Electrical

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MODULE 5

INTRODUCTION

This module covers the following areas pertaining to electrical:

- Basic electrical theory
- Transformers
- Generators
- Protection

At the completion of the module the participant will be able to:

1 OBJECTIVES

1.1 BASIC ELECTRICAL THEORY

- explain the following electrical terms: current, potential, resistance, capacitance, magnetic flux, inductance, frequency, reactance, impedance, active power, reactive power, apparent power, power factor;
- identify the unit of measurement of electrical quantities;
- explain relationship between electrical quantities;
- describe how excessive moisture and temperature can affect the insulation; resistance of materials used in electrical machines;

1.2 TRANSFORMERS

- explain how tap changers are used to change the ratio of input to output voltage;
- explain the operational limitation of off-load tap changers;
- identify the factors that cause heating in transformers;
- explain the operating conditions that affect heat production;
- identify the limitations on transformer operation.

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1.3 GENERATORS

- explain why excitation is only applied when a generator is at or near rated speed;
- explain why the electrical parameters parameters must be within acceptable limits before a generator can be connected to an electrical system;
- identify how synchroscope indication is interpreted to ensure correct conditions exist to close the breaker;
- explain how a generator responds when the breaker is closed onto a dead bus with capacitive or inductive loads attached;
- identify why electrical loads should be disconnected prior to energizing a bus;
- define finite and infinite bus
- describe how generator terminal voltage is automatically controlled
- describe the function of a turbine governor;
- describe how generator parameters are affected by changes in either turbine shaft power or excitation current when a generator is connected to an infinite grid;
- describe the factors that influence steady state limit and transient stability in generators and transmission lines;
- explain why limits are placed on generator parameters;
- describe the changes that occur during a load rejection from load power;
- describe the speed and voltage control systems response during a load rejection from full power;
- explain why heat is produced in generator components and the consequence of excessive heat production;
- identify how heat is removed from the rotor and stator;
- explain why stator water conductivity is limited;

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- state the consequences of exceeding the conductivity limit;
- explain how the ingress of water or air into the generator impairs the ability of the hydrogen to insulate and cool the generator.

1.4 PROTECTION

- explain how differential protection is used to provide protection to a bus;
- identify why differential, over-current back-up, ground fault and under voltage are required to provide protection for electrical busses;
- identify why instantaneous over-current, differential, gas relay, thermal overload and ground fault are required to provide protection for electrical transformers;
- explain why instantaneous over-current, timed over-current, thermal overload, ground fault, stall and over-fluxing are required to provide protection for electrical motors;
- identify why it is acceptable to immediately reset a thermal overload relay on an electrical motor and not an instantaneous over-current relay;
- identify when a class A, B, C, or D turbine trip can occur;
- explain why over-current, differential, ground fault, phase imbalance, loss of field, over-excitation, under-frequency, pole-slip, reverse power and rotor ground fault are required to provide protection for electrical generators.

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2 BASIC ELECTRICAL THEORY

2.1 INTRODUCTION

The first section examines the definitions and interrelations of the basic electrical quantities (Amps, Volts, Watts, Vars, Power Factor, etc.). It will also investigate basic ac/dc electrical theory that forms the basis of operation of electrical equipment (motors, transformers, generators, power converters and un-interruptible power supplies)

2.2 ELECTRICAL TERMS

What is commonly defined as electricity is really just the movement of electrons. So, let's start at that point.

2.2.1 Current (I, Amps)

Current (as the name implies) is the movement or flow of electrons (I) and is measured in units of Amperes. This is usually abbreviated to Amp or, even shorter, A. The flow of electrons in an electrical current can be considered the same as the flow of water molecules in a stream.

To get anything to move requires potential and the same thing happens to electrons.

2.2.2 Potential (V, Volts)

Potential is the force (called Electromotive Force or EMF) that drives the electrons and has a measurement of voltage. This is abbreviated as a unit of measurement to Volt or even further to V.

2.2.3 Resistance (R, Ohms)

Resistance is the property that resists current flow. It is analogous to friction in mechanical systems. The unit of this is ohm (we have to give some credit to the fellow who first named it). It is sometimes shown with its official ohm mark (Ω) and the short form of the word resistance is always R. Resistance not only depends on the material used for the conductor but also upon size and temperature.

Increase in the cross-sectional area will decrease the resistance

Increase in the length will increase the resistance

- Increase in the temperature will increase the resistance (for most materials that conduct electricity)

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2.2.4 Capacitance (C, Farads)

Any two conductors separated by an insulating material form a capacitor or condenser. Capacitance of a device is its capacity to hold electrons or a charge. The units of measurement are farads. We commonly see it in smaller amounts called microfarads μF and pico-farads pF. Capacitance depends on the construction.

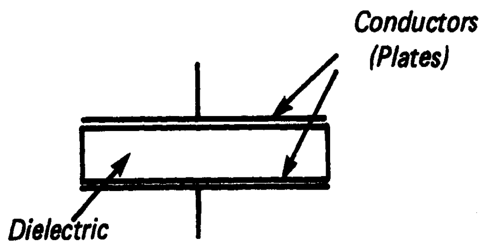

Figure 1
Capacitance

- The closer the plates are together the larger the capacitance
- The larger the area of the plates the larger the capacitance

2.2.5 Magnetic Flux (Unit of Measurement is Webers)

When current flows in a conductor, a magnetic field is created around that conductor. This field is commonly presented as lines of magnetic force and magnetic flux refers to the term of measurement of the magnetic flow within the field. This is comparable to the term current and electron flow in an electric field. The following illustration shows the direction of magnetic flux around a conductor and the application of the easily remembered right-hand-rule.

Mentally, place your right hand around the conductor with the thumb pointing in the direction of current flow and the fingers will curl in the direction of magnetic flux.

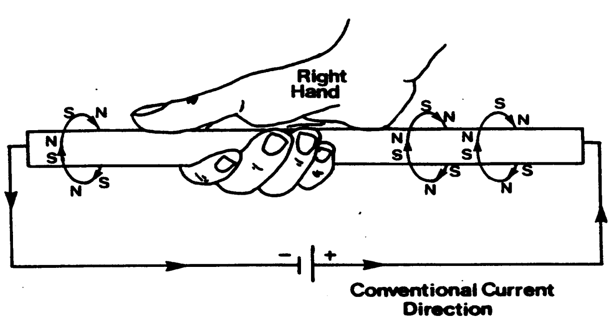

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Figure 2
Magnetic Lines of Force (MMF)

Lines of magnetic force (MMF) have an effect on adjacent conductors and even itself.

This effect is most pronounced if the conductor overlaps itself as in the shape of a coil.

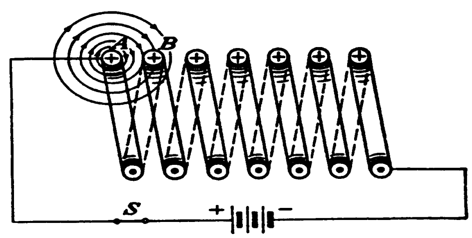

Figure 3
Magnetic Self-Inductance

Any current-carrying conductor that is coiled in this fashion forms an Inductor, named by the way it induces current flow in itself (self-inductance) or in other conductors.

2.2.6 Inductance (L, Henrys)

Opposition to current flowing through an inductor is inductance. This is a circuit property just as resistance is for a resistor. The inductance is in opposition to any change in the current flow. The unit of inductance is Henry (H) and the symbol is L.

2.2.7 Frequency (f, Hertz)

Any electrical system can be placed in one of two categories direct current (dc) or alternating current (dc). In dc systems the current only flows in one direction. The source of energy maintains a constant electromotive force, as typical with a battery. The majority of electrical systems are ac.

Frequency is the rate of alternating the direction of current flow. The short form is f and units are cycles per second or Hertz (short-formed to Hz).

2.2.8 Reactance (X, Ohms)

The opposition to alternating current (ac) flow in capacitors and inductors is known as reactance. The symbol for capacitive reactance is X_C and for inductive reactance $X_{L.}$

Notes

Although we will not go into the derivation of the values, it can be shown that when f is the frequency of the ac current:

$X_L = 2\,\Pi f\,L$

$X_C = 1/2\Pi fC$

2.2.9 Impedance (Z, Ohms)

The total opposition or combined impeding effect of resistance plus reactance to the flow of alternating current is impedance. The word impedance is short formed to Z and the unit is ohms. The relationship can be illustrated in a simple series circuit shown below:

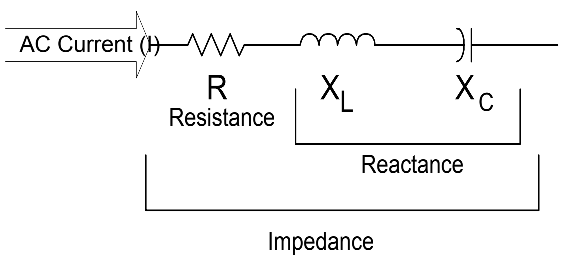

Figure 4
Impedance

2.2.10 Active Power (P Watts)

Instead of working directly with the term electrical energy, it is normal practice to use the rate at which energy is utilized during a certain time period. This is defined as power. There are three components of power: active, reactive and apparent.

Active power or real power is the rate at which energy is consumed resulting in useful work being done. For example, when current flows through a resistance, heat is given off.

It is given the symbol P and has the units of Watts.

2.2.11 Reactive Power (Q, Vars)

Reactive power is the power produced by current flowing through reactive elements, whether inductance or capacitance. It is given the representative letter Q and has the units volt-amp-reactive (VAR).

Reactive power can also be considered as the rate of exchange of energy between a capacitor or inductor load and a generator or between capacitors and inductors.

Notes

Although it does not produce any real work, it is the necessary force acting in generators, motors and transformers. Examples of this are the charging/discharging of a capacitor or coil. Although this creates a transfer of energy, it does not consume or use power as a resistor would.

2.2.12 Apparent Power (U, Volt Amps)

Apparent power is the total or combined power produced by current flowing through any combination of passive and reactive elements. It is given the representative letter U and has the units volt-amps (VA).

2.2.13 Power Factor (PF)

Real power/ apparent power

Power Factor is the comparison of Real power to apparent power.

- For a resistor, there is no reactive power consumed. Thus apparent power used is totally real. The power factor would be 1 or often referred to as unity power factor
- For a pure inductor or capacitor, the apparent power consumed is entirely reactive (real power is nil). The power factor would then be 0.
- For power consumed by an impedance consisting of resistance, inductance and capacitance the power factor will of course vary between these two limits.

The most efficient use or consumption of power is obtained as we approach unity power factor

2.3 RELATIONSHIPS OF THE BASIC ELECTRICAL QUANTITIES

2.3.1 Voltage vs. Current in a Resistor, Capacitor or Inductor

Elements in an electrical system behave differently if they are exposed to direct current as compared to alternating current. For ease of explanation, the devices have often been compared to similar every day items.

- Resistors in electrical systems are similar to rocks in a stream of water.
- A capacitor is comparable to a boat paddle inserted into the stream.
- The action of inductor is similar to a coiled spring.

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2.3.2 dc Circuit Components

Let us first look at the simple case of a dc circuit composed of a constant EMF (battery) and the three basic elements and two configurations (series/parallel).

2.3.3 Resistors

As the current flows through the resistors, in the same way that water flows over rocks, it expends some of its energy. If the rocks in a stream were in the form of rapids, the stream would have considerable resistance. However, if the same amount of rocks were placed in a row across the stream, the overall resistance to current flow would be less.

The diagrams below illustrate the basic but underlying principle in the majority of electrical systems. The amount of potential required to force 1 Amp through 1 Ohm of resistance is 1 Volt (Ohms Law). This is often written as V=IR.

In the series circuit (on left), the same current flows through every resistor, but the applied voltage is divided between them. In the parallel circuit (on right), the same voltage is applied to all resistors but the current divides between them.

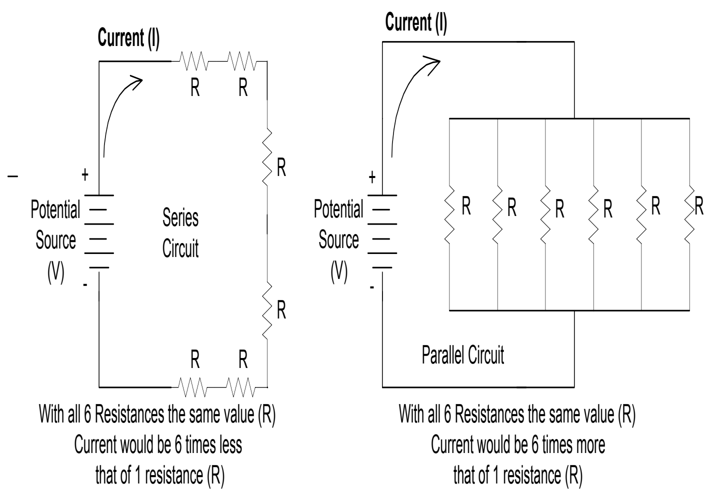

Figure 5
dc Circuit Resistance

For a series circuit the total resistance is stated as $R_{Total}=R_1+R_2+(\text{etc.})$. In this example $R_{Total} = 6R$.

Notes

- For a parallel circuit the total resistance is stated as $1/R_{Total} = 1/R_1+1/R_2+$(etc.). In this example $1/R_{Total} = 6/R$ or $R_{Total} = R/6$.

- Circuits containing a combination of series and parallel portions apply the same basic theory with more lengthy calculations.

2.3.4 Capacitors

A capacitor, as previously described, is physically made of two conducting surfaces separated by an insulator. In an electrical circuit capacitors have both a steady state and transient effect on the circuit. As the electrical conductors are not in physical contact, it will not, in the long-term pass direct current. The action is the same as placing a boat paddle against a stream of water - it blocks current flow. However when voltage is first applied to a capacitor current will flow until the capacitor is charged. This is a transient effect.

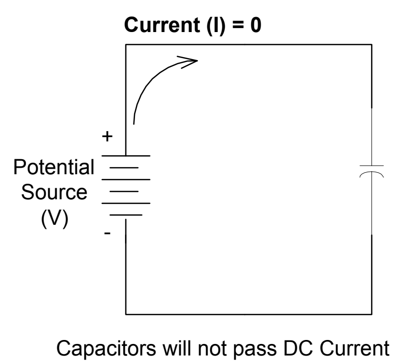

Figure 6
dc Circuit Capacitance Steady State Effect

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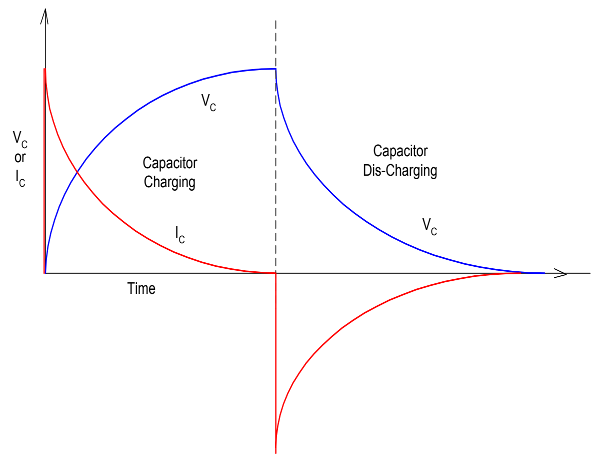

Figure 7

dc Circuit Capacitance Transient Effect

2.3.5 Inductors

The inductor as illustrated in Figure 8 is similar to a coiled spring and in the steady, has no resisting capability. If a steady force is exerted on it, it can pass huge amounts of energy limited only by the supply capability or heaviness of the inductor. An inductor in a dc system has to be used with caution as it allows unrestricted flow of energy and will drain the energy source or damage the inductor itself. However, when voltage is first applied the inductor impedes current flow in the circuit.

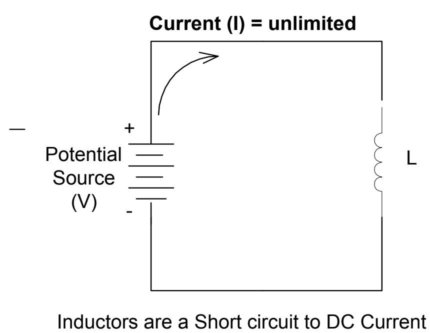

Figure 8
dc Circuit Inductance Steady State Effect

Notes

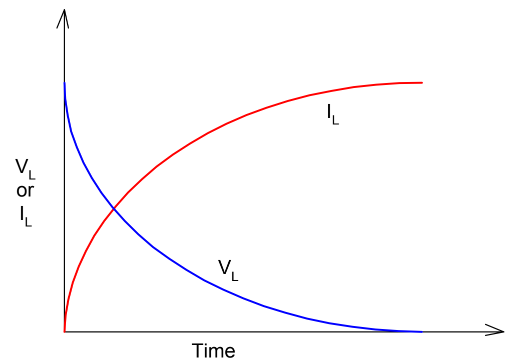

Figure 9

dc Circuit Inductor Transient Effect

2.3.6 Transient Effects

The transient effects of capacitors and inductors are the result of stored energy in the electrical circuit. Energy is stored in two forms, as stored electrical charge in a capacitor and in the magnetic field in an inductor. The amount of energy stored in an inductor depends on the current in the circuit; the amount of energy in a capacitor depends on the voltage across it. If the circuit conditions change so will the amount of energy stored in the component and a transient will occur.

One way of looking at the transient effects of these components is that inductors resist changes in current flow in a circuit and capacitors resist changes in voltage. In basic dc circuits inductors and capacitors are for the most part curiosities. However, in an ac circuit the voltage and current are continuously changing so capacitor and inductors have a continuous effect on the circuit.

2.4 PHASORS

The voltages and currents in ac circuits are continuously changing in sinusoidal patterns. In ac theory not only are we concerned with the magnitude of the voltage and current sine curves but also, the phase (the angle between the peaks) of them. There are numerous mathematical methods of representing these sine curves; one of the most common in electrical work is the phasor diagram.

Notes

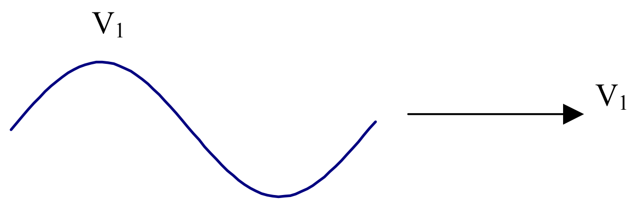

Figure 10

Sine curve and Phasor

A phasor looks a lot like a vector however it is not. A vector represents a magnitude and direction; a phasor represents a magnitude and an angle. Although, when it comes to manipulating phasor (adding or subtracting) quantities, all of the rules of vector addition and subtraction apply. Representing a single sine curve with a phasor is a little silly but when we go to compare sine curves then phasors are a handy tool.

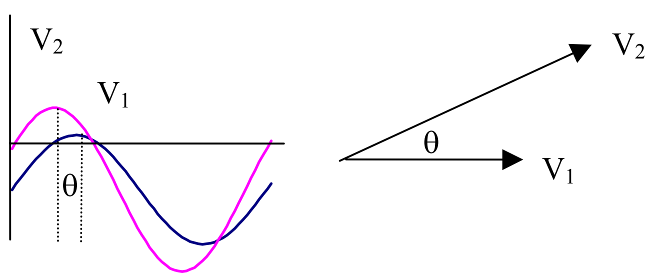

Figure 11

Phasor representation of two voltages

Figure 11 shows the phasor representation of two voltages that are not in phase nor equal in magnitude. In this diagram we would say that V_2 is larger than V_1 and that V_2 leads V_1 by the angle θ.

