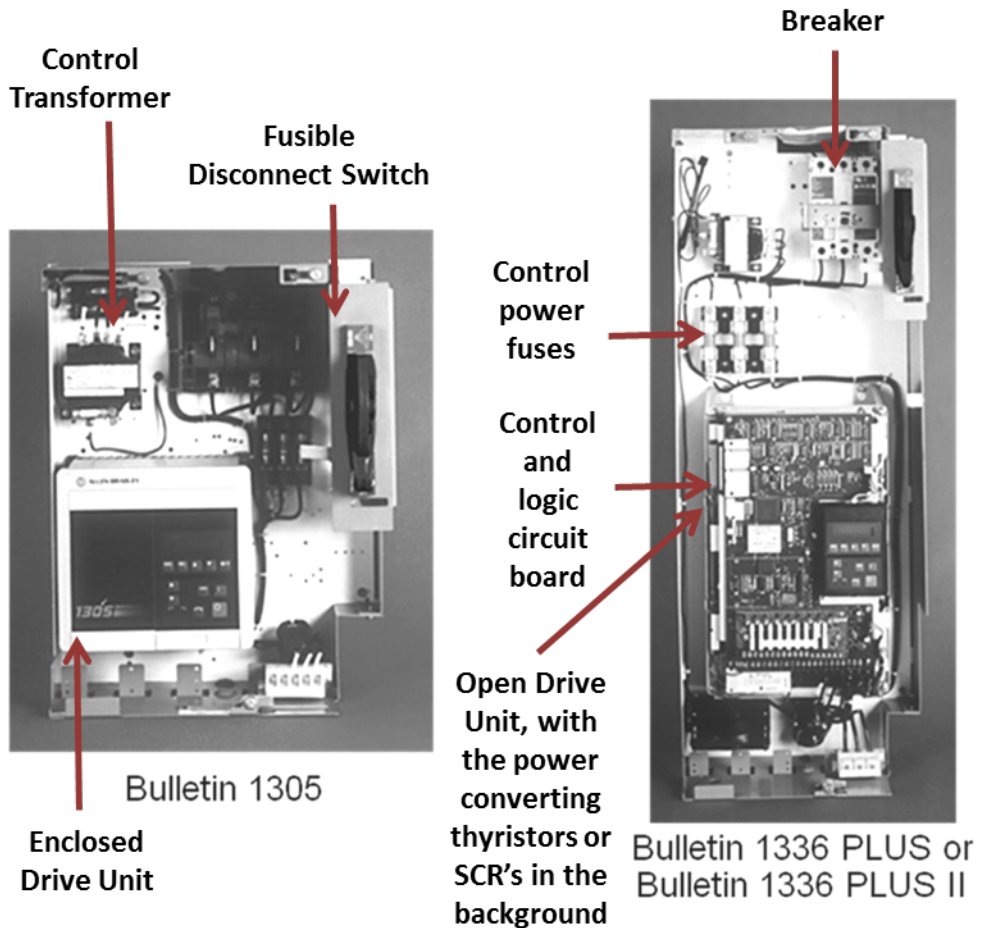


Figure 3.18: VFD, Variable Frequency Drives.

Smart Motor Controllers (SMCs) - Up to 500A

The Allen-Bradley, like other power and controls manufacturers, offers various smart motor controllers that allow motor loads to be operated at multiple, *discrete*, speeds to take advantage of energy savings in accordance with the *fan laws* or *affinity laws*. This essentially means that if the motor is operated at 50% of the normal full load speed (rpm), the power or energy consumption of the motor drops to 12.5%.

The smart motor controller featured in Figure 3.19 is an SMC-50 smart motor controller by Rockwell Automation. It is a solid-state motor controller that is premised on three-phase, solid-state, silicon-controlled rectifiers (SCR's, or thyristor's).



Figure 3.19: SMC 50, Rockwell-Automation Smart Motor Controller.

Motor Soft Starts

Soft Starters are typically employed in power control systems to limit excessive initial inrush of current associated with motor start up and provide a gentler ramp up to full speed. Contrary to VFD's, soft starters are only used during startup of motors. See Allen-Bradley soft start pictured in Figure 3.20.



Figure 3.20: Rockwell-Automation Soft Start.