2.5 ac CIRCUIT COMPONENTS

2.5.1 Resistors

Resistive devices behave the same way to ac current as they do to dc as described previously and large amounts of energy are dissipated in the device.

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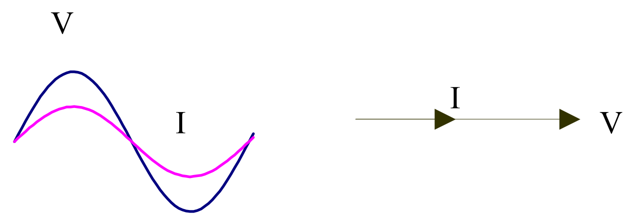

Figure 12

Phasor representation of a resistive circuit

2.5.2 Inductors

Inductors delay the current flow but do not take any energy from the current.

Example: This is similar to pushing on one end of a coiled spring. There is a delayed movement at the other end of the spring but the spring still puts out the same energy as was applied to it.

Series inductors or increasing the size of an inductor will increase the effect (like a longer spring) and impede the motion. Parallel inductors will decrease the effect (as would many short springs in parallel). The action of inductors or springs uses energy, even though it does not consume any. As can be seen from the following diagram, the inductive ac circuit follows Ohms Law similar to a resistance. Where X_L is the inductive reactance of an inductor as described previously, $V = I X_L$.

Notes

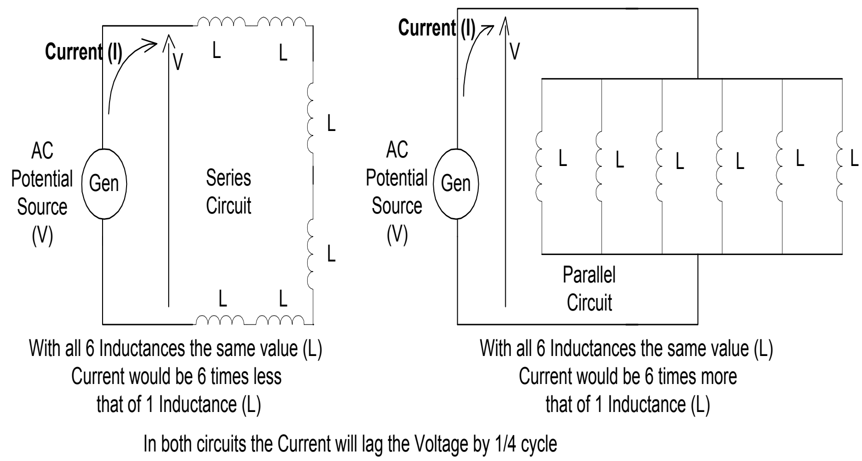

Figure 13
ac Circuit Inductance

The important thing to remember is the delayed action: The current into an inductor lags the voltage as indicated by the diagram below.

Figure 14
Inductive Circuit Phasors

2.5.3 Capacitors

The Boat Paddle:

Capacitors can be considered the same as a boat paddle inserted in water and moved in a rowing motion. The flow of water moves ahead of the force of paddle the same way as the flow of current moves ahead of the applied voltage. The larger the paddle or the more paddles placed in parallel, the larger the resulting current movement.

The action of a capacitor or boat paddle uses energy, but does not consume any. As can be seen from the following diagram, the capacitive ac circuit follows Ohms Law similar to a resistance. Where X_C is the capacitive reactance of a capacitor as described previously, $V = I X_C$.

Notes

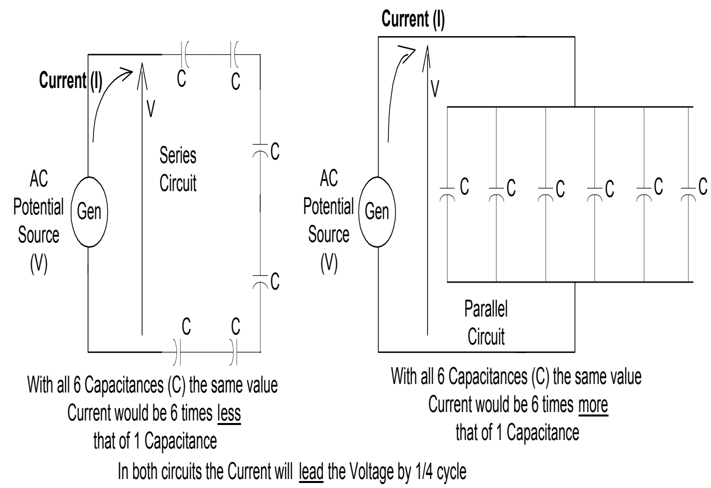

Figure 15
ac Circuit Capacitance

The important thing to remember is the delayed action: The current into a capacitor leads the voltage as indicated by the diagram below. This is exactly opposite to an inductor and they are called complementary devices.

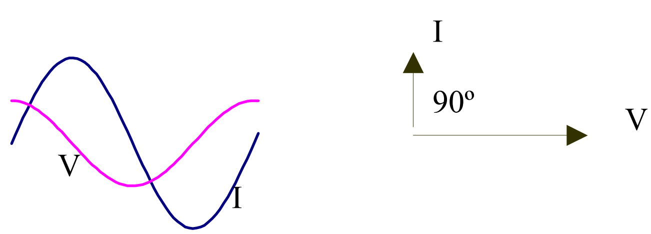

Figure 16
Capacitive Circuit Phasors

Note: In ac electrical systems the current lag for ideal inductors or current lead for ideal capacitors is a constant ¼ cycle.

2.5.4 Circuits with multiple components

In practice all ac circuits contain a combination of inductors, capacitors and resistors. The current can be at any angle from 90° leading to 90° lagging the voltage. Overall, most circuits are inductive in nature and have a phase angle in the neighbourhood of 20° to 30°.

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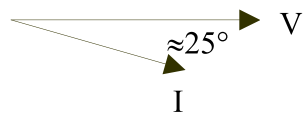


Figure 17

Phasor Diagram for Typical ac Circuit

In an ac circuit with combinations of resistance, inductance and capacitance the phase shift between the voltage and current depends on the relative sizes of the components. Because of the 90º-phase shift between reactive and active components the arithmetic can become somewhat tedious in complicated circuits. However all circuits can be reduced (with perseverance and tenacity) to a single voltage, a resistor and either a capacitor or inductor connected in series. Here we will show how to solve this type of circuit.

Assume we have a 20Ω resistor connected in series with a 10Ω inductor. The series combination is supplied with a 50-volt source. What is the current and phase angle in the circuit?

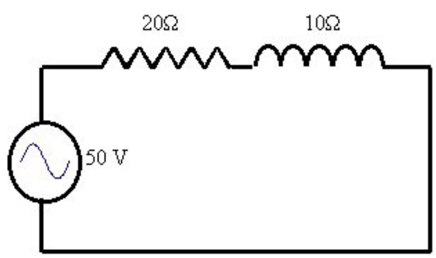


Figure 18

Simple Electrical Circuit

Because of the 90º-phase shift caused by the components of the impedance they are not added arithmetically but according to the great theorem of Pythagoras.

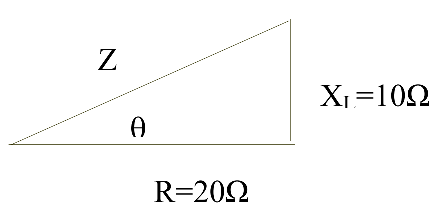


Figure 19

Impedance Triangle

Notes

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{20^2 + 10^2} = 22.4\Omega$$

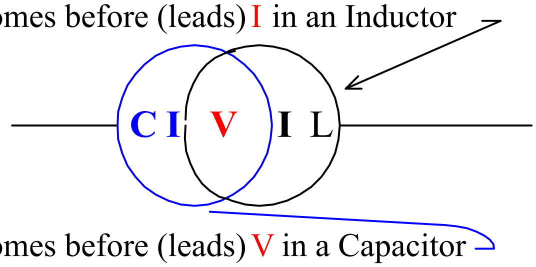
$$\theta = \tan^{-1}\frac{X_l}{R} = \tan^{-1}\frac{10}{20} = 26.6°$$

Since it is an inductive circuit we know the current lags the voltage by 26.6º

2.5.5 Acrostic

It is sometimes helpful to remember the relationship between voltage and current in capacitors and inductors as follows:

V comes before (leads) I in an Inductor



I comes before (leads) V in a Capacitor

Figure 20

Use of Acrostic CIVIL

2.5.6 Heat vs. Current in a Resistor

Energy can never be destroyed. It is converted from one form to another. One of the most familiar forms of energy is heat. When a current (I) is forced through a resistor (R) by applying a potential (V), the electrical energy is converted to heat energy as observed by the rise in temperature of the resistor. Remember that power is the rate at which energy is consumed. The energy dissipated in the resistor then is equivalent to the power it consumes multiplied by the length of time current is flowing.

In this case, electrical power (in units of Watts) consumed by a resistor is equivalent to the product of applied Voltage and the Current flowing through it. This is called active or real power.

Note: Heat is only produced by a resistive load (electrical friction) and not in an inductive or capacitive load.

The value of the real power (P) consumed by the resistor is:

Power = Voltage x Current (P = V x I)

Notes

Since we already know that an applied Voltage (V) is required to force Current (I) through a resistor (R), another way of defining Power is:

Power = $(\text{Current})^2$ x Resistance ($P = I^2 \times R$)

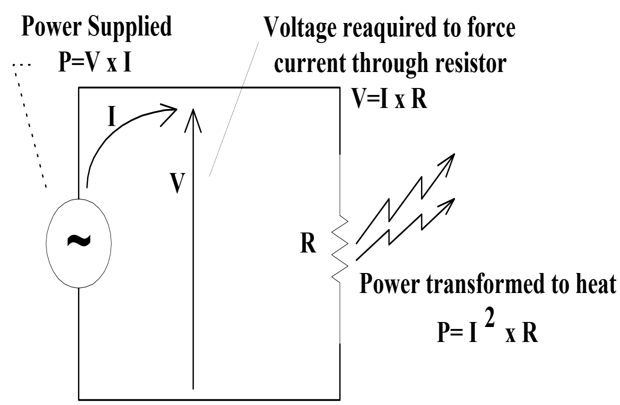


Figure 21
Heat vs. Current in a Resistor

Note: Real power only occurs when the magnitude of the voltage and current increase and decrease at exactly the same rate as illustrated below. This is called being in-phase and will only happen for a resistive load.

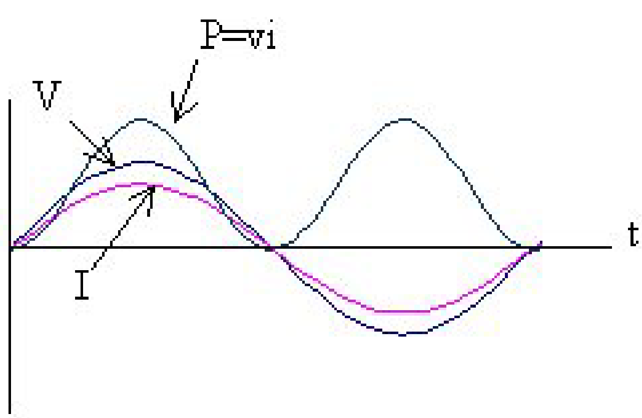


Figure 22
Real Power Volts and Amps

Notes

At any time in an ac circuit the instantaneous power flow in the product of the voltage and the current. In ac circuits the power flow is not constant but fluctuates with the voltage and current. The integral of the power with respect to time is the energy delivered to the load. In a purely resistive circuit the product of voltage and current is always positive. In the course of one complete ac cycle energy is delivered to the load.

2.6 ACTIVE, REACTIVE, APPARENT POWER AND POWER FACTOR

In the previous example, we related the energy dissipated or heat generated in a resistor, to the electrical power applied to it. As we have stated, instead of working directly with the term energy, it is normal practice with electricity to use the rate at which energy is consumed over a certain interval of time (power). There are three components of power:

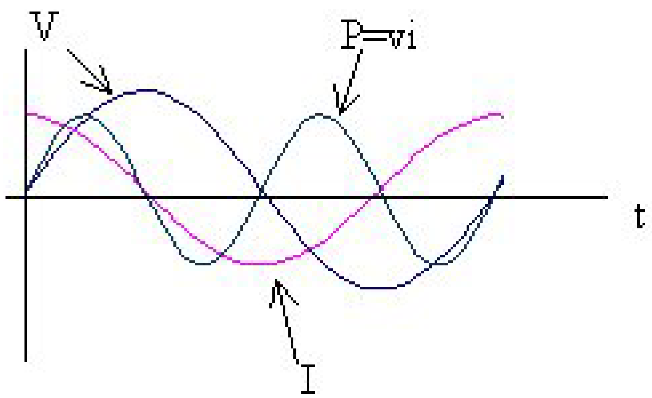
2.6.1 Active or Real Power (Measured in Watts or W)

As we have seen, results in useful work being done and is the power dissipated in resistive loads. This originates with the prime mover, which, for a nuclear station, is a steam turbine. Therefore, control of active power is mainly achieved by control of the prime mover, which is the steam flow. Adjusting steam flow will also have some affect on the generator reactive power output due to armature reaction. (This will be explained later.)

2.6.2 Reactive Power (Measured in Volt Amp Reactive or VAR's)

It is exchanged in an ac system between the generator and the loads requiring these fields for their operation. As we have described, it is the power dissipated in reactive loads (capacitive and inductive). The waveforms for reactive power into a capacitive load (Figure 23) and an inductive load (Figure 24) are indicated below as a reference. Note that the average value of pure reactive power is zero.

Notes



Voltage, Current and Power in a capacitor

Figure 23
Reactive Power into Capacitance

Although very necessary to the ac system and placing a burden on the system, no useful work is done by this type of power. Control of reactive power is achieved by controlling the generator's output voltage by adjusting the exciter current.

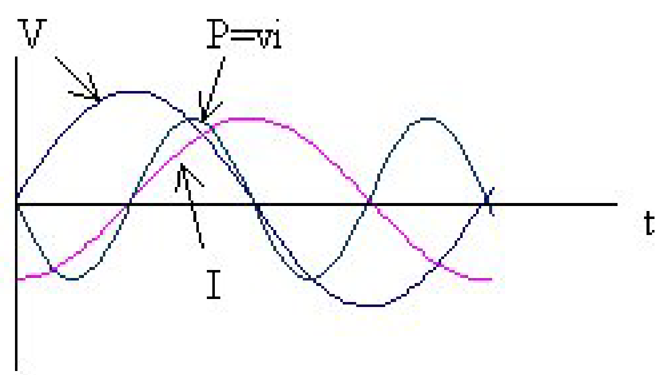


Figure 24

Voltage Current and Power in an Inductor

2.6.3 Apparent Power (Measured in Volt Amps or VA)

Does an ac generator supply the combination of active and reactive power? Figure 25 is a representative diagram of apparent power into a combined active and reactive load.

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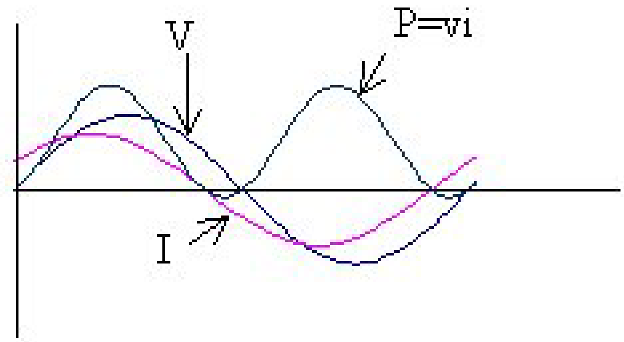


Figure 25

Voltage Current And Power In A Circuit With Combined Resistance And Inductance

2.6.4 Apparent Power

The practical significance of apparent power is as a rating unit. For example, an ac generator supplies apparent power at essentially constant voltage and frequency. Its output capacity is then described in Mega Volt Amps (MVA). Transformer and motor capacities are also rated in MVA or KVA for similar reasons.

Although the utility must provide apparent power, it receives direct compensation only for active power utilised by its customers. The ratio of active to apparent power is therefore, an important quantity and is defined as the power factor. This number can range from zero to one but good economics requires it to be as close to unity as possible. It can be thought of as a measure of the system's effectiveness in using apparent power to do useful work. The terminology can be in any one of the following forms:

Power Factor = PF

= Real Power/Apparent Power

= Watts/ Volt Amps

Note: There is a time lag between the apparent power and real power. This corresponds to the time lag between voltage and current for reactive loads. For capacitive loads, we have a leading power factor. For inductive loads, it is lagging. Power Factor Angle is a measurement that describes how close the apparent power is to being totally real or supplying a pure resistive load. The Power Factor rating can be summarized in two main areas:

Notes

- Efficiency: The lower the power factor, demanded by the load which requires a given amount of active power, the greater the size of line current that has to be supplied by the generator and sent through the transmission system. This means higher winding and line losses and reduced efficiency;

- Voltage Regulation: The lower the power factor and the greater the generator current, the greater the reactance voltage drops along the line. This means a lower voltage at the load and, consequently, poorer system voltage regulation.

The relationship between apparent, active and reactive power is that of a right-angled triangle.

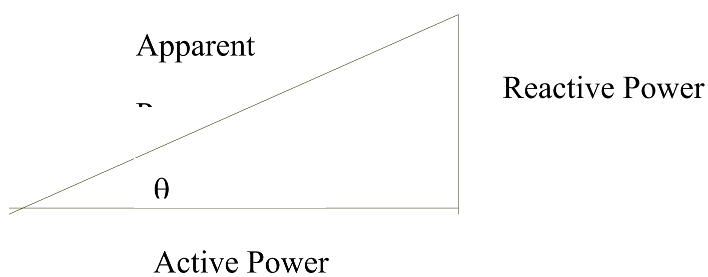


Figure 26
Power Triangle

The following relationships exist between voltage, current, apparent power (U), active power (P) and reactive power (Q).

$U^2 = P2 + Q^2$

$U = VI$

$P = VI \cos\theta$

$Q = VI \sin\theta$

The power factor is equal to $\cos\theta$

Notes

2.7 MAGNETIC FIELD PRODUCED BY A CURRENT FLOWING IN A CONDUCTOR

We have seen that magnetic flux is produced by a current carrying conductor and that this flux can be considered as a field with lines of magnetic force. In motors, generators and transformers, the field is concentrated through the use of windings or coils of wire as demonstrated below. This allows the transfer of usable energy.

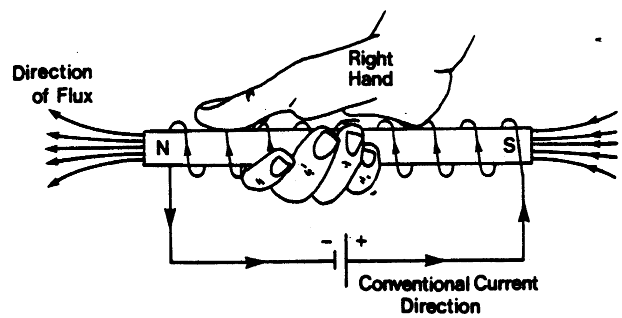


Figure 27
Concentrated Magnetic Flux

In the above diagram, the coils of wire are wound on a metal bar for further concentration of flux. This forms a crude electro-magnet. A handy rule to remember is the right hand rule. Form your right hand around the coil(s) in the direction of current flow and your thumb will point in the direction of the flux.

Concentrated magnetic flux has the capability to transfer large amounts of power:

- It will react to other magnetic fields producing force.
- It will create magnetic fields in and around other adjacent conductors

The majority of control systems in a generating station apply this basic principle in some fashion. These are usually in the form of relays or solenoids. Control signals that energize a remote coil are sent from many devices, including temperature or pressure logic detectors. The coil, in turn, attracts a metal plate to which contacts are attached and the contacts then energize other devices.

Before proceeding, we have to examine the effect of magnetic flux on a conductor.

Notes

2.8 INDUCED VOLTAGE PRODUCED BY A CHANGING MAGNETIC FIELD IN A CONDUCTOR

If a magnetic field is moved near a conductor, the field will bend around the conductor as shown in the diagram below. Notice the fields around the conductor in the centre (cross-section view) with the magnet (two poles shown) being drawn down past it.

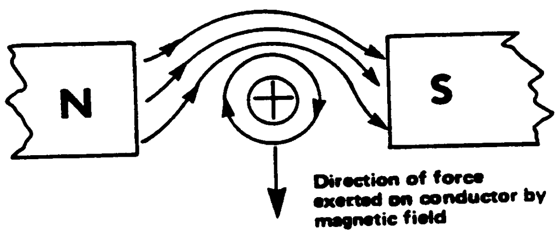


Figure 28
Voltage Produced by a Magnetic Field in a Conductor

For the conductor in Figure 28

- There is a resulting force against the conductor
- A circular magnetic field built up around the conductor
- A potential to do work is developed

As the magnetic field moves past the wire, energy from the moving magnetic field is transferred to the wire and a potential is built up in it as it moves. The wire then has the ability to produce power.

Notes

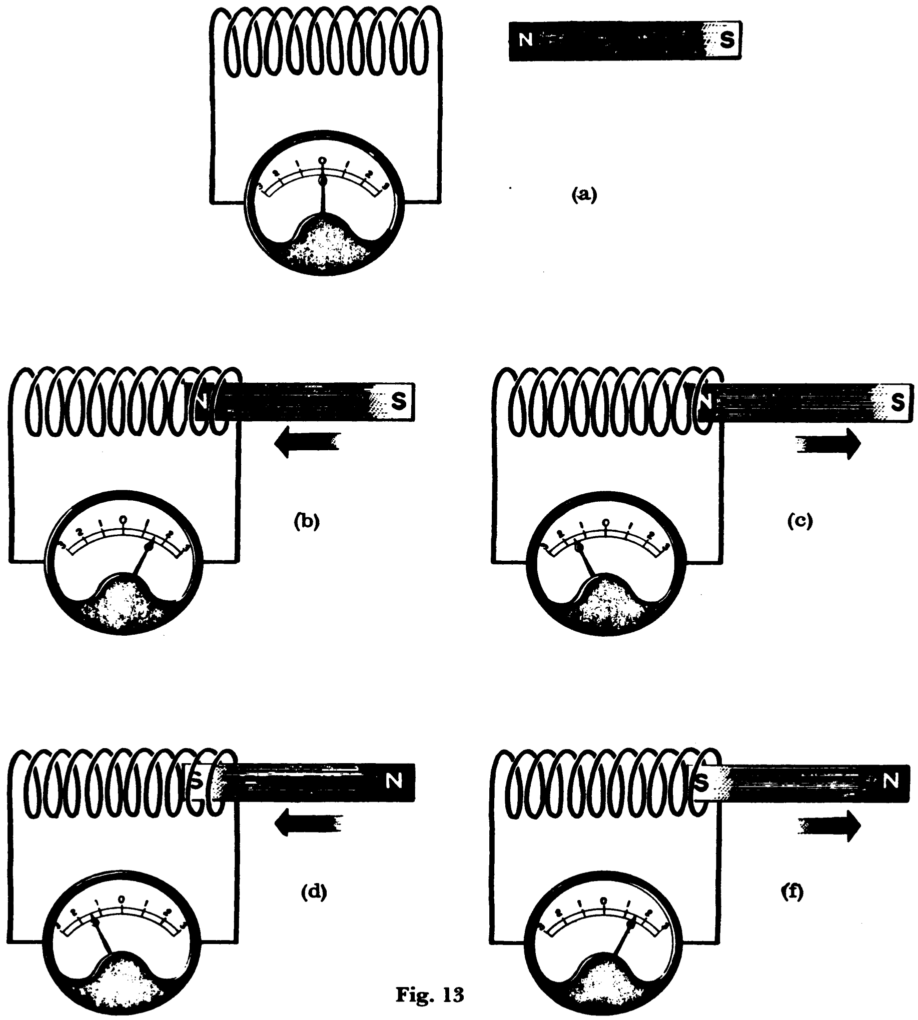


Figure 29
Voltage Produced by a Changing Magnetic Field in a Coil

The magnitude of the driving EMF force can be easily demonstrated. In the above diagram (Figure 29) a concentrated source of magnetic flux (magnet) is moved into and out of, a coil of wire and the result is observed on a voltmeter.

Remembering the right-hand rule, we observe that the meter will move upscale and down scale while the magnet is in motion in and out of the coil. The voltage produced is both polarity sensitive and direction sensitive. Also, the voltage increases in magnitude as the rate of movement increases

Notes

2.8.1 Transformer Action

By combining the previous two principles, we now have the basic operation of a transformer:

When alternating current (I_1) is forced by a potential (V_1) through a conductor, a magnetic field consisting of lines of flux (M) is set up around the conductor.

When the magnetic field (M) moves relative to a conductor, a potential (V_2) is produced across that conductor. This will supply a current (I_2) to connected load.

In the example below, since both coils share the same flux (M) then the input and output EMF's are proportional to the number of turns of conductor around that flux:

$$E_2/E_1 = N_2/N_1$$

Or the output voltage = $V_2 = V_1 \times (N_2/N_1)$

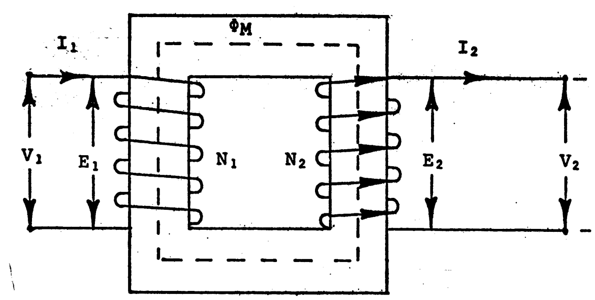


Figure 30
Transfer Actions

Although the concept is simple, it is the basis of every transformer. From the largest power transformer to the smallest found in logic controllers, the only difference is the construction due to voltage level, KVA rating and alternating frequency.

2.8.2 Magnetic Force on a Current Carrying Conductor

In the previous section, we examined the magnetic force on a conductor and the resulting EMF (Voltage) produced. If the conductor formed a closed loop, this voltage would create current in the conductor. In the diagram, the + mark on the conductor represents the tail of the current direction arrow. If current is forced through the conductor by an external potential, the reaction to the external magnetic field is increased. Any increase in coil current has a proportional increase in force against the magnetic field.

Notes

The following Figure 31 demonstrates the effect of placing a loop of wire in a magnetic field.

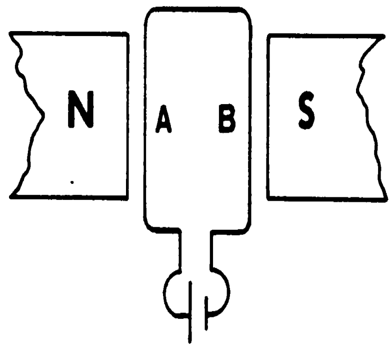


Figure 31
Current Loop in a Field

In the cross section view (Figure 32) below, when electric current is forced into the wire by an external electrical potential, side A will be thrust downwards and side B moved upwards. The loop of wire will then try to turn counter-clockwise. This basic rotational action is the principle behind all motors. It should also be noted at this point that the force created by the dc current in the coil is the principal behind dc excitation in the rotors (rotating component) of generators. Generator action will be pursued later in this module.

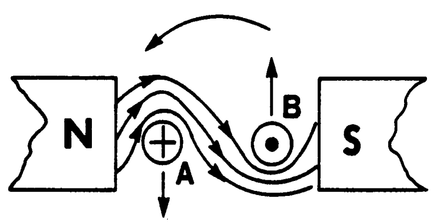


Figure 32
Magnetic Force on a Current Loop

Although the previous diagram depicts a basic dc motor operation, ac motors use the same principles. Below is a series ac motor showing the current movement during the two directions of alternating current flow. Note that a constant forward output torque would be produced even with an alternating input current.

Notes

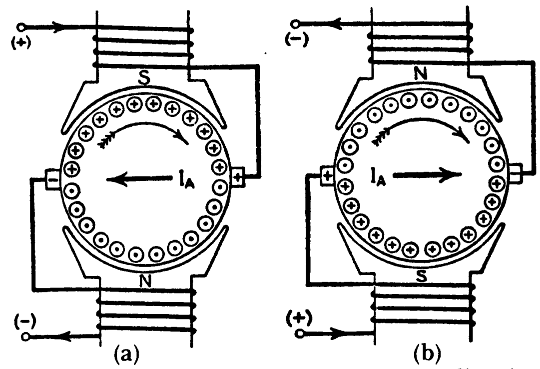


Figure 33

Basic ac Motor

The alternating current fed through carbon brushes to the centre armature is reversed every half cycle. With the current applied in such a manner, the main stationary field and the rotating field remain in the same relative direction. The term often used is the commutating action. Constant clockwise rotor direction is thereby maintained.

2.8.3 Induced Voltage in a Conductor

Up to this point, we have examined the various relationships between Voltage, Current and Magnetic Flux and the equipment that use these principles:

- Transformer Action – Magnetic field created by a current carrying conductor and induced voltage produced by a changing magnetic field.
- Motor Action - Force produced by a magnetic field on a current carrying conductor.

Now, we will examine the Voltage produced in a conductor by a rotating magnetic field. For ease of explanation, we will view it first as magnetic field is stationary and the conductor rotating.

If the conductor is formed into a coil and rotated at constant speed (Figure 34), the resulting EMF (measured on slip rings) reverses its direction at time intervals corresponding to the coil rotation and is continuously changing its value. The result is that of a basic generator with a waveform as show in Figure 35

Notes

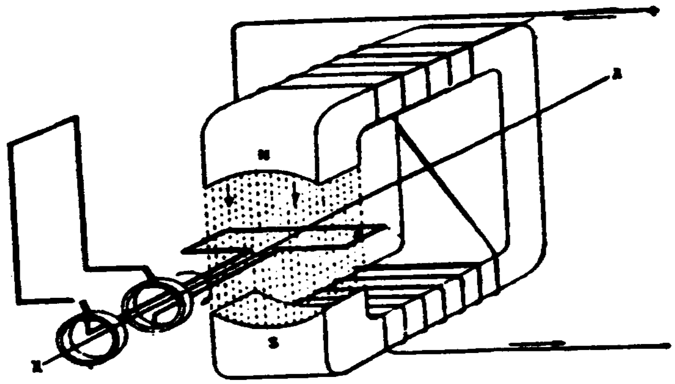


Figure 34
Rotating a Current Carrying Coil in a Magnetic Field

Notes

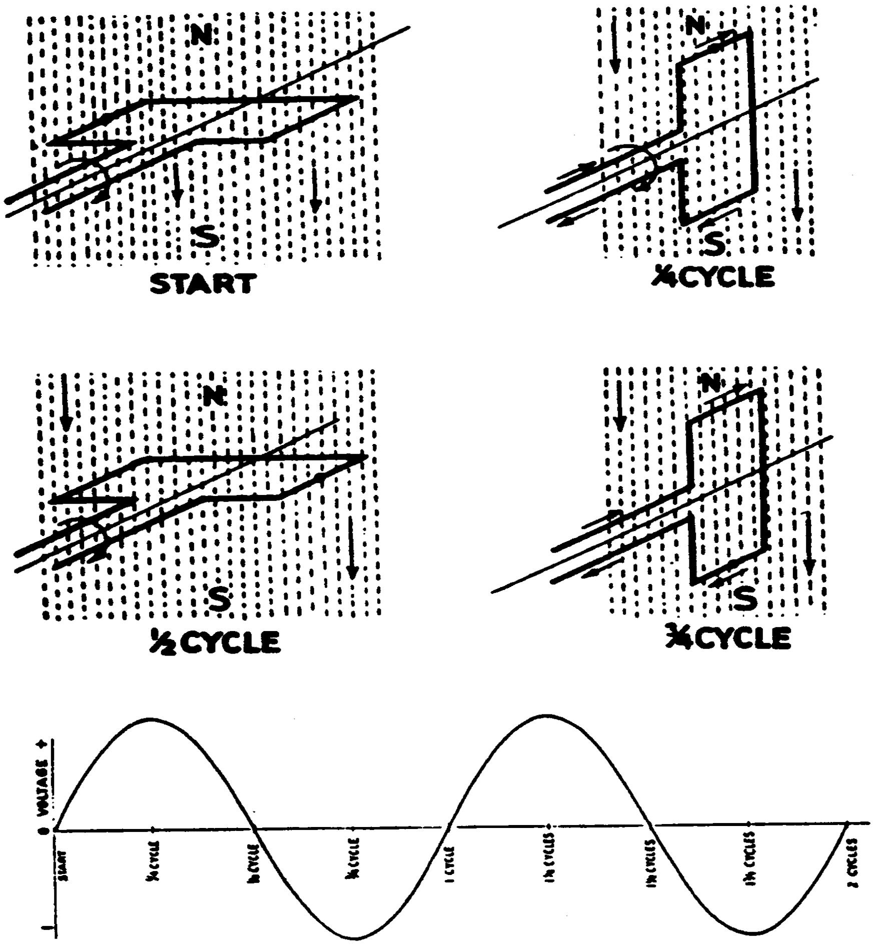


Figure 35
Output Waveform of an ac Generator

In the previous diagram (Figure 35) note that the points ¼ cycle and ¾ cycle are those at which the rate of cutting of the flux reaches a maximum and, therefore, points of maximum induced voltage E. The minimum occurs at start and ½ cycle. The output waveform is called a sine wave or sinusoidal.

In practical cases, it is usual for the wire loop to remain stationary (stator) and for the magnetic field, to be rotated through it. This allows the output stator coils to be heavier in construction as compared to the rotating field coils. The field coils would be many turns of finer wire wound on the rotating component (rotor) and fed by dc (excitation). The basic action is demonstrated below (fig 36), but the principle is a previously described.

Notes

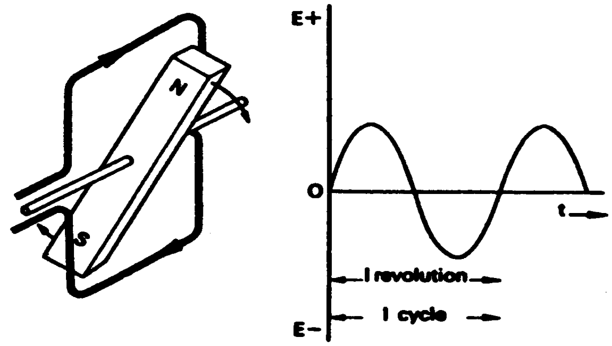


Figure 36
Simplified Single Phase ac Generator

Poles

It is important to point out that the illustrations presented have only shown one set of poles. This is purely for analysis and ease of viewing. The prime mover would have to rotate at 60 revolutions per second or 3600 rpm to produce a 60-cycle waveform. Water-driven generators at 300 rpm would of course have 12 sets of poles. It is enough to say that the number of poles only affects the required rotor speed. The general theory remains the same.

3 Phase

In practice, most ac generators are three-phase. The three-phase system is basically three single-phase systems at 1/3 of a revolution (120^0) apart. There are many advantages to the three-phase system but among the most important are:

- It is most economical to build and run;
- It has balanced forces on the shaft.

Notes

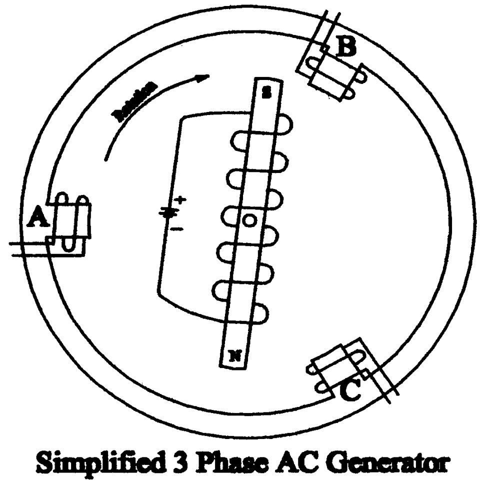


Figure 37
Simplified 3 Phase ac Generator

In a functioning generator, the poles and coils are naturally not as pronounced as depicted in the examples. To minimize the air gap (which would cause high losses in magnetic flux) and increase the efficiency, the rotor and stator windings are formed of many coils imbedded in slots of the generator iron. The cylindrical rotor is spun at high speeds and forced cooled (usually by hydrogen gas) with only a small gap between it and the outside stator. An example of this is illustrated in Figure 38. For a three-phase generator, remember that each phase will peak sequentially as the rotor field passes the coils producing three identical sinusoidal waveforms 1/3 of a cycle apart.

Notes

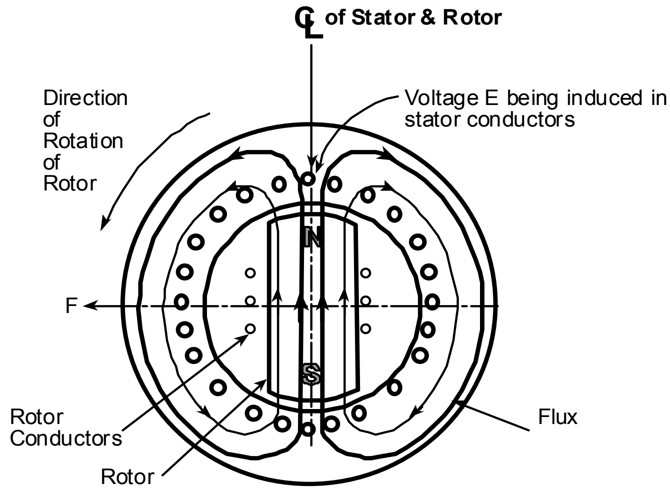


Figure 38

ac Generator with Imbedded Windings

2.9 THREE PHASE CONNECTIONS

The three windings of a three-phase generator are normally connected together to give a three-phase supply. There are in practice two ways in which the three windings are connected together. They can each have one end connected to a common or neutral point in a star or wye connection or they can be interconnected so the start of each winding connects to the finish of another in a delta connection.

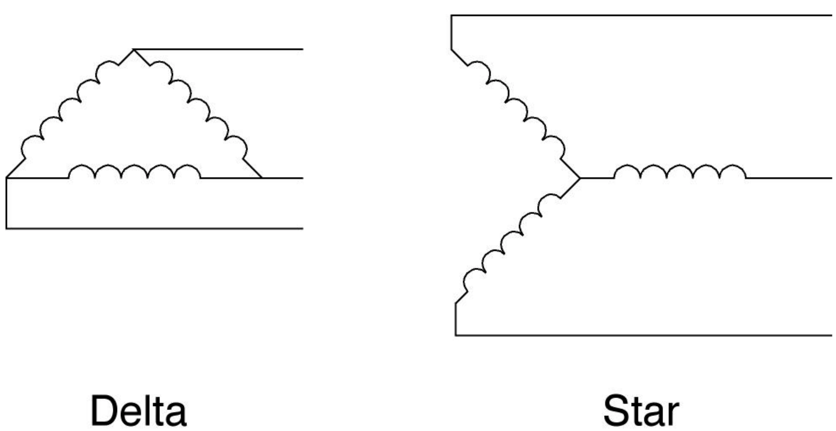


Figure 39

Winding Connections

There are advantages and disadvantages to each connection. Typically a star connection is used for sources of electrical supply.