In pump applications, a soft start can be installed to avoid pressure surges. Soft starts can facilitate smoother starting, as well as prevent jerking

and stressing of mechanical drive components, e.g. in conveyor belt systems that are loaded with bulk materials, intermittently. Using soft starts, fans or other systems with belt drives can be started slowly to avoid belt slipping. In essence, a soft start *limits the inrush current, improves stability* of the power supply and *reduces transient voltage drops* that may affect other loads and the overall power.

Among “non-electronic” methods for “soft-starting” are means such as the installation of a *series reactor* (coil or inductance, in general). Presence of a series reactance limits motor starting current.

Comparison between SMC’s, VFD’s and Soft Starts

The key differences between the application of VFD’s versus SMC’s are as follows:

- 1) VFD’s have the ability to vary the armature frequency and the motor speed in practically continuous, gradual or analog fashion. Smart motor controllers, on the other hand, allow variation of the motor at multiple discrete, preset, levels or steps.
- 2) While VFD’s tend to cost more than the SMC’s, the continuous adjustability of the VFD’s can provide “finer,” higher resolution, control of AC motors. This could provide the end user better process control, in addition to the energy savings opportunity.
- 3) SMC’s and Soft Start systems tend to be smaller, in physical size, than VFD’s.
- 4) VFDs offer the greatest energy savings for fans and pumps.
- 5) Soft-starts tend to present the smallest footprint as compared to SMC’s and VFD’s.

PLC and I/O Chassis

Even though the focus of discussion through the exploration of Allen-Bradley MCC’s has been attainment of a better understanding of power or motor control devices, we will probe the hardware aspects of PLC’s (Programmable Logic Controllers) in this section, primarily because the SLC-

500 and Bulletin 1771 PLC's can be integrated into a typical Allen-Bradley MCC. See Figure 3.21. Of course, smaller PLC's, i.e. the Micro-Logix series, could be specified to be included in a section of a PLC, just as well.

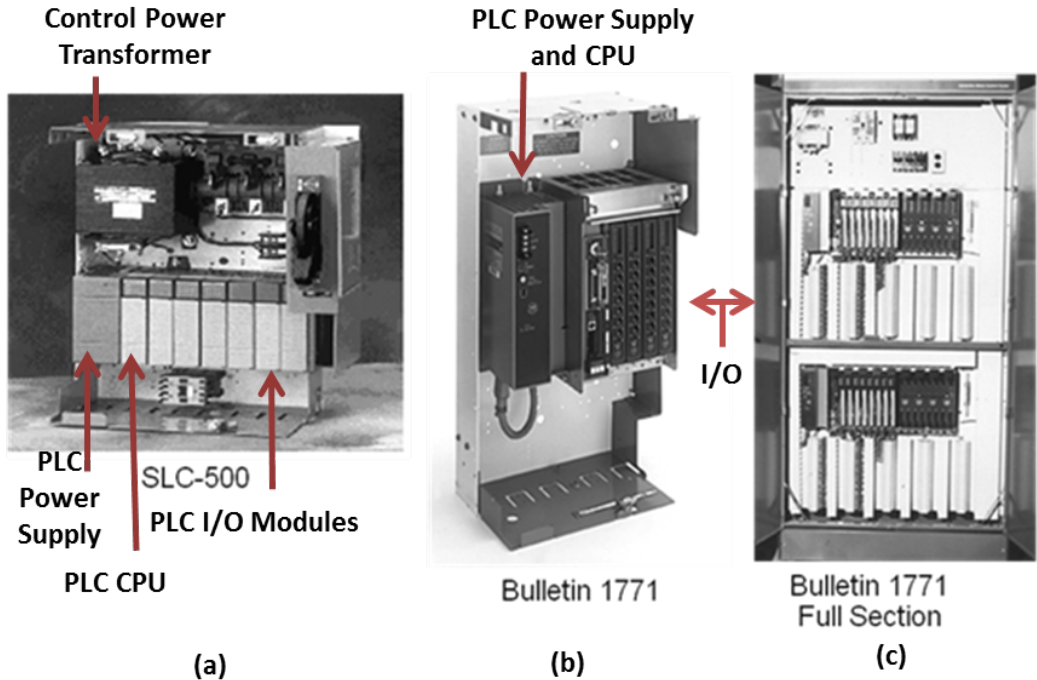


Figure 3.21: PLC's incorporated into an Allen-Bradley MCC.