Notes

This connection provides a convenient place to connect the system to ground. There are serious safety considerations that make the connection of an electrical system permanently and securely to ground at the source of supply the ideal thing to do.

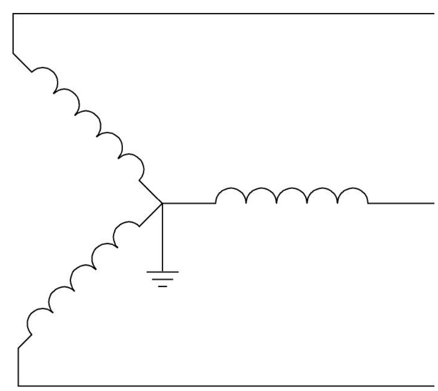


Figure 40

Grounded Star Connection

Loads are connected in delta or star connections mostly based on economic considerations. Star connections are used when the loads may not be balanced (shared equally) between the three phases. The neutral conductor allows unbalanced currents to flow and the voltages at the load remain balanced.

2.10 MAGNETIC CIRCUITS

Most of our practical ac machines (motors, generators ad transformers) depend heavily on the magnetic field for operation. The core iron of the machine provides a path for the magnet field. There are a number of phenomena in the iron that are of interest as the terms keep coming up in future sections.

2.10.1 Eddy Currents

Eddy currents are electrical currents that flow in the core iron of an ac machine. To generate voltages in takes a magnetic field, conductors and some change between them. In an ac machine the magnetic field is always in phase with the current, it is continuously changing. The iron is a conductor and voltages will be induced into the iron and current will flow. The induced voltages are low but the currents can be high. The current flow will heat the iron.

Notes

If steps are not taken in machine construction cores would get extremely hot and the power loss would be huge. The core of a practical ac machine is made of thin sheets of metal. The sheets break up the circulating path and the eddy currents are minimized.

2.10.2 Hysteresis

Hysteresis is a phenomenon that occurs in core iron. It takes a certain amount of energy to magnetize iron. The magnetic dipoles of the iron must be aligned. The external magnetic field acts on the dipoles and forces then to align. In an ac core the dipoles are continuously being realigned so there is a continuous energy loss in the core. This loss shows up as heat in the core. Hysteresis losses are minimized by the use of steel that is easy to magnetize.

Hysteresis and eddy currents always occur together. Like Bert and Ernie or beach and beer they are inseparable. Both are a result of the changing magnetic field in the core and both cause heating in the core. In the terminology of ac machines together they make up the core losses. Part of the power input into any ac machine shows up as heat in the core and is an inefficiency of the machine.

2.10.3 Magnetic Saturation

Most electrical machines depend on a magnetic circuit. This circuit is invariable made of iron with properties that make it easy to change the magnitude and direction of the field in the core. One of the limiting characteristics of a magnetic circuit is the saturation of the iron with the magnetic field.

The magnetic field is generated by passing current through a coil that s somehow wrapped around an iron core. As the current in the coil increases, the magnetic field in the core increases. Initially this is a fairly proportional relationship. Double the current and you double the field. However, the core eventually becomes saturated with the magnetic field and it becomes harder and harder to increase the field strength so it takes more and more current. The relationship between field strength and current changes from one where relative small changes in magnetic field cause large changes in magnetic field to one where it takes large changes in current to get small changes in magnetic field.

Notes

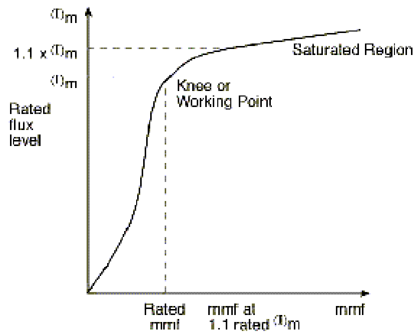


Figure 41

Typical Saturation Curve

Most electrical equipment is designed to run below the saturation region and moving into the saturation region has negative consequences. Most of our machines (transformers, generators & motors) are alternating current machines and depend on induced voltages in the windings for their operation. The induced voltages are dependant on the rate of change of the magnetic field in the core. The relationship between the magnetic field and induced voltage is captured in Faraday's law.

$$e = -N\frac{d\Phi}{dt}$$

Faraday's Law

e = induced voltage

N = the number of turns in the coil

Φ = magnetic field

t = time

Notes

In an ac machine the flux voltage and frequency are all related. If the system voltage increases at a given frequency the magnetic field strength in the machines must increase. If the frequency (related to the rate of change of flux) drops the magnetic field must increase to maintain a fixed voltage.

Most machines are designed to run with the magnetic field strength just below saturation. An increase of field in the neighbor hood of 10% will cause the core to go into saturation. A saturated core requires large amounts of magnetizing current. Large currents will cause large I^2R heating in the windings.

In an ac machine the core is heated by the continuously changing magnetic field. The continuous changing field produces eddy currents and hysteresis losses in the core. Eddy currents are electrical currents produced in the core iron itself. They heat the iron by electrical heating. Hysteresis losses are losses internal to the iron and are related to the forces required to change the direction and magnitude of the field in the core. They are magnetic heating effects. In a situation where the magnitude of the magnetic field increases so will the heating effects of eddy currents and hysteresis.

2.11 POWER CONVERTERS

By directly coupling motors and generators, a wide variety of power conversion devices can be made available. The driving force (motor) can be:

- dc at any voltage level
- ac Single Phase
- ac 3 Phase
- 60 cycle or matching supply system (ie: 50 Hz)

The generator output can also be any of the above. In industry and plants, the most economical heavy-duty power converter is a Motor-Generator (MG) set with the motor and generator matched to the source and size /type of load. Although many un-interruptible power supplies are now solid-state devices, heavy-duty dc to ac requirements use MG sets.

2.12 MACHINE INSULATION

Notes

The most frequent failure in electrical equipment is the degradation and breakdown (flashover) of the insulation. Hence, it is necessary to mention in this module n basic electrical theory the effect of operating environment on electrical machine insulation.

Electrical insulation can be liquid or solid, organic or inorganic. Organic insulation material consists of enamels, varnishes, resins, or polymers that are applied to the steel surface to provide high inter-laminar (between windings) resistance as found on most air-cooled machinery and some oil-immersed transformers.

Larger transformers are oil-filled with pure mineral oil to provide higher insulation capability and more effective heat dissipation when equipped with external radiators, fans and pumps. Physical insulation inside these transformers is often in the form of oil-impregnated paper wrapped around the conductors.

Inorganic insulation material can include a combination of magnesium oxide, silicates, phosphates, and ceramic powder. This type of insulation is usually heat-treated into the surface of the steel and is less common than organic insulation.

No matter what the type of insulation, the two most common contributing factors in insulation failure are moisture and heat.

2.12.1 Excessive Moisture

On air-cooled electrical machinery, the moisture content of the air is very important. With aging of the insulation, small hairline cracks will appear in the insulation. Moisture will seep into these cracks and allow an electrical path to short-circuit between adjacent turns of wire. Although the voltage between the turns is quite small, when they short together, a closed loop to the magnetic flux is provided, and this causes tremendous currents to flow in the shorted loop. This usually destroys the electrical machine, and it has to be removed and re-wound/replaced.

On oil-cooled machinery (i.e., transformers), moisture can only be detected by regular oil samples. Moisture will be sucked into the oil via the oil expansion air vent, through the continuous process of transformer heating and cooling cycles. Special air dryers (i.e., Drycol) and absorbents can assist in decreasing the rate the moisture is absorbed into the oil.

Notes

With oil-filled transformers it is important to note that very little moisture content is required to tremendously decrease the insulation value of the oil. Only 30 parts of water per million parts of oil can decrease the insulation capability by 50%.

2.12.2 Excessive Temperature

On air-cooled electrical machinery, prolonged high temperature causes thermal aging. This causes the insulation to become brittle. Eventual failure can occur due to moisture penetration as just discussed, or by physical contact of conductors.

In oil-filled transformers the effect is called insulation aging. Chemical aging occurs more rapidly at high temperatures, with the loss of insulation life being almost exponential with temperature. As an example – for a standard 65^0C (temperature rise) rated insulation the loss of life increases from 0.001% per hour at 100^0C to 0.05% per hour at 140^0C and 1.0% per hour at 180^0C. Translated into time span the expected insulation life would be 11.4 years at 100^0C, 83 days at 140^0C, 100 hours at 180^0C. It is fairly clear to see the importance of maintaining a daily record of the operating temperatures and ensuring that all electrical equipment are kept at low ambient temperatures.

Notes

2.13 REVIEW QUESTIONS - BASIC ELECTRICAL THEORY

1. Explain the meaning of the following terms and give the commonly used units and symbols.

    a. current,
    b. potential,
    c. resistance,
    d. capacitance
    e. magnetic flux,
    f. inductance,
    g. frequency,
    h. reactance,
    i. impedance,
    j. active power,
    k. reactive power,
    l. apparent power,
    m. power factor

2. A 5 Ω resistor is connected to a 25-volt battery. What is the current in the circuit?

3. A 10Ω, 5Ω and 2Ω resistor are connected in series. The combination is connected to a 10-volt battery. What is the current in the circuit?

4. A 10Ω, 5Ω and 2Ω resistor are connected in parallel. The combination is connected to a 10-volt battery. What is the current in the circuit?

5. A circuit contains a resistor and an inductor in series with a switch and battery. Sketch the current flow and the voltage drop across the inductor from the time the switch is closed until the circuit reaches a stable state.

6. A circuit contains a resistor and a capacitor in series with a switch and battery. Sketch the current flow and the voltage drop across the capacitor from the time the switch is closed until the circuit reaches a stable state.

Notes

7. A 100V, 60Hz ac circuit with a 26.5 μF capacitor. What is the current in the circuit? What is the relationship between the voltage and the current in the circuit?
8. A 0.265 H inductor is connect to a 20 V 60Hz supply. What is the current in the circuit? What is the relationship between the current and the voltage in the circuit?
9. A dc 100V supply and is connected to a resistance of 20Ω. What is the power in the circuit?
10. An ac voltage of 100 volts is connected to a 50Ω resistor. What is the power in the circuit?
11. An ac voltage of 100 volts is connected to a capacitor with a capacitive reactance of 50 Ω. What is the reactive power in the circuit?
12. An ac voltage of 100 volts is connected to a series combination of a 50Ω resistor and an inductor with an inductive reactance of 20Ω. What is the total current in the circuit? What are the active power, reactive power, apparent power and power factor of the circuit? Draw a phasor diagram showing the voltage, current and phase angle.
13. An ac voltage of 100 volts is connected to a series combination of a 25Ω resistor and a capacitor with a capacitive reactance of 50Ω. What is the total current in the circuit? What are the active power, reactive power, apparent power and power factor of the circuit? Draw a phasor diagram showing the voltage, current and phase angle.
14. Briefly describe how a 3-phase ac generator is constructed. Name the connection most often used for the windings.
15. State two common contributing factors in insulation failures. Briefly explain how each factor contributes to insulation failure.

Notes

3 TRANSFORMERS

3.1 INTRODUCTION

One of the main reasons for the popularity of alternating current systems is the ease with which ac voltage and current levels can be transformed. Large amounts of power can be transmitted from a generating station at high voltage and comparatively low current levels. These are changed to lower voltages and higher currents in the locality where the power is to be used. This module will examine the general operating principles and main parameters of transformers, including, varying the turn ratio with tap changers, the limitations of transformers and sources of heat.

Although transformers can vary, from a miniature high-frequency audio transformer to a large power transformer, the operating parameters are still the same. These can be divided into eight groups and are posted on the nameplate of any transformer of significant size: VA rating, cooling, transformer rating, frequency, voltage, phase, connections, and taps.

3.2 TRANSFORMERS - GENERAL

3.2.1 VA Rating

Every transformer has a maximum output current that it can deliver at its standard output voltage. This VA rating (KVA or MVA for large power transformers) is dependent on the ambient temperature or cooling provided. Exceeding the VA rating will cause over-heating of the core and windings and subsequent damage.

3.2.2 Cooling

Cooling requirements for the VA rating(s) are usually listed on the nameplate along with the ambient operating temperature. Oil filled transformers, will include the type of cooling at which the full rated load can be delivered. A typical 1000kVA oil filled transformer that has radiators to allow natural air cooling of the oil, would be listed as:

Transformer Rating: 1000 KVA 55^0C ONAN, which stands for the capability to supply 1000KVA with a temperature rise of 55^0C with normal oil circulation (no fans or pumps).

Notes

The various abbreviations that you will find for transformer cooling are:

- ONAN cooling. ONAN is an abbreviation for Oil Natural (thermo-syphon) circulation with Air Naturally circulated for cooling.
- ONAF abbreviation denotes that the transformer has provision for Oil Natural Air Forced cooling. Forced air-cooling would allow the rating to be increased by a small amount.
- OFAF stands for forced (pumped) oil circulation and forced (fan) air-cooled radiators.
- OFW - The main transformers at large generating stations are OFW types with oil forced cooling, where the oil is, in turn, cooled by water.

For large power transformers, there are usually multiple ratings depending on the type of cooling applied. Typical cooling requirements for transformers equipped with circulating oil pumps and air-cooled radiators are usually listed as:

450/600/750 MVA 65^0C
ONAN/ONAF/OFAF

This rating, with a 65^0C ambient temperature rise, would be:

- 450 MVA with normal oil circulation, no fans or oil pumps on.
- 600 MVA with normal oil circulation, fans on.
- 750 MVA with both fans and oil pumps on.

3.2.3 Frequency

All transformers are designed for the optimum flux linkages and lowest heating and power loss at a certain frequency. An induced voltage is created by an alternating magnetic field. At higher-than-rated frequency, there is excessive core loss due to lower efficiency in flux linkages. At lower-than-rated frequency, there is excessive winding loss due to decrease of flux linkages.

Notes

Transformers are basically inductors:

- Increasing frequency increases impedance and lowers current (less flux).
- Decreasing frequency decreases impedance and increases winding current (more heat).

3.2.4 Voltage

The available winding insulation is the governing factor for the voltage rating on the transformer. As well as the rated operating voltage, the rated transient (spike) voltage that the transformer can withstand is usually included. This is listed as the impulse level or BIL.

3.2.5 Phase

Single Phase on a Common Iron Core

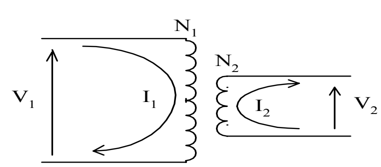
Quite often, large three-phase power transformers are installed by constructing three single-phase transformers and tying their input or output windings together. Such as the case for most main power output transformers that transform the generator power from high current, isolated phase buses to high voltage electrical system. Construction of a single three-phase transformer would be out of the question.

Single Phase on a Common Iron Core

Most power transformers encountered are of this construction for size and cost efficiency.

3.2.6 Windings

Separate windings (standard).

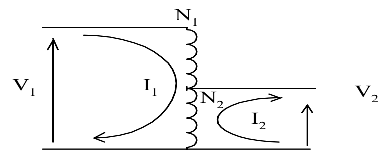


$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

Figure 1
Two Winding Transformer

Notes

Auto-transformer.



$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

Figure 2
Auto-Transformer

The autotransformer has the same ratios (turns, voltage and current) as a transformer with two separate windings. However, the output is tapped off a portion of the single winding. This configuration yields itself to creating variable tapped output voltages, as we will discuss later.

3.2.7 Connections

The common transformer connections are single phase, 3 phase star, 3 phase delta, or zigzag. (The latter connection is used explicitly in grounding transformers and will not be discussed in this course.)

Figure 3 below is an example of the connections for a three-phase transformer. Individual three-phase inputs are transformed into two separate outputs - one star or "wye", the other delta.

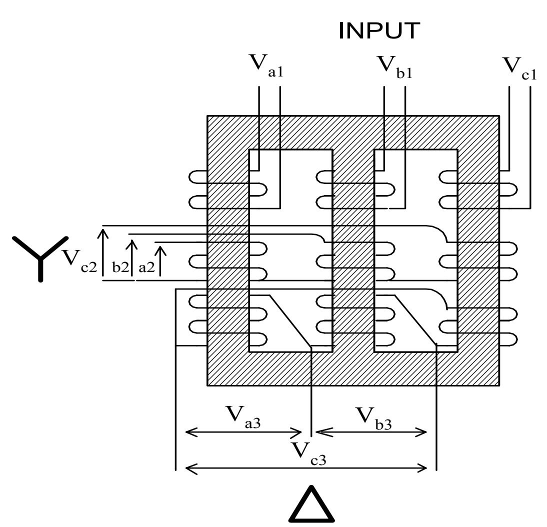


Figure 3
Star – Delta Transformer

The primary and secondary windings on most three-phase transformers are connected in either star or delta formation.

Notes

The star point, (see Figure 3) of a star winding is connected to ground and this ensures the line terminals have equal and balanced voltages to ground. The delta winding, because it does not have a common (star) point, is not connected to ground at the transformer.

3.2.8 Taps

Winding taps are provided in transformers to adjust the turns ratio between input and output and, hence, adjust the output voltage.

- Off-load taps are for use in transformers that rarely require output voltage adjustments. For example, a generator main-power output transformer.

- On-load taps that require frequent operations as customer or system load fluctuates during the day.

3.3 TAP-CHANGERS

When a transformer is required to give a constant load voltage despite changes in load current or supply voltage, the turns ratio of the transformer must be altered. This is the function of a tap changer and we will look in more detail at the two basic types:

- Off-load.

- On-load.

First, let's consider how a standard tap changer works by considering a common example.

Example 1

A 13800V/4160V transformer has five taps on the primary winding giving -5%, -2 1/2%, nominal, +2 1/2% and +5% turns. If, on-load, the secondary voltage reduces to 4050V then, which tap, should be used to maintain 4160V on-load (assuming the supply voltage remains constant)? The following answer results:

Answer:

To keep the secondary voltage at (or as close as possible to) 4160 V, either primary supply voltage or the HV winding tap position must be altered.

Notes

Examining the relationship:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$ or $V_1 N_2 = V_2 N_1$ indicates that, to keep the equation in balance with primary voltage and secondary winding turns fixed, either V_2 or N_1 must be adjusted. Since the objective is to raise V_2 back to nominal, then N_1 must be reduced. To raise V_2 from 4050 to 4160V requires an increase in secondary volts of:

$\frac{4160}{4050} = 1.027$ or 102.7%. N_1 must be reduced to $\frac{1}{1.027} = 0.974$.
Therefore N_1 must be reduced by (1 – 0.974) = 0.026 or 2.6%.

Reducing N_1 by 2.6% will accomplish the increase in secondary voltage output. The nearest tap to select is -2 1/2% (see Figure 4).