However, once again, care should be exercised to protect the PLC, and associated I/O, Inputs and Outputs, from potential EMI emitted from power components in close proximity. The leftmost picture of a PLC shown in Figure 3.21 (a) depicts a SLC 500 PLC and associated I/O blocks. In Figure 3.21 (a), adjacent to the CPU (Central Processing Unit), the PLC Power Supply is shown mounted to the “*back plane*” of the PLC. A backplane, often, consists of a circuit board with rigid connectors that the I/O modules, CPU module and the power supply can be plugged into. A PLC, not unlike a PC (Personal Computer), operates off of low DC voltage, 5 to 10 V. This low DC voltage is generated by the PLC power supply. The power supply, in turn, is powered by low AC voltage. The PLC *control transformer*, shown in Figure 3.21 (a), transforms the 480 V_{AC} available at the 480 V_{AC} bus stabs into a lower AC voltage (≈ 14 V_{AC}). This lower AC voltage is converted from AC to DC by the rectifier in the power supply.

Larger Bulletin 1771 Allen-Bradley PLC's are pictured in Figures 3.21 (b) and (c). The PLC depicted in Figure 3.21 (b) is a Bulletin 1771 PLC with combined power supply, CPU and I/O on one panel. The PLC depicted in Figure 3.21 (c) is a Full Section Bulletin 1771 PLC, with power supply and the CPU on one panel and the I/O rack on a separate panel. The split panel configuration of the Full Section 1771 PLC system accommodates a larger number of inputs and outputs.

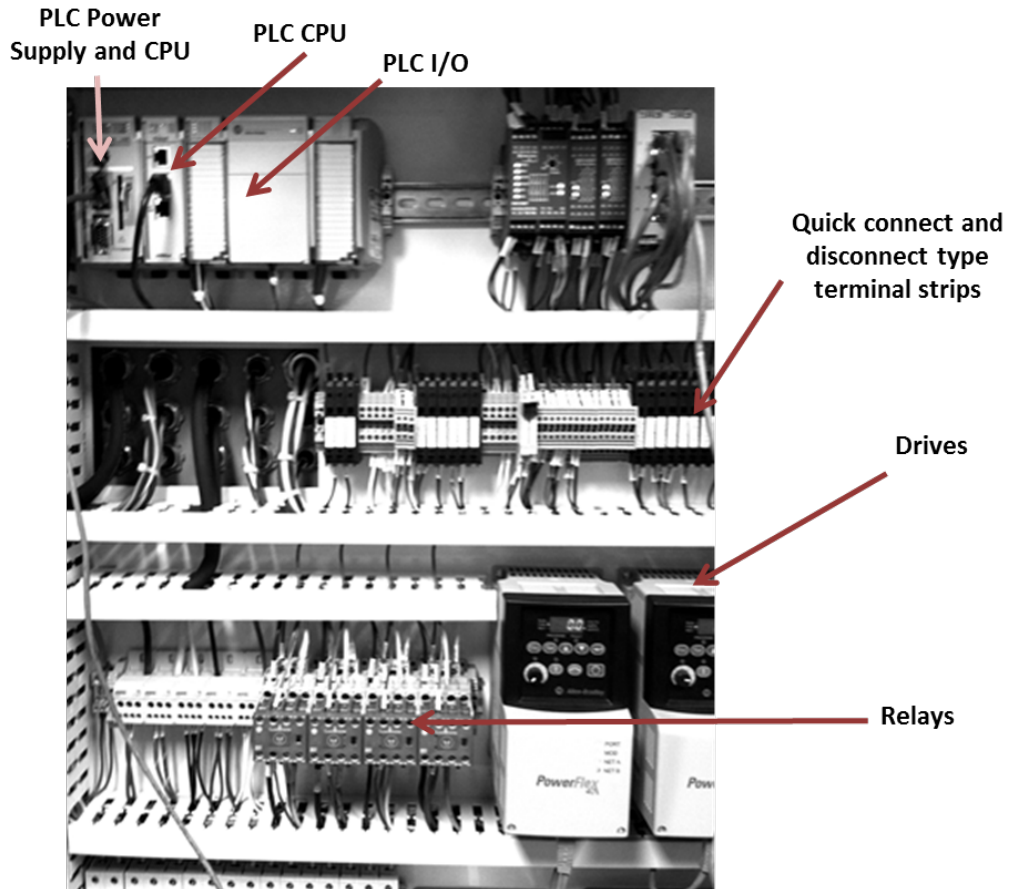


Figure 3.22: Complete control system in single control cabinet.

Often, PLC's are integrated into a single cabinet with peripheral control equipment such as variable frequency drives for automatic speed control and the control of higher current field devices through relays and contactors. Figure 3.22 depicts one such scenario.

Metering Units



Analog Metering Unit



Powermonitor II Metering Unit

Figure 3.23: MCC compatible power monitoring equipment

It is common for engineers to specify and incorporate power monitoring equipment into an MCC. Examples of typical power monitors are pictured in Figure 3.23. The power monitoring unit shown on the left reads the monitored power parameters in the traditional analog format, while the unit on the right is a more contemporary digital power monitor. The digital power monitors tend to be more versatile; they are often designed to capture and display electrical parameters like: three phase voltage, current, kW's (or real power **P**), kVA's (or apparent power **S**), kVAR's (or reactive power **Q**), power factor, frequency, etc.

The rear of a multifunctional, digital, power monitor is displayed in Figure 3.24 below. The wires bringing the current signal from line current measuring CT's (current transformers) would be terminated at terminals **I₁**, **I₂** and **I₃**. The voltage signal coming from the voltage or potential transformers would be terminated at points labeled **V₁**, **V₂** and **V₃**. Also, note the Ethernet connection port in the top right corner of Figure 3.24. This Ethernet port allows the power monitor to transmit all data to a central power monitoring work station through an *Ethernet LAN*, Local Area Network. Such network connectivity allows multiple monitors to feed data to a central location for display and control purposes. The digital communication attribute of digital power monitors and the connectivity to LAN also permit users to broadcast the data for off-site monitoring through *routers* and *modems*.



Figure 3.24: Rear termination points on an Allen-Bradley Power Monitor

Main Switch Yard and Medium Voltage Switchgear

During the course of our discussion of power distribution equipment in this text we made mention of “Main Switch Yard.” For illustration purposes, a picture of the main switch yard of a facility is shown in Figure 3.25. Main switch yards are compounds, on-site at the consumer’s facility, where the utility (power company) “lands” the power into the customer’s facility and transforms it from high voltage to medium voltage, i.e. 100kV to 13kV.

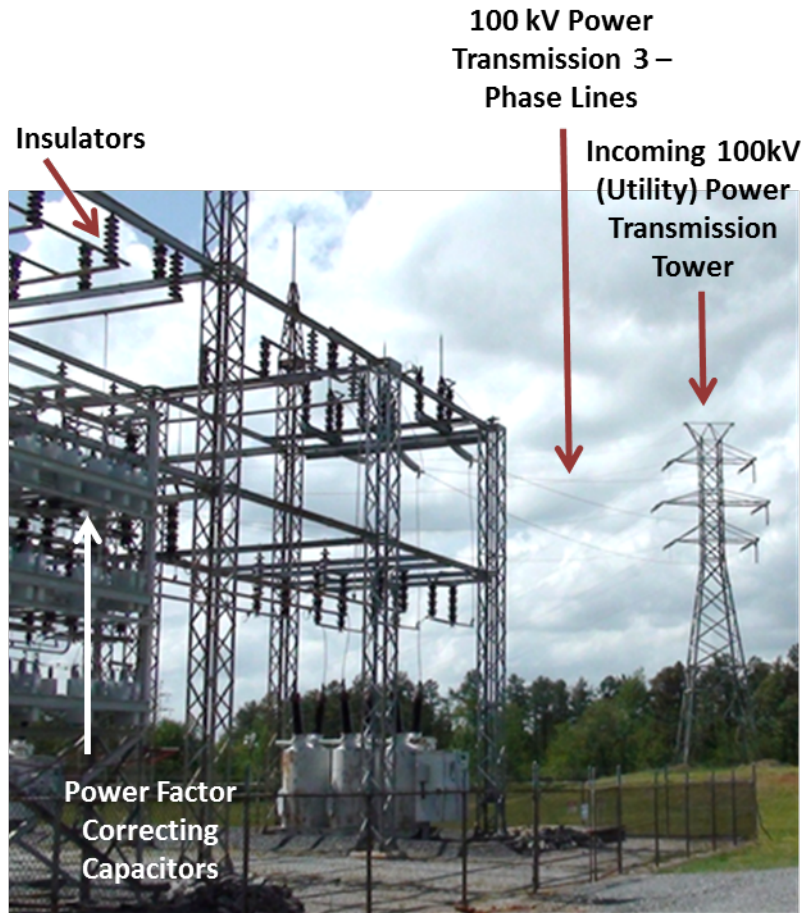


Figure 3.25: Main Switch Yard; 100kV.