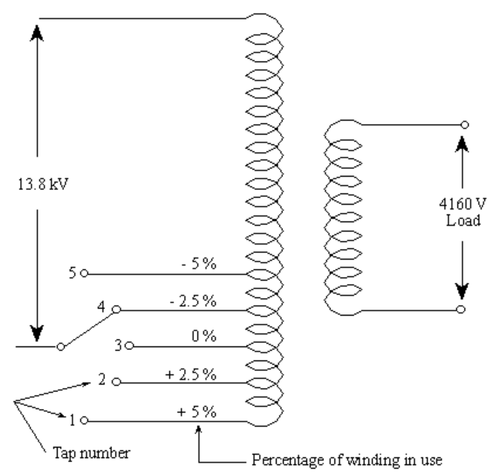


Figure 4
Basic Tap Changer

3.3.1 Off-Load Tap Changers

Most transformers associated with medium level voltage distribution for nuclear generating stations have off-circuit tap changers. With this type of tap changer, the transformer has to be switched out of circuit before any tap changing can be done. The contacts on the tap changer are not designed to break any current, even the no-load current. If an attempt is made to change the tap positions while on-line, severe arcing will result which may destroy the tap changer and the transformer.

Notes

3.3.2 On-Load Tap Changers

On-load tap changers, as the name suggests, permit tap changing and hence voltage regulation with the transformer on-load. Tap changing is usually done on the HV winding for two reasons:

- Because the currents are lower, the tap changer contacts, leads, etc., can be smaller.
- As the HV winding is wound outside the LV winding, it is easier to get the tapping connections out to the tap changer. Figure 5 shows the connections for an on-load tap changer that operates on the HV winding of the transformer.

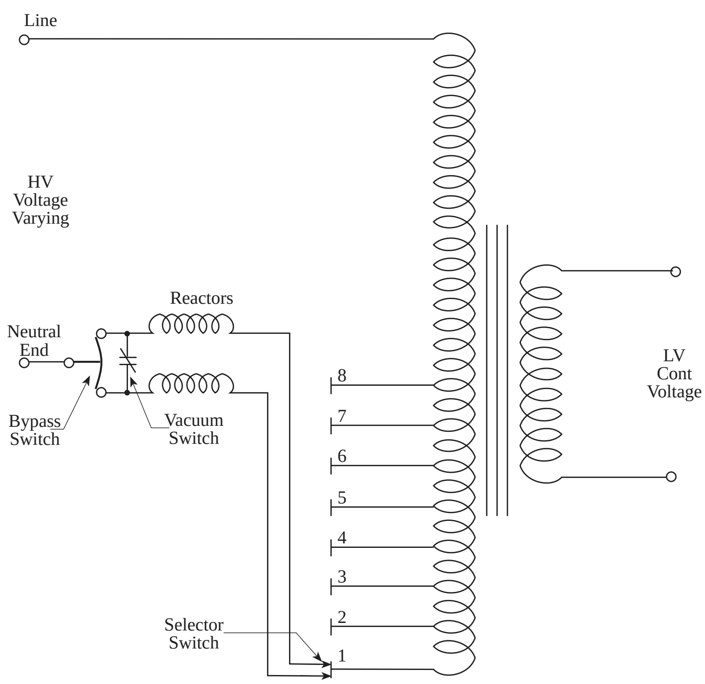


Figure 5
On-Load Tap Changer

The tap changer has four essential features:

Selector Switches

These switches select the physical tap position on the transformer winding and, because of their construction, cannot and must not make or break the load current.

Notes

Reactors

The load current must never be interrupted during a tap change. Therefore, during each tap change, there is an interval where two voltage taps are spanned. Reactors (inductors) are used in the circuit to increase the impedance of the selector circuit and limit the amount of current circulating due to this voltage difference. Under normal load conditions, equal load current flows in both halves of the reactor windings and the fluxes balance out giving no resultant flux in the core. With no flux, there is no inductance and, therefore, no voltage-drop due to inductance. There will be however, a very small voltage drop due to resistance. During the tap change, the selector switches are selected to different taps (see Figure 6) and a circulating current will flow in the reactor circuit. This circulating current will create a flux and the resulting inductive reactance will limit the flow of circulating current.

Vacuum Switch

This device performs the duty of a circuit breaker that makes and breaks current during the tap changing sequence.

Bypass Switch

This switch operates during the tap changing sequence but, at no time, does it make or break load current, thoughh it does "make before break" each connection.

An example of the tap changing sequence is detailed in Figure 6 - diagrams 1 through 10. Table 1 describes the sequence of operations for the tap changer of Figure 6 to change from tap 1 to tap 2. Changing to any other tap position is done similarly with the selector switch always moving sequentially (i.e., it is impossible to go from tap 1 to tap 3 directly, the order must be tap 1, tap 2, then tap 3).

The operating mechanism for the on-load tap changer is motor driven. Manual operation is used in the event of motor failure. The sequence of operation is mechanically linked, or interlocked, to ensure that all contacts always operate in their correct order. Any failure of the operating mechanism can result in severe damage to the transformers and tap changers.

Notes

	DETAILS OF TAP CHANGER OPERATION
1	Present position - tap changer selected to tap 1, bypass switch in, A + B, home position.
2	Bypass switch selects lower circuit arm.
3	Vacuum switch opens, removing load current from upper circuit arm freeing one half of selector switch for move.
4	As there is no load current on upper arm of selector switch, it moves to tap 2.
5	Vacuum switch closes - both selector switches on-load, circulating current is limited by reactors.
6	Bypass switch selects upper arm circuit arm. No arcing occurs as vacuum switch is closed and in parallel.
7	Vacuum switch opens, removing load current from lower circuit arm, freeing lower selector switch for move.
8	As there is no load current on lower arm of selector switch, it moves to tap 2.
9	Vacuum switch closes - both selector switches on-load, in parallel, on tap 2.
10	With vacuum switch closed and selector switch on a single tap, the bypass switch can now return to its home position. Both reactor circuits stay normally in parallel. The tap change is now complete.

Table 1
Description of Tap Changing Sequence for Figure 6

Notes

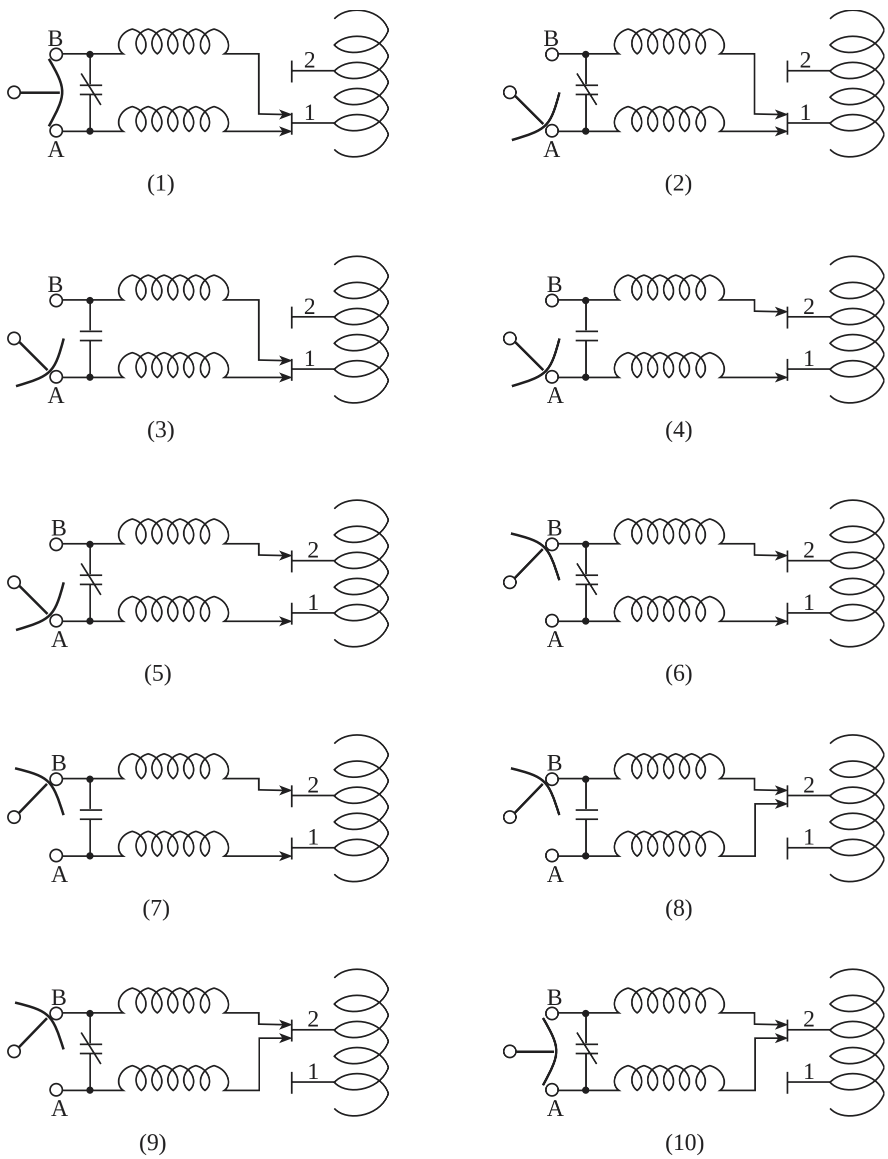


Figure 6
Illustration of an On-Load Change Operation

The previous example describes one type of on-load tap changer. There are several other types in use however, which may differ significantly from the type described. Differences are usually in how the selection of taps is made and the degree of mechanization. However, most importantly, all on-load tap changers allow voltage changes to take place without interrupting the power circuit.

Notes

3.4 OPERATING LIMITATIONS

3.4.1 Transformer Losses (Heat)

The thermal ratings of a transformer are determined by the following three factors:

- the amount of heat produced in the windings and connections;
- the amount of heat produced in the iron core; and
- how effectively the heat can be removed from the transformer when the thermal rating of the transformer is reached. At this point, the heat being produced must equal the heat being removed or dissipated - thermal equilibrium.

The efficiency of power transformers is high, especially, for large transformers at full load. However, losses are present in all transformers. These losses may be classified as copper or I^2R losses and core or iron losses.

3.4.2 Copper (or Winding) Losses

Copper losses are resistive and proportional to load current and are sometimes called "load losses" or "I^2R losses". As the transformer is loaded, heat is produced in the primary and secondary windings and connections due to I^2R. At low loads, the quantity of heat produced will be small but as load increases, the amount of heat produced becomes significant. At full load, the windings will be operating at or near their design temperature. Figure 7 shows the relationship between load-current and the heat produced in transformer windings and connections.

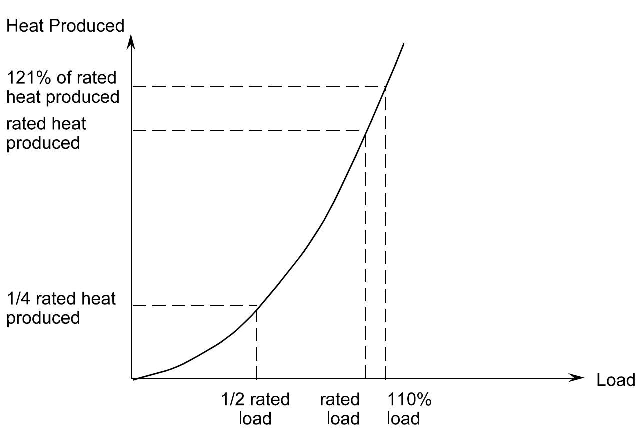
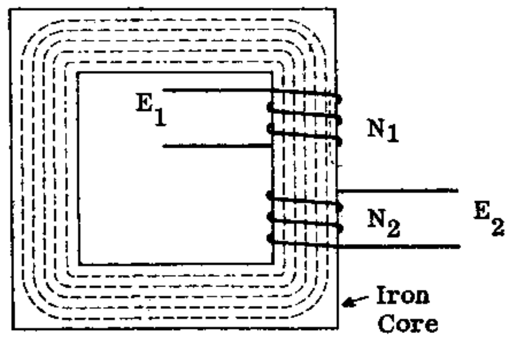


Figure 7
Relationship between Load and Heat Produced in Transformer Windings

Notes

3.4.3 Iron (or Core) Losses

The iron loss is due to stray eddy currents formed in the transformer core. As you will recall from module 1 of this series, lines of flux are formed around the current-carrying conductors. The majority of the



flux is as indicated in the following Figure 8, flowing around the core.

Figure 8
Circulating Core Flux

Some of the flux however, will try to flow at angles to the core and will cause eddy currents to be set up in the core itself. The term eddy is used because it is aside from the main flow. To combat this effect, the core is laminated as illustrated in Figure 9. The laminations provide small gaps between the plates. As it is easier for magnetic flux to flow through iron than air or oil, stray flux that can cause core losses is minimized.

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Notes

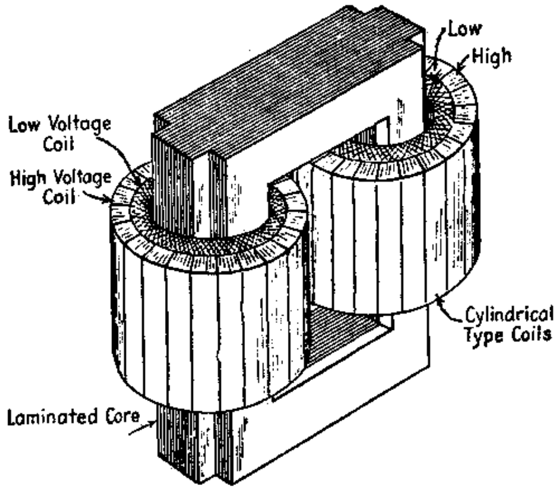


Figure 9
Transformer Core Laminations

3.4.4 Transformer Temperature Limitations

For dry (air-cooled) transformers (that normally have their windings insulated with silicone resin), a temperature limit of 155°C is usually imposed. Allowing air to circulate through the windings and over the core cools these transformers. Assuming a maximum ambient temperature of 40°C, then the temperature rise is limited to 155° - 40° = 115°C.

For oil-insulated transformers, there is usually a measurement of oil temperature and winding temperature provided. The simulated winding temperature is called hot-spot. It is derived by passing a representative amount of load current through a resistor located in the oil and measuring the resulting temperature (see Figure 10).

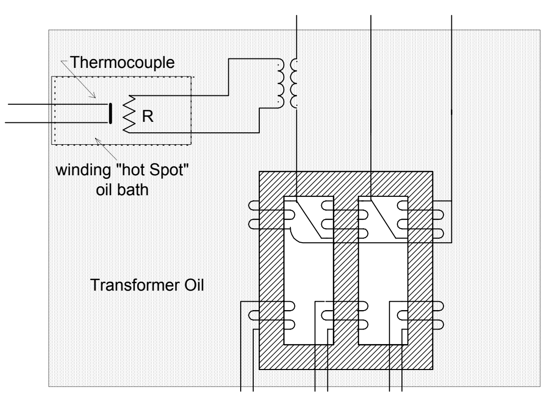


Figure 10
Transformer Hot Spot

Notes

Note: The oil and hot spot temperatures are very important to be monitored. If sufficient cooling is not available the transformer load will have to be reduced.

3.4.5 Current Limits

Current has two direct effects on the transformer:

It produces heat in the windings of the transformer as we have just discussed.

It produces a voltage drop across the output winding proportional to the load current. As the transformer is loaded, the secondary voltage will fall due to the affects of winding resistance and reactance.

Example: A transformer having an impedance of 5% will have a secondary voltage drop of 5% between no load and full load. At half load the voltage drop will be half, i.e., 2.5%.

In all circumstances, the loading of the transformer must be kept below the VA rating.

3.4.6 Voltage and Frequency Limits

We have previously discussed how the operating voltage and frequency must be kept within rated values due to the physical design (winding insulation and core construction). The subtle effect of these parameters on the overheating of the core is sometimes overlooked.

When any transformer is operating at its rated voltage and frequency, it will be operating with its rated value of flux in the core. If the voltage rises while the frequency remains constant, or the frequency falls while the voltage remains constant, the core flux will increase. The core will heat up due to the effects of hysterisis and eddy currents in the core.

A voltage increase of 10% above the rated value will give a flux level of 10% above its rated value. From Figure 11, it can be seen that, if the flux level is 10% above normal, the iron has commenced to saturate. As soon as iron begins to saturate, the heating, due to the eddy currents and hysterisis affects increases rapidly (see Figure 12).

For this reason, the voltage applied to a transformer should never be allowed to exceed the rated value by more than 10%.

Failure to observe this precaution will cause overheating of the core. This over-heating may cause the insulation which coats each of the laminations to fail, larger eddy currents will flow and extreme heating

Notes

will follow. This can lead to a core failure, where in extreme cases; there will be melting of the iron laminations.

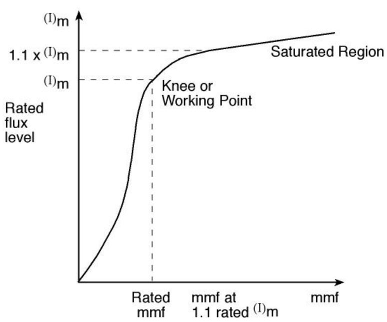


Figure 11
Typical Magnetization Curve for a Transformer Core

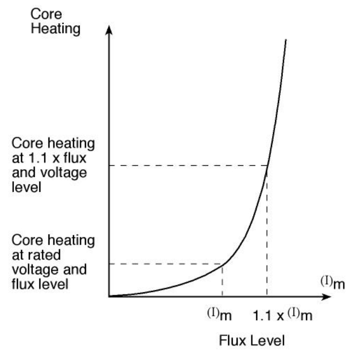


Figure 12
Relationship Between Core Flux and Core Heating

3.5 Instrument Transformers

Although all transformers are the same they change the voltage and current levels in an electrical circuit and transfer energy through a magnetic circuit. The specific characteristics that are of interest in the transformer vary a bit according to the use of the transformer. Most of the discussion in this section had dealt with the characteristics and parameters of concern with power transformers. Another classification of transformer important in the electrical system is the instrument transformer. Instrument transformers are used to measure and scale down the voltages and currents in an electrical system to safe values for input into protection and metering service. Instrument transformers are divided into two types, potential (or voltage) transformers and current transformers.

3.5.1 Potential Transformers

Potential transformers are two winding transformers rated to accurately measure voltages. Typically, there are one or two sets of potential transformers connected to each electrical bus in a system. The generally has an output voltage of 120 V ac. Their accuracy is rated at a specific load at a specific power factor.

3.5.2 Current Transformers

Current transformers measure current in the system. Many of them have only one winding on a toroidal core. The primary winding is simply the conductor in with the current that is being measured.

Notes

Current transformers have standard outputs of 5A or 1A on the secondary side.

Current transformers designed for use in metering circuits have their accuracy rated at normal current levels. Ones deigned for use in protection circuits have their accuracy rated at fault current levels. Many current transformer designs have a tapped secondary winding so a variety of ratios are available.

Current transformers have one little quirk. Some really neat electrical phenomena occur around current transformers. The secondary side must always be either short circuited or connected to a low impedance load. If this is not done high voltages many be induced into the secondary winding. Causes damage to the windings, insulation system and/or act as a safety hazard to personnel. In addition, the core will be over fluxed and the accuracy of the transformer can be permanently affected.