Medium Voltage Switchgear – Loop Switch

Switching within facilities, at the medium voltage level, is accomplished through loop switches and breakers. A typical, three phase, 13kV loop switch is pictured in Figure 3.26. Some of the key functional components of the loop switch, i.e. the operating mechanism, viewing ports and switch status (Open or Closed), are annotated on Figure 3.26.

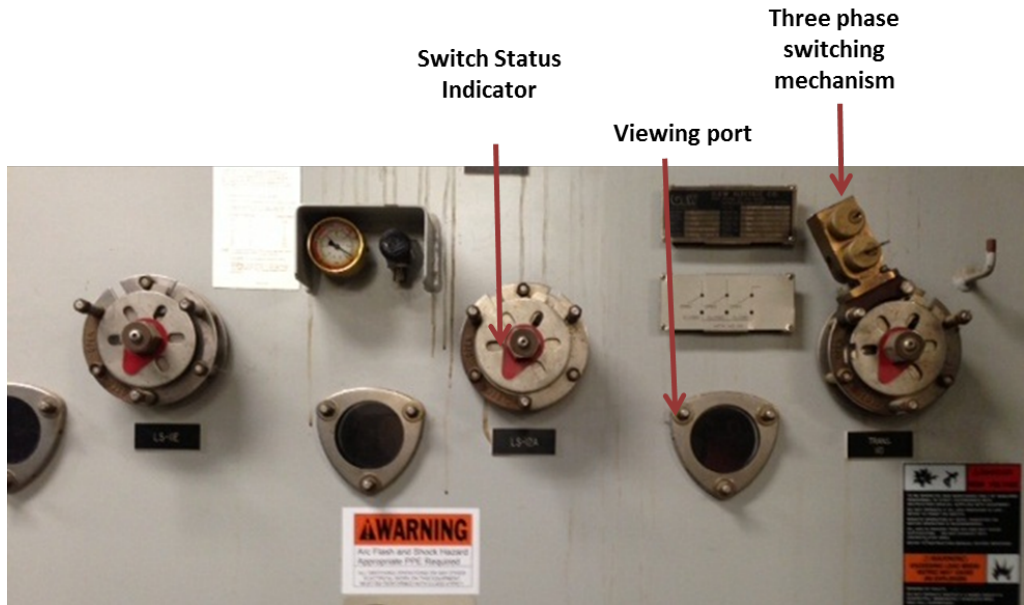


Figure 3.26: 13kV Loop Switch.

Power factor correcting capacitors and step down transformer, Main Switch Yard

Power factor correcting capacitors, installed on the power company side of the main switch yard, are pointed out in Figure 3.27 below. Also annotated are the large 100kV to 13kV step down transformers on the power company side of the switch yard.

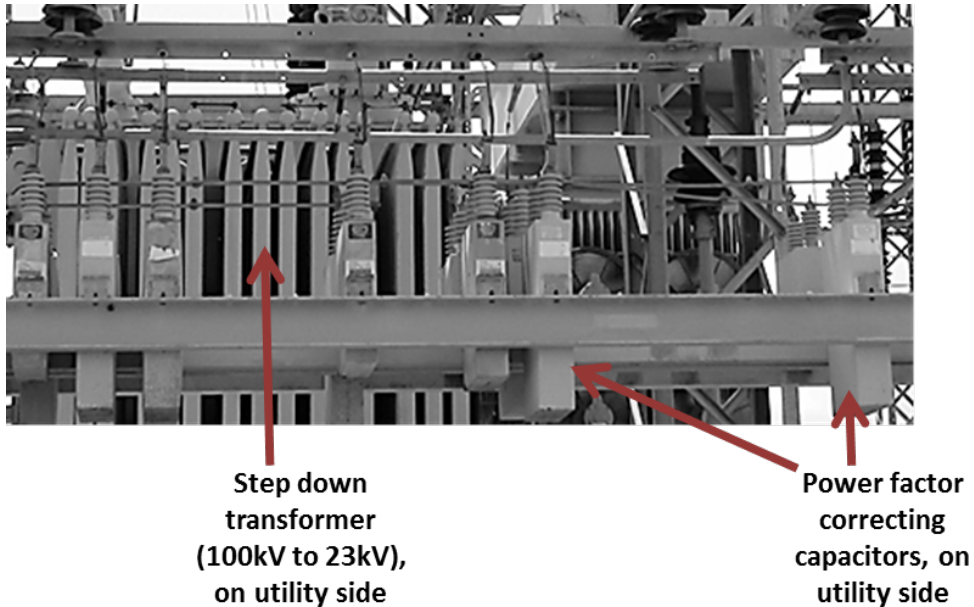


Figure 3.27: Power factor correcting capacitors and main step-down transformer in a Main Switch Yard.