REVIEW QUESTIONS - Transformers

Notes

1. State the purpose of a tap-changer in an electrical system.
2. Briefly, describe how a tap-changer is constructed to serve its purpose.
3. Explain the major operating restriction of an off load tap-changer.
4. Both on and off load tap changers are found in a nuclear generating plant. States the typical locations of the on-load tap-changers.
5. The limitation on a power transformer is heat. Heat is generated in both the core and the windings. Explain the source(s) of heat in both of these locations.
6. The electrical parameters of voltage, current and frequency all have an effect on the amount of heat produced in a transformer. Explain how varying each of these parameters from its normal value will affect the heat production in the transformer.
7. A single-phase transformer with a nominal voltage ratio of 4160 to 600 volts has an off load tap changer in the high voltage winding. The tap changer provides taps of 0, ±2½ & ± 5%. If the low voltage is found to be 618 volts. What tap would be selected to bring the voltage as close to 600 volts as possible?

Notes

4 GENERATORS

4.1 INTRODUCTION

Generators can truly be described as the reason for being a power station. The operation of the turbine-generator system is second in criticality only to the operation of the nuclear reactor and the associated HP steam systems. The fundamental principles of the generator must be understood to understand the operating procedures and event reports regarding its operation. To approach this topic, the module content will address the basic issues that are applicable to all nuclear power generating stations and not go into the many possible design variances.

In this module we will examine synchronous machines and generator pre-synchronous run-up requirements, then the actual generator synchronism and finally generator loading. To conclude the module, we will look at some possible adverse generator operating conditions and heat production.

4.2 FUNDAMENTALS OF GENERATOR OPERATION

The first module of this course discusses the three basic requirements for electromagnetic induction.

- A magnetic field
- Coils of wire to induce into which a voltage is induced
- A change between them

In a power generator the magnetic field is placed on the rotating part or rotor of the machine. The magnet is an electromagnet; the rotor contains windings, which are supplied from a direct current source called the excitation system. In an 800 MW generator the dc field will be about 400 Vdc and 4000 A when the generator is at full load. The rotor is turned by the prime mover, which in the case of the main units in a plant is steam.

The coils of wire into which the voltage is induced are embedded into the iron of the stator. The spinning magnetic field causes the magnetic field linking these conductors to be continuously changing.

The continuously changing magnetic field induces a voltage into these conductors. The induced voltage will be sinusoidal. The magnitude of

Notes

the voltage will depend on the strength of the magnetic field and the speed of rotation of the rotor. The period of the voltage waveform will depend on the speed of rotation only.

To make a three-phase generator the stator has three separate windings placed 120° apart on the stator. The rotating of the rotor will induce a sinusoidal voltage into each winding. The voltages will however, be shifted 120° with respect to each other.

4.3 SYNCHRONOUS OPERATION

To many people, the operation of a synchronous generator is very mysterious and strange. Here is this huge machine which runs are a constant speed whether the 4 - 24 inch steam valves are wide open or shut tightly the machine speed is constant. Changing the steam flow into the machine changes the power output but has no effect on the speed.

Then there is the strange concept of reactive power. Reactive power flows are not supposed to be taking any energy and yet they change as the steam valves open and close.

Changing the excitation on the generator will change the voltage at the terminals but just a little. It has nowhere near the effect that changing the excitation would have on the machine when it is not synchronized or connected to the system. This section of the course will, hopefully, explain some of these phenomena.

4.3.1 The Magnetic Fields

One of the keys to understanding the strange behavior of the generator is develop a mental image of the magnetic field in the generator. Although there is only one magnetic field, for the most part we can consider it to be two; and a lot of the behavior of the machine can be explained by the interaction of the two magnetic fields. For simplicity a two-pole generator is considered. The same arguments hold for generators with more poles however, the pictures and words to describe the interactions get more complicated.

The first magnetic field is the one set up in the rotor by the excitation system. It is field that is constant in strength and rotates around the machine at the speed of rotation of the rotor. The magnitude is directly proportional to the field current (as long as we do not saturate the magnetic circuit).

Notes

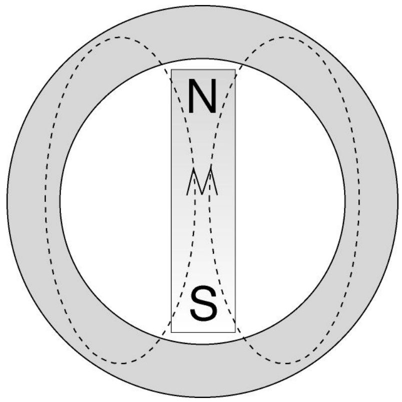


Figure 1

Rotor Magnetic Field

The second magnetic field is the one set up by the current flow in the three-phase stator winding. If a three-phase supply is connected to three windings displaced around the core of the generator, the winding will generate a rotating magnetic field. The strength of the magnetic field will depend on the current flow in the winding and the speed of rotation will depend on the frequency of a supply. In a two-pole machine with a 60 Hz. Supply the speed of rotation will be 60 revolutions per second or 3600 rpm.

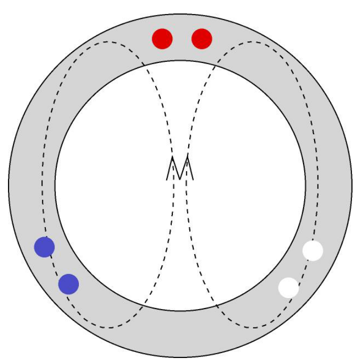


Figure 2

Stator Magnetic Field

Notes

It is the interaction of these two magnetic fields that create the forces in the generator that transfer the energy to the electrical circuit. In a large generator these forces can reach orders of magnitude of 10^6 Newton’s. This is the sort of force requires to push space ships into space. In a synchronized machine it is this force that keeps the rotor turning at the speed determined by the frequency of the system. The magnetic field from the stator current and the magnetic field of the rotor lock together and rotate at the same speed around and around in never ending circles.

The magnetic fields do not line up perfectly unless the machine is producing no power output. There is an angle between them. The angle is called the load angle or torque angle and it is related to the power output of the machine.

4.3.2 Forces between the Magnetic Fields

The force between the magnetic fields it the force between the shaft and the electrical system. It is this force that transmits the energy from the shaft to the electrical system.

When the fields are perfectly lined up with no angle between them there is no force and no power is transmitted. This is the no load state. The governor valves are open and allow just enough steam into the machine to overcome the frictional and windage losses of the unit turning at the synchronous speed. If the governor valves are opened more steam is admitted and the rotor starts to accelerate. As it moves ahead the magnetic fields in the generator come out of alignment. This creates a force between them opposing the acceleration of the machine. Energy will flow from the machine to the system. The rate of energy flow or power output of the machine is proportional to the strength of the magnetic fields in the machine and the sine of the load angle.

Notes

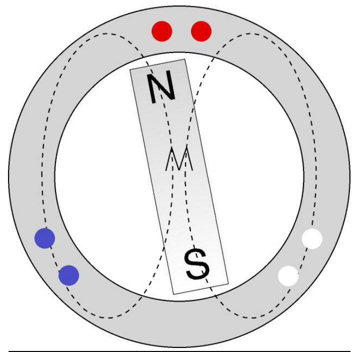


Figure 3

Forces between fields

If more steam is admitted the angle increases (so does the sine of the angle) the force opposing rotation increases and the machine speed stays constant. If the strengths of either magnetic filed is increased the power out put of the machine remains constant but the increased forces between the fields pulls the rotor back towards its no load position and the load angle decreases. The power output cannot change; the steam flow into the machine determines the power alone. Energy in must always equal energy out.

In the operation of an individual synchronized machine there are two things that can be altered the governor valve and the rotor field strength, both affect the load angle. Increasing the field strength decreases the load angle but the load stays the same. Increasing the steam flow increases the load angle and the power output of the machine increases.

4.3.3 Motoring

If the steam valves are closed to allow less energy in than that required overcoming the friction losses the rotor will tend to slow down. The magnetic fields will go out of alignment and a force will be generated to pull the rotor in the direction of rotation. This condition is called motoring. The machine is driven as a synchronous motor. Motoring is a condition that may or may not be allowed in a generator. Most large steam turbines in CANDU plants have the capability of motoring at least of a time period.

Notes

4.3.4 Limits

There is a limit to this phenomenon; if the load angle of the machine reaches 90° it has reached its maximum power output for the strength of the magnetic fields. If the power input to the machine pushes the rotor past the 90° position the retarding forces on the shaft start to decrease not increase. The rotor will start to accelerate. It will start to travel faster than the rotating magnetic field of the armature. However, lets not forget the millions of Newtons force that the magnetic fields can produce. And the rotor takes an extra revolution it will undergo severe mechanical stresses as the horrendous magnet force put torques on the shaft first trying to brake the machine and then trying to accelerate it. These torque pulsations will cause damage, possibly catastrophic damage to the machine. This phenomenon is called slipping a pole. It should be noted here that the load angle is a measurement of the electrical angles. These are the same as mechanical angles only in a two-pole machine. In a four-pole machine the mechanical shift of the generator shaft is one half of the load angle. In machines with even more poles the mechanical angles become smaller and smaller.

4.3.5 Synchronized Generator Equivalent Circuit

The first key to explaining the behavior of a synchronized generator is the idea of load angle; how it changes with field strength and how it changes with load. The second key is the simplified equivalent circuit. It consists of a generator and inductor and a load with a voltage fixed across it by the system. The generator represents a theoretical generator. The generated voltage E_g is directly proportional to the strength of the magnetic field of the rotor.

If the excitation current is increased E_g will increase. The phase of Eg will be determined by the load angle. Increasing the load angle will advance the phase angle of E_g. The inductive reactance X represents the impedance of the windings on the machine. The resistance of the windings is small compared to the inductive reactance and can be ignored in a circuit designed to give one a feel for machine operation rather than a look into the minute detail. The terminal voltage V_t is a voltage that is determined by the rest of the system. A single generator in a large system has little effect on the frequency and the voltage or the system. For our simple little generator it will be the voltage at the terminals of the machine. A couple more important things to recall, the voltage drop across X (V_X) will lead the current by 90° and V_t and V_X will add to give $E_{G,}$ so long as we remember that when we add ac stuff we have to use phasors.

Notes

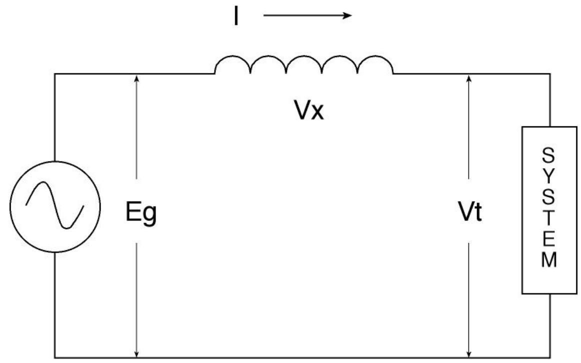


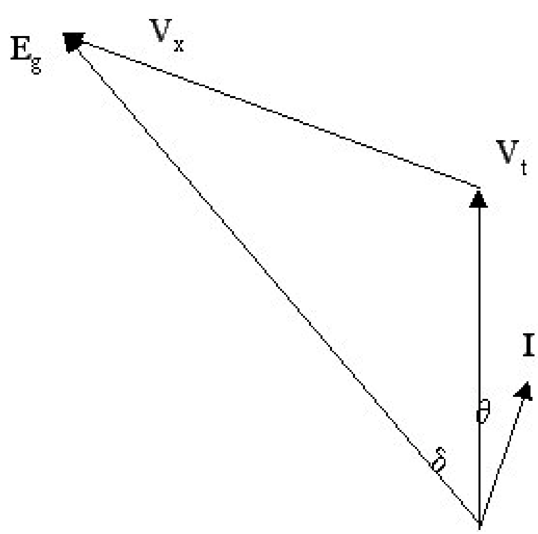
Figure 4

Generator Simplified Equivalent Circuit

4.4 STEADY SATE PHASOR DIAGRAM

A generator will typically be running with a lagging power factor at the terminals. The current from the machine will lag the terminal voltage buy some angle θ. The load angle δ is the angle between the terminal voltage and the generated voltage. The voltage drop across the inductive reactance is 90 ahead of the current and it added to the terminal voltage result in the generated voltage.

The machine output power will be VI cosθ and the reactive power output will be VI sinθ.



Notes

Figure 5
Phasor Diagram of a Loaded Generator

4.4.1 Increasing steam flow

If the steam flow to the machine is increased the load angle will increase and the power output will increase. Eg will advance in time. The power angle θ will be affected by the change in the real power component and by the phase shift increase between Eg and Vt. The result is that the power angle will be come more leading. The reactive power output of the machine will decrease to 0 and then increase again in the leading direction. It all depends on the size of the power increase.

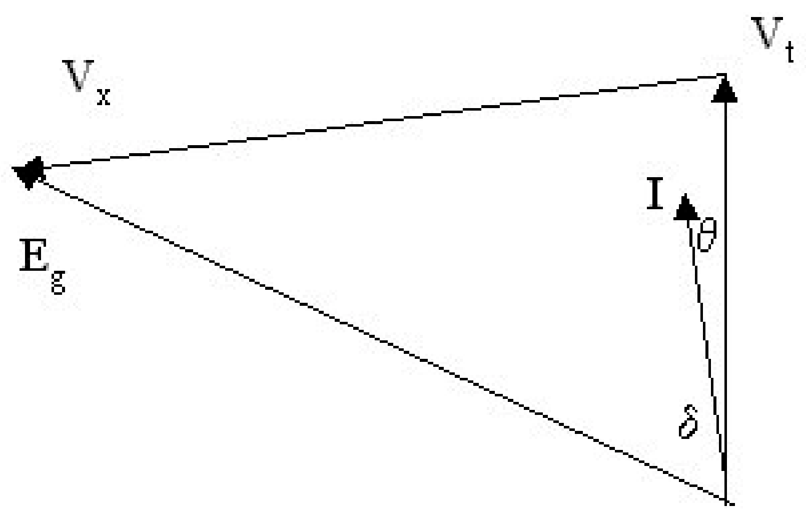


Figure 6
Increased Load

4.4.2 Increasing Excitation

If the excitation is changes the power output cannot change. The energy flow into the machine is determined by the steam flow. When excitation is increased the value of Eg increases and the strength of the magnetic field increases. The increased magnetic field strength will cause the load angle to decrease. The stator current is forced to become more lagging.

If you can remember this little circuit and the fact that changing steam flow changes the power output and the load angle and that changing

Notes

excitation changes the generated voltage and the load angle then you can predict the bulk behaviour of the generator under many conditions.

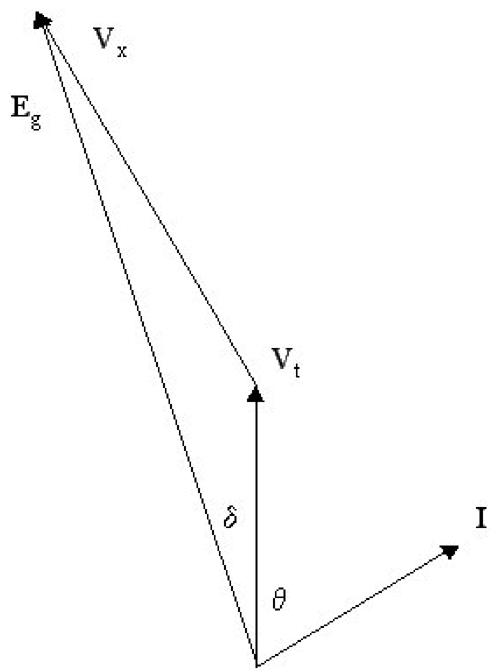


Figure 6

Increased Excitation

4.5 GENERATOR RUN-UP TO SYNCHRONIZATION

4.5.1 Runup

The term run-up is used for the entire process required to bring a generator from turning gear, where it is rotating at a few rpm, to near synchronous speed. Synchronous speed occurs when the speed of the rotor is such that if the exciter field were to be applied, the frequency of the stator output would match the external system (60Hz). As the steam conditions in CANDU plants dictate a slower turbine speed, they use 4-pole rotors that have a synchronous speed of 1800rpm to create the 60Hz output.

The many processes required to bring the generator up to synchronous speed will be described in other modules (Reactor Physics, Heat and Thermodynamics, etc.). Our only concern in this module is that thermal energy from the boiler comes in as steam to the blades of the turbine and is converted to mechanical energy. This mechanical energy turns the rotor to bring the turbine-generator shaft up to synchronous speed.

Notes

4.5.2 Applying Rotor Field

When dc voltage is applied to the rotor winding, exciter current will flow in the rotor winding and a voltage will build up on the rotor. As the rotor is moved past the stator windings a voltage is produced in the stator as indicated in Figure 5 below.

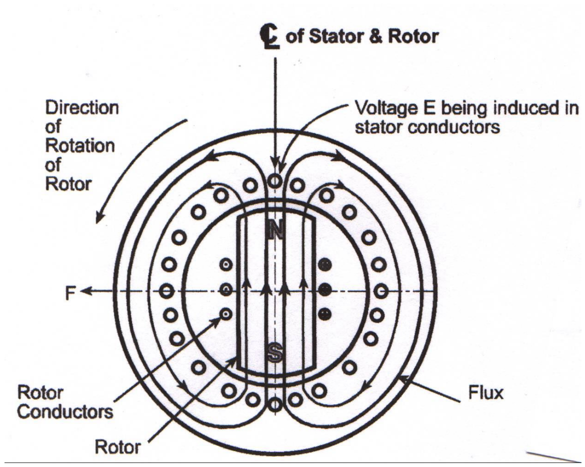


Figure 7

Generator Stator Voltage

To avoid saturation of the magnetic circuit, it is very important that the rotor excitation is only applied at or near rated speed. The flux in the iron core of an ac device is proportional to the applied voltage and inversely proportional to the frequency
($\phi \alpha$ V/f **)**. This relationship is termed volts per hertz and must always be maintained within the operating range of the device.

If the exciter field voltage V is applied at lower than rated rotor speed, the rotor and stator iron will saturate. This over-fluxing (see Figure 8 below) will cause heating of the rotor and stator iron and high current in the rotor with resulting rotor winding I^2R heating. Left uncontrolled, over-fluxing the generator can quickly cause excessive heating in the rotor and stator core with possible damage to the generator.

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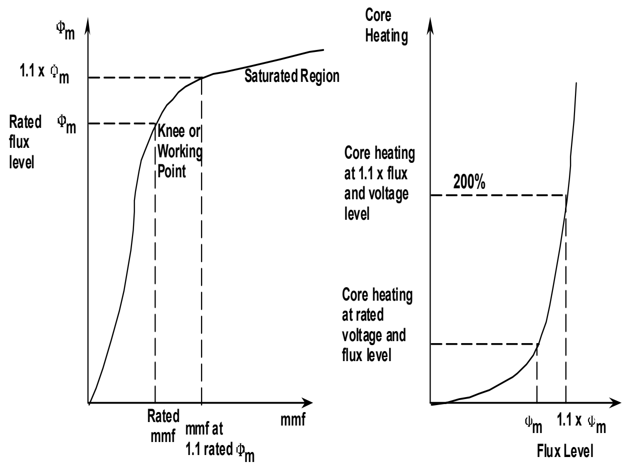

Figure 8
Core Heating as a Function of Magnetic Flux

Motors and generators are simply transformers with rotating windings. The rotor field current is increased to increase the generator induced output voltage E (Figure 9). Since the generator breaker is not yet closed and no stator current is flowing, this voltage E is actually the terminal voltage V_T

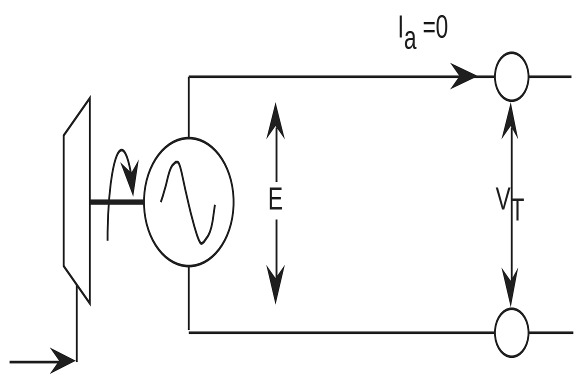

Figure 9
Generator at No Load

The rotor excitation is usually brought up to a set point on the generator Automatic Voltage Regulator (AVR) to match the external electrical system (Grid). However, we initially consider doing the synchronizing process manually.