Circuit Breakers

A circuit breaker is an over current protection device that is automatically operated. A circuit breaker basically is an electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit. Its core function is to detect a fault condition and interrupt current flow. Unlike a fuse, which operates once and then must be replaced, a circuit breaker can be reset (either manually or automatically) to resume normal operation. The most common and basic type of circuit breaker is the type that is often applied in residential dwelling breaker panels. Circuit breakers are categorized based on the following features or functions:

- a) Voltage
- b) Current
- c) Principle of operation

Circuit breakers for large currents or high voltages are equipped with sensing and transducing devices that detect fault current and operate the trip or circuit opening mechanism. The term “trip,” essentially means “opening” of an electrical circuit such that the current ceases to flow. The trip function is

typically executed by a solenoid that releases a latch that keeps the breaker closed (ON). In order to maintain the fail safe properties typically required in control systems, the tripping solenoid is often energized by a separate battery. High-voltage circuit breakers are self-contained with current transformers, protection relays, and an internal control power source.

Upon detection of a fault, or fault current, contacts within the circuit breaker open to interrupt the circuit. Often, mechanically stored energy in springs or compressed air is used to separate and force open the contacts, thus interrupting the flow of current.

Low voltage circuit breakers

As the name implies, low voltage breakers are applied in domestic, commercial and industrial application, operated at less than 1000 V_{AC}. The design of low voltage breakers is premised on thermal or thermal-magnetic operation. Low voltage power circuit breakers can be mounted in multi-tiers in low-voltage switchboards or switchgear cabinets. Low-voltage circuit breakers are also made for DC applications, i.e. electrical protection of subway lines.

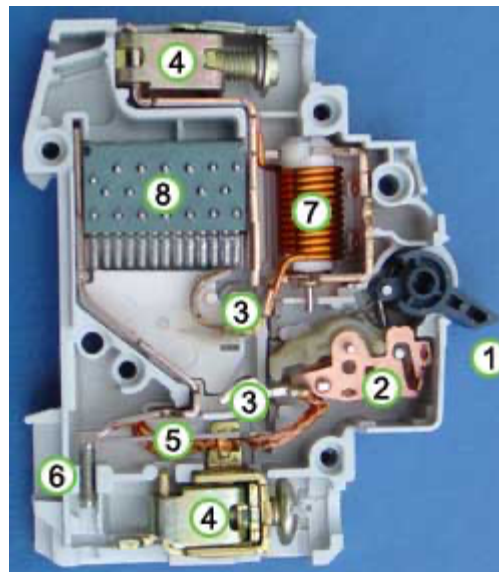


Figure 3.28: Sectional diagram of a common rail-mounted thermal-magnetic miniature circuit breaker. Dorman Smith circuit breaker, annotated by: Ali, UK.

A sectional diagram of a common 10 ampere DIN rail-mounted thermal-magnetic miniature circuit breaker is depicted in Figure 3.28. Where,

1. Actuator lever - used to manually trip and reset the circuit breaker. The legend on the breaker typically indicates the status of the circuit breaker (ON or OFF).
2. Actuator mechanism - forces the contacts to “close” or “open.”
3. Contacts - Allow the load current to flow when *closed* interrupt the flow when *open*.
4. Terminals.
5. Bimetallic strip for thermal operation or tripping of the breaker under prolonged overload conditions.
6. Calibration screw - allows the manufacturer to precisely adjust the trip current of the device after assembly.
7. Solenoid.
8. Arc divider or extinguisher.

Medium-voltage circuit breakers

Medium-voltage circuit breakers are classified based on the medium (or substance) used within to extinguish the arc. Some of the medium-voltage circuit breakers types are discussed below:

Vacuum circuit breakers: The vacuum circuit breakers, rated up to 3000 A, interrupt the current by creating and extinguishing the arc in a near vacuum environment, within a sealed container. The vacuum circuit breakers are generally applied for voltages up to about 35,000 V; they tend to have longer life expectancies, and they offer longer service spans between overhauls than do air circuit breakers.

Air circuit breakers: Air circuit breakers are rated, in current, up to 10,000 A. Their trip characteristics are often fully adjustable including configurable trip thresholds and delays. They are often electronically controlled.

SF₆ circuit breakers: The SF₆ medium voltage circuit breakers extinguish the arc in a chamber that is filled with *sulfur hexafluoride gas*.

High-voltage circuit breakers

High voltage circuit breakers are often applied in electrical power transmission networks. High-voltage breakers are almost always solenoid-operated, with current sensing protective relays operated through current transformers. A high voltage circuit breaker, rated 110 kV, is depicted in Figure 3.29. This breaker is designed for 50 Hz operation and is equipped with dielectric oil based arc quenching system.

High-voltage breakers are broadly classified based on the medium used to extinguish the arc. Technically, any of the following can be used for arc quenching:

- Bulk oil
- Minimum oil
- Air blast
- Vacuum
- SF₆, sulfur hexafluoride gas

However, due to environmental and cost concerns over insulating oil spills, most new breakers use SF₆ gas to quench the arc.

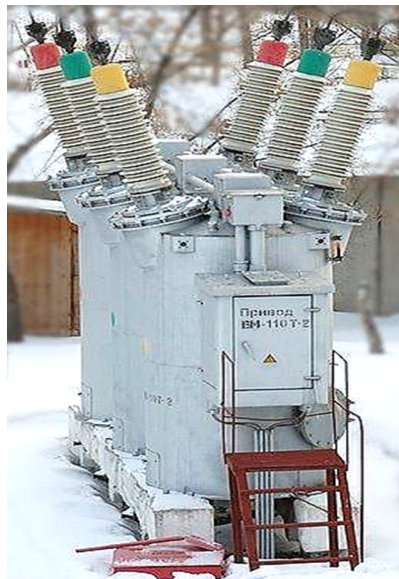


Figure 3.29: Oil circuit breaker MKP-110 (110 kV) on traction substation 110 kV 50 Hz/3.3 kV DC of railway, Toliatti city, Russia. By: Vivan.

Self-assessment Questions – Segment 3

1. A substation in a manufacturing facility is being fed from a 13kV transformer secondary. This switchgear in this substation would be categorized as:

- A. Medium voltage
- B. Low voltage
- C. High voltage
- D. Medium voltage
- E. None of the above

2. Power transmission lines would be categorized as:

- A. Medium voltage
- B. Low voltage
- C. High voltage
- D. Medium voltage
- E. None of the above

3. The breakers installed in residential breaker panels are:

- A. OCB's
- B. Thermal magnetic circuit breakers
- C. Low voltage thermal magnetic circuit breakers
- D. None of the above
- E. Both B and C

4. The vacuum circuit breakers tend to offer longer service spans between overhauls than do air circuit breakers.

- A. True
- B. False

5. The SF₆ type high voltage circuit breakers are not preferred due to environmental concerns.

- A. True

B. False

6. MCC's are not designed to accommodate PLC's and VFD's.

A. True

B. False

7. The bus bars in MCC's are commonly constructed out of:

A. Aluminum

B. Silver plated copper

C. Silver

D. Iron

8. Pilot devices on MCC's:

A. Control circuit breakers

B. Indicate the status of MCC

C. Indicate the status of motor/load

D. Include "Start" and "Stop" controls

E. Both (C) and (D).

9. Power control cubicles in MCC's are fixed and cannot be removed while the main fusible disconnect switch of the MCC is ON.

A. True

B. False

10. A control transformer, in a given MCC compartment:

A. Steps down the voltage for control circuit operation

B. Provides power for MCC cabinet lighting

C. Is seldom needed

D. Serves as an isolation transformer

E. Both (C) and (D)

APPENDICES

Appendix A

Solutions for Self-Assessment Problems

This appendix includes the solutions and answers to end of segment self-assessment problems and questions.

MADE AVAILABLE UPON PURCHASE OF COURSE

Appendix B

Common Units and Unit Conversion Factors

MADE AVAILABLE UPON PURCHASE OF COURSE

Appendix C

Greek Symbols Commonly Used in Electrical Engineering

MADE AVAILABLE UPON PURCHASE OF COURSE