4.6 PREPARING TO SYNCHRONIZE

In order to synchronize a generator to the grid, (Figure 8) four conditions must be met.

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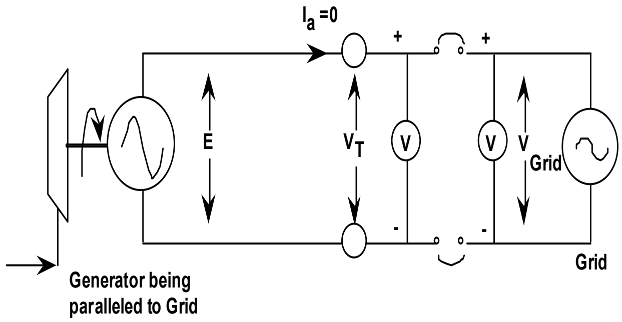

Figure 10
Synchronizing a Generator to the Grid

4.6.1 Phase Sequence

The phase sequence (or phase rotation) of the three phases of the generator must be the same as the phase sequence of the three phases of the electrical system (Grid).

The only time that the phase sequence could be wrong is at initial installation or after maintenance. There are two possible problem sources. The generator or transformer power leads could actually be interchanged during maintenance or the potential transformer leads could be interchanged during maintenance.

4.6.2 Voltage Magnitude

The magnitude of the sinusoidal voltage produced by the generator must be equal to the magnitude of the sinusoidal voltage of the grid.

If all other conditions are met but the two voltages are not the same, that is there is a voltage differential, closing of the ac generator output breaker will cause a potentially large MVAR flow. Recall that before a generator is synchronized to the grid, there is no current flow, no armature reaction and therefore the internal voltage of the generator is the same as the terminal voltage of the generator. If the generator voltage is higher than the grid voltage, this means that the internal voltage of the generator is higher than the grid voltage. When it is connected to the grid the generator will be overexcited and it will put out MVAR. If the generator voltage is less than the grid voltage, this means that the internal voltage of the generator is lower than the grid voltage. When it is connected to the grid the generator will be under-excited and it will absorb MVAR.

Notes

4.6.3 Frequency

The frequency of the sinusoidal voltage produced by the generator must be equal to the frequency of the sinusoidal voltage produced by the grid.

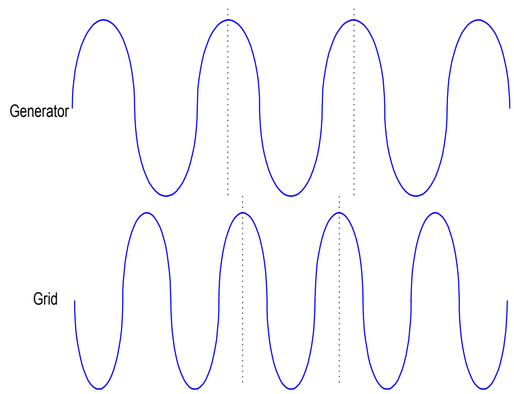

Figure 11

Generator Slower than Grid

In Figure 11 above the generator is slower than the grid. The synchroscope would be rotating rapidly counter clockwise. If the generator breaker were to be accidentally closed, the generator would be out of step with the external electrical system. It would behave like motor and the grid would try to bring it up to speed. In doing so, the rotor and stator would be slipping poles and damage (possibly destroy) the generator as described previously. The same problem would occur if the generator were faster than the grid. The grid would try to slow it down, again resulting in slipping of poles.

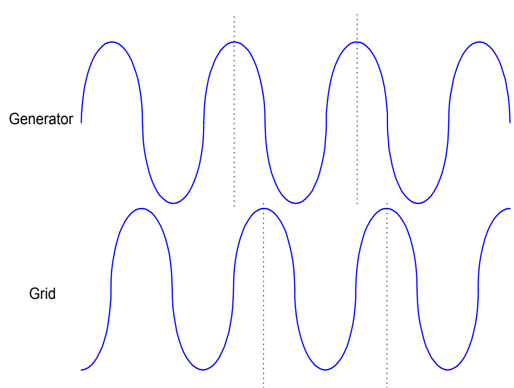

Figure 12
Generator at Same Speed as Grid but not in Phase

Figure 12 shows the condition where the generator and grid have matching speed. The high points and zero crossings of the sinusoidal

Notes

voltages occur at the same rate of speed. However, if you notice in 2 with the grid and a phase angle exists between them.

This would appear as a non-rotating synchroscope (both generator and grid at same frequency), where the pointer would appear stuck at about 9:00 o'clock (generator lagging grid). If the generator breaker were to be closed at this time, the grid would pull the generator into step. However, this again would cause a large current in-rush to the generator and high stresses on the rotor/stator with subsequent damage to the generator. If the generator were leading the grid, it would try to immediately push power into the grid with the same destructive forces as mentioned. Hence the generator must be brought to a point where the grid voltage waveform exactly matches what it is producing.

4.6.4 Phase Angle

As previously mentioned, the phase angle between the voltage produced by the generator and the voltage produced by the grid must be zero. The phase angle (0 to 360^0) can be readily observed by comparing the simultaneous occurrence of the peaks or zero crossings of the sinusoidal waveforms. If the generator breaker is closed when they match exactly, the connection will appear smooth and seamless. At that instance (Figure 13 below), the pointer on the synchroscope would indicate 12:00 o'clock. The worst case occurs if the generator is exactly out-of phase, with a phase angle of 180^0 and the synchroscope pointing at 6:00 o'clock.

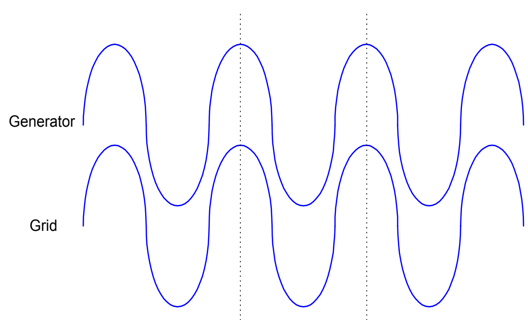

Figure 13Generator in Phase with Grid

4.7 SYNCHRONIZING

Having discussed the principles of synchronizing, we will look briefly on the physical method of accomplishing it. In theory, there are at least two simple measurements or indications, which can be used for synchronizing a generator to a grid. When two voltages satisfy the conditions of being equal in magnitude, have the same frequency and an angle of zero between them, then around the voltage loop they add

Notes

to be zero at each and every instant of time on the sine waves. Consequently voltmeters connected across each of the synchronizing breaker contacts will both read zero. Lights placed in the same position will also be totally out when all the synchronizing conditions are satisfied.

In practice, we need information which the voltmeters and light will not give us in order to synchronize a generator to the grid. During the actual physical process of synchronizing, we want to know whether the generator or the grid is fast and by how much. The instrument, which will provide this information, is the synchroscope. Figure 14 shows the connection of a synchroscope between the generator being synchronized and the grid.

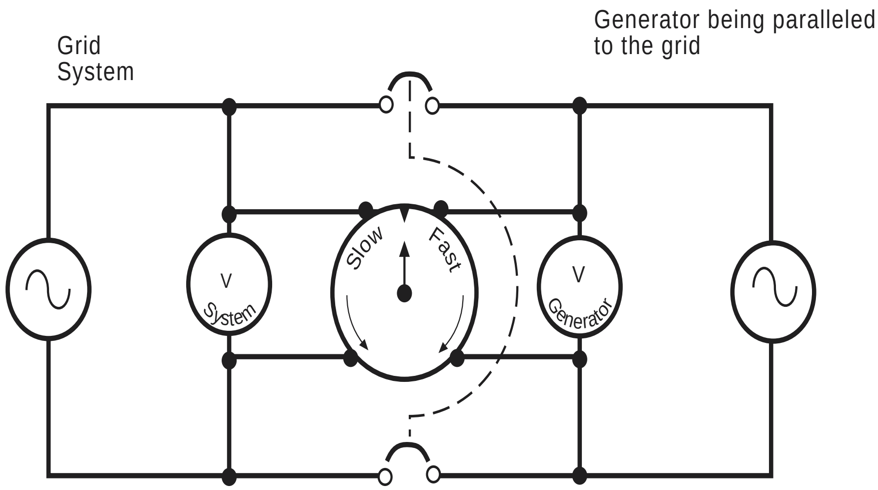

Figure 14
Synchroscope checking Angle and Frequency

We will still need to use two voltmeters to check that the generator and the grid voltage are the same (noting that these two voltmeters are not the ones referred to above, since those ones were placed across the synchronizing breaker contacts).

The position of the synchroscope pointer indicates the difference in angle between the generator voltage and the grid voltage. When there is a zero angle between the two voltages, the synchroscope pointer is in the vertical or 12 o'clock, position.

The speed of rotation of the pointer indicates the difference in frequency of the two voltages. The pointer will rotate in the Slow or counter clockwise, direction when the generator frequency is below the grid frequency. The pointer will rotate in the Fast or clockwise, direction when the generator frequency is greater than the grid frequency. It should be pointed out that the synchroscope will only

Notes

rotate for small differences in frequency of up to 2 Hz. With larger frequency differences, the synchroscope is designed to not rotate.

The last two paragraphs indicate that when:

- the pointer is vertical or at 12 o'clock,
- the pointer is steady, not rotating; then the two voltages are in phase and the frequencies of the generator and grid are equal.

In practice the synchronizing breakers are closed when the generator is just slightly fast and at about the 5 minutes to 12 position moving toward 12 o'clock. This allows a little bit of time for closing the synchronizing breakers and it assures that the generator will not act as a motor once the synchronizing breaker is closed.

It is important to check the correct operation of the synchroscope before each synchronizing is attempted. To do this, the generator is operated at less than synchronous speed and the synchroscope must rotate in the slow direction. Similarly when the generator is operated at a speed greater than synchronous, the synchroscope must rotate in the Fast direction.

4.8 GENERATOR SYNCHRONIZATION

Now that the generator is at the point where the output breaker can be allowed to close, consideration has to be taken on the external electrical system. In the previous section, we considered that the electrical system was already energized and that we were in the process of synchronizing with it. This not only is the normal process, but also allowed clearer explanations of the parameters involved.

Before we proceed with this in detail, we should look at the situation of picking up a de-energized load or often called dead load. All of the above factors still apply. The generator must be operating at rated voltage and frequency, plus have the AVR and speed controller in service. The last two items will be covered in more detail later. The first concern is the amount and type of load that will be picked up and what the expected result will be on the generator.

The magnitude and type of load has a unique impact on the turbine-generator through the output medium – the current. As you can recall at the start of the series on electrical equipment the generation of electricity is actually the process of pushing electrons or pushing electric current. Also recall that a generator is nothing more than a transformer with a rotating primary winding. The current draw on the secondary winding (stator) will of course affect the primary winding

Notes

(rotor) and the drive source (steam). This affect is called armature reaction.

4.8.1 Armature Reaction

When the generator is loaded and current flows in the stator conductors, there is a second flux ϕ_S produced by the stator coils. Armature reaction is the interaction of the magnetic fields of the stator ϕ_S and rotor ϕ_R windings that produces a resultant magnetic field referred to as the air gap flux. Armature reaction has the following three characteristics:

4.8.2 Active Component

The active component of the current that produces Real or Active power, weakens the flux linkage across the air gap. The flux linkage in the air gap stretches (Figure 15). If the MW loading increases, without increasing the exciter voltage, the flux lines get stretched more, this means that the load angle increases. This cannot be allowed to happen or a pole slip may occur as discussed previously. Hence as load increases the exciter current has to be increased (over-excitation) to maintain the strength of the field. Although it will be discussed later, it should be noted that a heavy fault current can pull the generator out of step and pole slip occur because the prime-mover (steam) and automatic voltage regulator (AVR) cannot react fast enough to correct the flux deficiency.

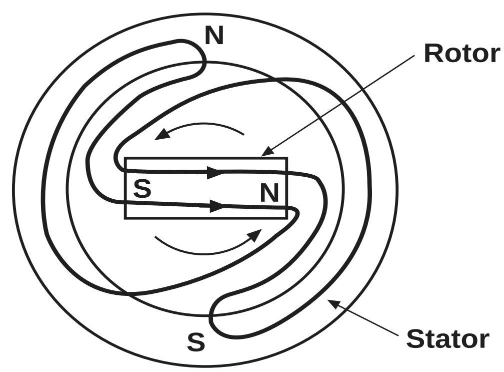

Figure 15
Air Gap Flux Stretching

4.8.3 Reactive Lagging Component

With a lagging load on the generator, lagging current is pulled from the stator and the generator is seen to be producing MVARS. The lagging stator current creates a resulting flux that directly opposes the field flux. As induced voltage is proportional to flux **($V \propto f$)** the

Notes

generator output voltage drops to maintain rated voltage the rotor field has to be increased and the generator then becomes over-excited.

4.8.4 Reactive Leading Component

With a leading load on the generator, lagging current is supplied to the stator and the generator is seen to be absorbing MVARS. The stator current creates a resulting flux that directly assists the field flux. As induced voltage is proportional to flux **($V \alpha f$)** the generator output voltage will increase. To maintain rated voltage the rotor field has to be deceased and the generator then becomes under-excited.

4.9 CLOSING ONTO A DEAD BUS

4.9.1 Closing onto a Dead Bus with Leading PF Load

It is possible to have a power system configuration where a bus might have capacitive loading.

- Static capacitors connected to it.
- Energizing a long high voltage transmission line. Note HV lines inherently appear like capacitors, which are able to supply MVARs.

In the capacitive loading situations the generator would have to absorb these MVARs. If the Automatic Voltage Regulator is in the Auto mode, the generator excitation is automatically decreased to cause the generator to take in the required MVARs and to hold the terminal voltage. If the Automatic Voltage Regulator is in the manual mode, the excitation is constant and the leading power factor current which is required for the generator to take in MVARs could cause the generator terminal voltage to go very high.

4.9.2 Closing onto a Dead Bus with Lagging PF Load

Inductive loading can take the form of:

- Connected power transformers
- Motor Loads

Inductive loading will cause a significant voltage drop when the generator breaker is closed, due to the load absorbing MVARS.

4.9.3 Closing onto a Faulted Bus

Closing the generator output breakers onto a bus, which has a short circuit fault, can cause generator damage because of high winding currents, stresses and possible pole slipping.

Notes

4.9.4 Closing onto a Dead Bus with no Connected Loads

This should not present a problem as long as the bus has been proven to be free of faults or working grounds.

4.10 GENERATOR LOADING

4.10.1 Closing onto a Finite vs Infinite System

When we enter into the topic of generator loading we must consider whether or not the connected electrical system is very large and hence strong or smaller and weaker. The first is classed as infinite and the second finite.

A generator connected to a very large (infinite bus) electrical system will have little or no effect on its voltage or frequency.

In contrast, a generator connected to a finite bus does have a substantial effect on voltage and frequency.

It is normally assumed that when a generator has a capacity of greater than 5% of the system size, then with respect to this generator, the system does not behave as an infinite bus. For example, when an 800 MW generator is loaded onto a grid having a capacity of l0,000 MW, the system voltage and frequency can vary and the system will behave as a non-infinite bus.

4.11 GENERATOR AVR CONTROL

There really are only two parameters, which can have direct electrical impact on both the plant and the grid. These are:

- The AVR, which automatically adjusts the generator field current to maintain a desired generator terminal voltage (or reactive power loading).

- The speed governor that is a closed loop control system that activates the steam inlet valves to the turbine to control the speed of the unit. When the unit is synchronized, the governor also controls the unit loading.

The first we will consider is the automatic voltage regulator or AVR. An excitation system must be able to provide the required dc rotor current and resulting magnetic flux, under the following conditions:

- When the generator is on no load, the excitation system has to provide sufficient flux to cause the generator to produce rated voltage at rated speed.

Notes

- From no load to full load operation, the excitation current has to be increased to counter-act the effects of armature reaction. Typically, between no load and full load, the excitation current has to be increased by a factor of 2.0 to 2.5, for example 1700 A to 4000 A.

- When faults occur on the grid system, due to lightening or other causes, the voltages are depressed or reduced. An excitation system must have a very fast response. It must be able to increase excitation very rapidly (typically within 0.25 seconds) to counter-act these voltage depressions and in turn, quickly restore the main ac generator output voltage to normal.

The actual AVR feedback control system can be one of many types, from separate dc generators to ac fed rectifiers.

The latter has been shown only for example (Figure 16), as they all have the main components:

- Reliable wide range dc source
- Generator ac output voltage sensor
- Reference signal
- Comparator
- AVR logic

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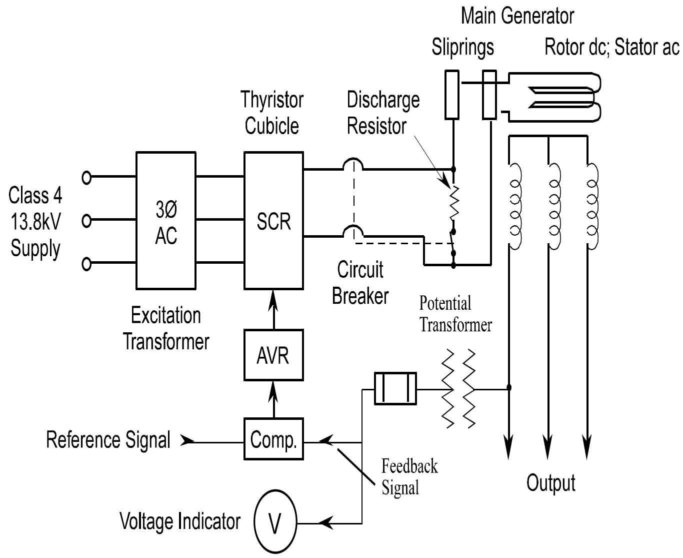

Figure 16
Typical AVR System

The comparator compares the voltage produced by the main ac generator with the voltage that is demanded by the control room operator. The voltage produced by the main ac generator is proportionally reduced by the potential transformer and is applied to one side of the comparator.

This signal is called the feedback signal because it is fed back from the output. The other side of the comparator is supplied with the voltage that is set by the control room operator. This signal is known as the reference signal.

4.11.1 AVR Action to Generator Loading

If while connected to a varying load, the output voltage of the main generator falls below the voltage setting applied by the operator, the comparator will sense the difference and send a signal to the AVR. The AVR will then raise the field current on the main exciter, which will increase its output voltage. The excitation will now be increased, enabling the generator to produce the required output voltage. Similarly, if the main generator output voltage rises, the comparator will once again sense the difference.

The AVR will lower the exciter output, which will reduce the main generator output voltage to the required value.

Remember that although a resistive load will cause a drop in voltage and hence require an increase in field current (AVR boost), inductive and capacitive loads have a greater impact.

Notes

4.11.2 Unity PF Load

To have a clearer understanding of the exciter/AVR action for various loads it is best to refer to an equivalent generator diagram. In Figure 17 below we have a generator that has an internal no-load voltage E, a passive armature reaction component R_G and an active stator flux component X_G. When the generator has a real or resistive load there is a voltage drop between E_G and the terminal voltage V_T equal to the value V_R. plus V_X. However the voltage drop across V_X is at 90 degrees to the terminal voltage so small changes in the load do not create large changes in terminal voltage.

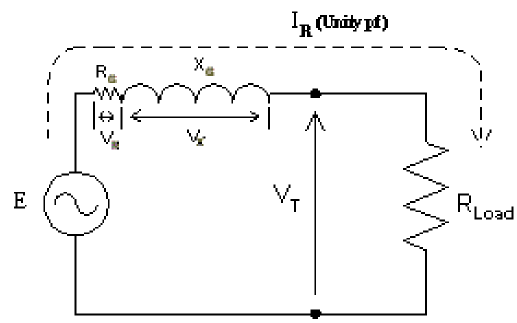

Figure 17
Generator with Unity PF Load

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4.11.3 Zero PF Lagging Load

If the load is inductive as in Figure 18 below, the inductive current causes a voltage drop V_X across the much larger reactive component X_G. This voltage drop is exactly opposite to the terminal voltage and a large decrease in terminal voltage will be seen. Again the AVR would detect the decreased terminal voltage V_T send a feedback signal to the exciter to increase field current.

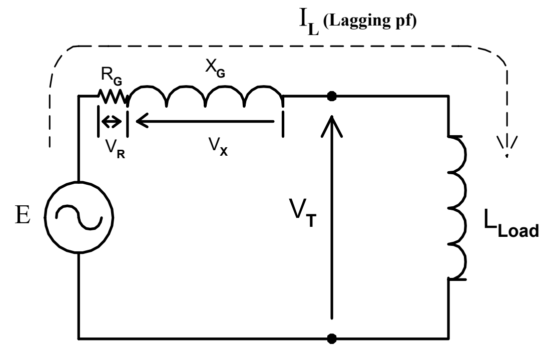

Figure 18
Generator with Lagging Load

If the load is capacitive as in Figure 19 below, the capacitive current causes a voltage drop V_X across the much larger reactive component X_G. However, as you recall from the basic electrical theory, capacitors are a source of leading current. The capacitive load current works in reverse of the losses caused by inductive currents. The main generator field is assisted and the terminal voltage V_T increases. Again the AVR would detect the increased terminal voltage V_T send a feedback signal to the exciter to decrease field current.

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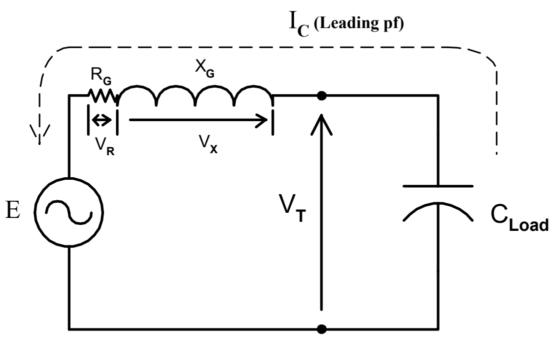

Figure 19
Generator with Leading Load

The overall effect on the exciter current for the different loading is illustrated on a generator V Curve, Figure 20.

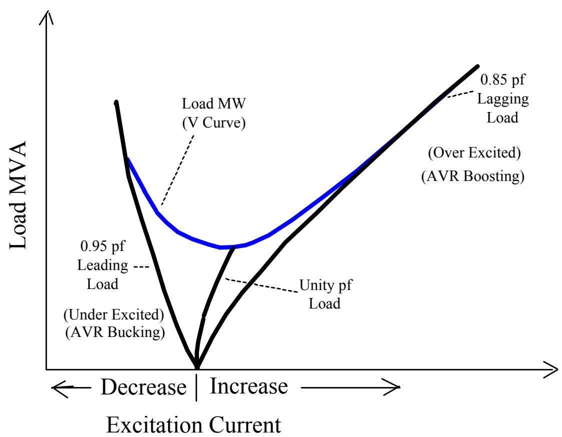

Figure 20
Typical Generator V Curve

If more than one generator is connected to a local (finite) bus then care must be taken to ensure that they use the same reference voltage and feedback settings. Otherwise, they will possibly oscillate (hunting) or fight against each other by counteracting the changes made by the AVR of the other generator. The AVR with the highest voltage setting would try to force MVARS into the other generators causing those AVRs to try to reduce the voltage.

As the connected electrical systems become very large (infinite), the AVR of a single generator will obviously have a decreasing effect on the overall system voltage. Instead the voltage setting can be used for AVR support. When the AVR voltage set-point is increased, the exciter current is increased. This over-excitation increases the VAR output as indicated on the V Curve Figure 20. This extra VAR support

Notes

will assist in bringing up the overall system voltage, but is dependent on the size of the units and thermal constraints (to be discussed later).

Above all else, it is important that neither the AVR nor excitation be removed while the generator breaker is still closed and the unit is paralleled with an external electrical system. Loss of excitation results in the generating unit acting as and induction motor. This affects the stability of the connected electrical system (heavy MVAR load) and over-heats the rotor and stator because of the heavy induced currents in the core.

4.12 GENERATOR GOVERNOR CONTROL

Turbine speed during run-up and while under load is controlled by the positioning of valves that control the steam flow. These valves are controlled by a speed error signal that is generated by the speed/load control mechanism or speed governor (see Figure 21).

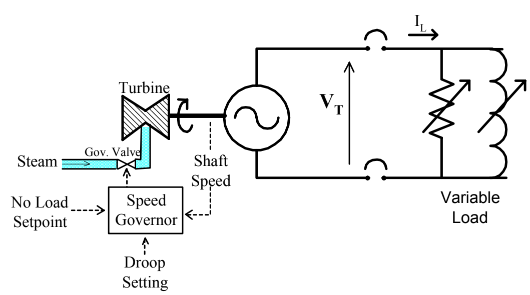

Figure 21
Generator Speed Governor

The governor is a proportional controller that compares the actual turbine speed with the no-load set-point and the required generator speed droop setting. The term droop, which will be explained in detail later, is the decrease of generator shaft speed as the load (required torque output) increases.

The speed governor has five purposes:

- To allow the synchronization the generator.
- To act so that the turbine-generator set supplies the customer MW load on demand.
- To change the load on the generator.
- To carry out frequency correction (if it is necessary).
- To control the turbine-generator during disturbance conditions.

Notes

4.12.1 Droop

In operation, the governor opens/closes the steam valves in proportion of the speed decrease/increase detected as compared to the total speed change allowed from no-load to full-load. The governor feedback control will continue to adjust the valves until the speed error is zero. The allowable speed change is determined from the droop setting. Droop can be defined as:

$$\text{Speed Droop} = \frac{\text{Total drop in speed (NL to FL)}}{\text{Rated Speed}}$$

$$= \left(\frac{\text{NL Speed - FL Speed}}{\text{Rated Speed}}\right) \%$$

While Generator goes from No Load to Full Load

The term speed droop is also some times called proportional band. A speed governor with a 2% speed droop or 2% proportional band is the same thing.

4.12.2 Isochronous

Let us look at the simple case of a governor with zero droop (Figure 22). This is termed an isochronous governor, because the speed is maintained constant regardless of generator loading.

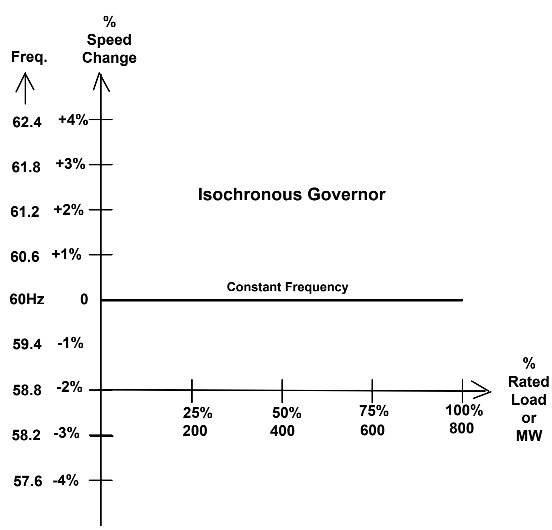

Figure 22
Isochronous Governor

This type of governor control with a constant frequency operation is sometimes called proportional plus reset and is used only on single generators that are not part of a load sharing system. Standby

Notes

generators often have this characteristic to maintain constant Station Service ac frequency, irrespective of loading.

If more than one generator is connected on the same bus they cannot have droops with zero slope. With a flat characteristic, the system would be inherently unstable. A very small frequency disturbance would cause one of the machines to grab the whole load. The result would cause hunting of the governors and rapid load swings between the generators.

4.12.3 Percentage Speed Droop

When a slope is added to the governor droop we obtain a characteristic similar to Figure 23 below. Five droop settings (A to E) are shown, all with the same slope. If you look at curve A, the slope is 4% droop per Total Rated Load. This droop setting is used on the majority of the generators connected to the Electricity Grid. We will describe why later.

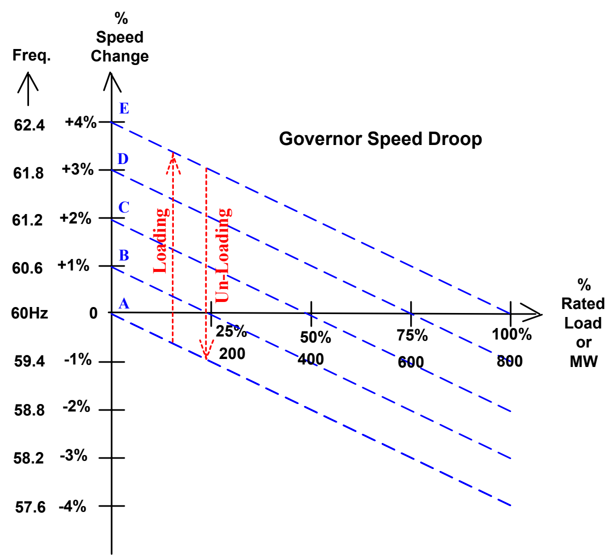

Figure 23
Governor Speed Droop

Initially, with the generator spinning unloaded, the governor No Load set point would be at A giving 60Hz at no load. If the NL set point were increased to +1%, the droop would go to curve B. The steam valves would proportionally open to bring the load up to 25%, at which point the error signal would be zero again and frequency at 60Hz. This could proceed all the way to +4% set point E, where the total output would stabilize at 100% rated load and 60Hz.

Notes

Obviously, the loading to full load is a slow process the rate that the unit is loaded (rate of varying the NL-set point) is determined by computer input to the speed governor to match available steam conditions.

Note that for a single generator with a connected load the amount of steam to the turbine can only serve to speed up or slow down the turbine. It cannot change the amount of the load. This is the major disadvantage of operating a single generator with a percentage speed droop as compared to isochronous mode. Figure 24 below illustrates the effect of a single generator with a large load suddenly applied (point B). The NL set-point has to be increased to bring the frequency back up to 60Hz (point C).

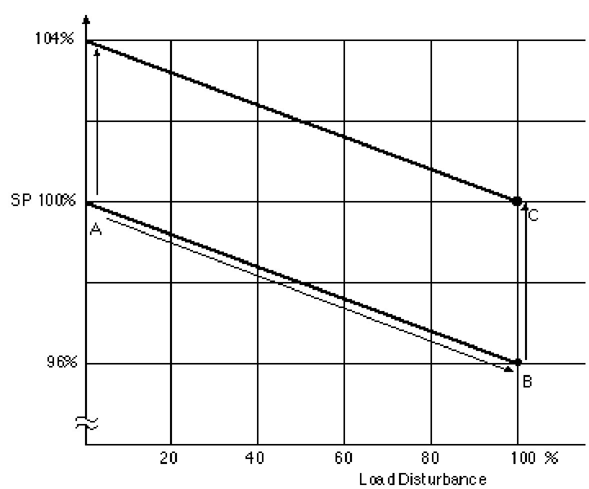

Figure 24
Single Generator Frequency Correction

Before we proceed on to the effect of varying the droop settings or varying the loading with constant NL settings, we must look closely at what is actually happening to the turbine generator as a whole. Observe that a 4% speed change equates to almost 100% movement of the steam valve (considering that it requires very little steam at No Load).

4.12.4 During Runup

The speed governor has to bring the turbine from turning gear (a few rpm) to synchronous speed (1800 rpm). Because of the small amount of steam (power) required, a separate high droop setting termed wide range speed control is used. This allows a very accurate control of the valves as the machine runs up from 0% to 90% rated speed with very little steam input to the turbine.

Notes

4.12.5 Normal Operation

Once the turbine reaches about 90% rated speed the error signal produced by the previous controller decreases and the running or narrow range speed control takes over with a low droop setting. The droop can then handle the large variations in steam valve operations from zero to full load.

Note also that if the generator breaker were to open at any time while under load, the no-load frequency would be excessively high for the generator and connected output/unit service transformers. The no-load set point has to be run back by computer to either no-load or the value required to sustain unit service load.

When we use the term normal operation, the governing action has different effects depending on the number of generators connected to the system.

It is best to describe the speed/load interactions for a very large (infinite system) and then to look at the differences as the electrical system becomes smaller.

4.12.6 Parallel Operation on a Large (Infinite) Bus

On a large system, the voltage and frequency will remain fairly constant regardless of the loading of the unit. Hence, the generator will pick up load according to the arrows in Figure 25 below.

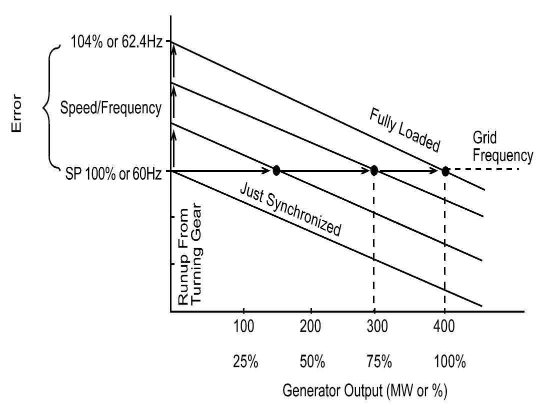

Figure 25
Generator Loading on a Large Grid

The connected generator is constrained to share the overall load according to it's droop characteristic, while the system frequency maintains steady at 60Hz. Observe Figure 24, where two (could be any number) generators are in parallel. Depending on the NL setpoint, the generators can be made to share the load at whatever amount desired.

Notes

In this case the NL set point of G2 is raised and G1 is lowered to shift 50 MW of load from G1 onto G2.

This action of changing the NL set-point to change the generator loading occurs many times a day on hydraulic or fossil fuelled steam turbines supplying the grid, but is usually steady for nuclear units. The former are usually used more for peaking loads and the latter for base loads due to physical anomalies of the nuclear process.

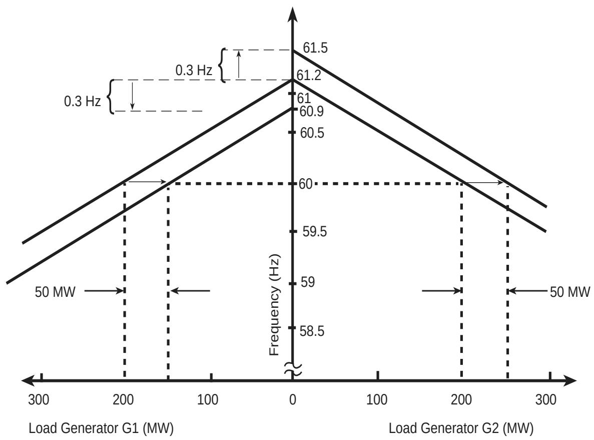

Figure 26
Varying Load Distribution on an Infinite Bus

From Figure 26 it is clear to see that increase in loading requires an increase in the NL set-point. To make a generator more responsive to changes in frequency the slope is decreased as per Figure 25 below.

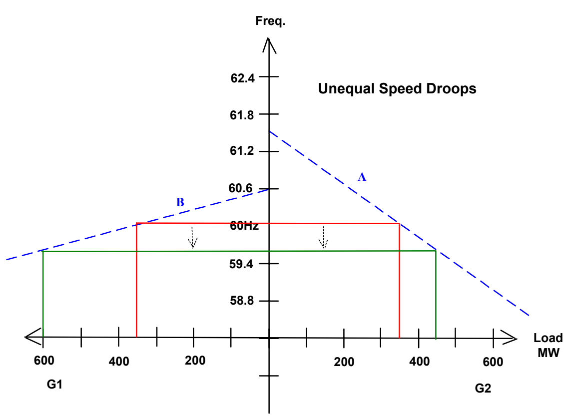

Figure 27
Effect of Droop Slope on Loading

In Figure 27 G1 has less of a droop than G2. It will react to load changes more than G2, which has the steeper droop. In the example, a system load increase of 350MW will be shared 250MW extra on G1

Notes

and 100MW extra on G2. Meanwhile the system frequency would decline to a little under 59.5Hz.

This is an exaggerated example for demonstration of the effect of slope. In actual practice with many generators feeding the large system, it would take a major load disturbance to drop the system frequency that much. However, it serves to demonstrate the effect of the % droop and why all large generators connected to the grid should have the same droop setting. With the same setting, they will equally share the load according to their capabilities and equally share in stabilizing the load during system disturbances.

4.12.7 Parallel Operation on a Finite Bus

The last section dealt with the ideal situation of a generator connected to a very large system where it had little impact on the overall voltage or frequency. We will now look at the normal situation where:

- there is a significant amount of impedance (long transmission lines) between the paralleled generators and the infinite grid; or
- the paralleled generators are in an island situation and not connected to the infinite grid

The governor action previously discussed still applies no matter what the size of the electrical system. Knowing this, we will look a little closer at what happens in a smaller electrical system. This can occur instantaneously due to major plant disturbances or failure of transmission lines. As the electrical system decreases, the effect on the operating frequency increases. In the example below (Figure 28) of a small system we have a load increase from 400MW to 600MW and the frequency dips to 59.4Hz.

Notes

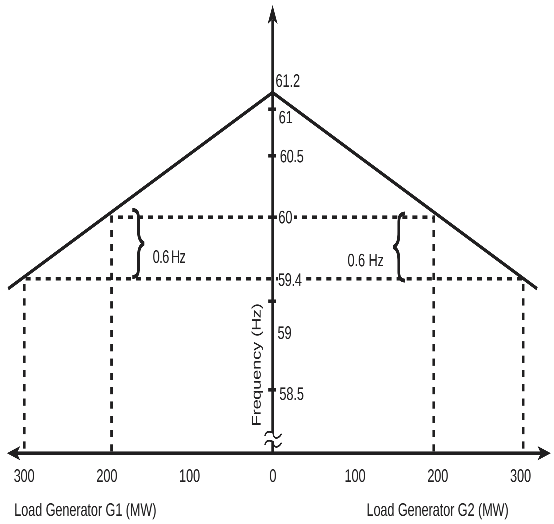

Figure 28
Finite Bus Load Increase

To return the output frequency to 60 Hz, the No Load setpoints would have to be increased to raise both speed droop curves so that the two generators can each supply 300 MW at 60 Hz. To accomplish this, the load/frequency setpoint or no load frequency of each governor must be increased by 0.6 Hz from 61.2 Hz to 61.8 Hz. This is the amount that it dropped during the load increase. Figure 29 shows the restoration of frequency.

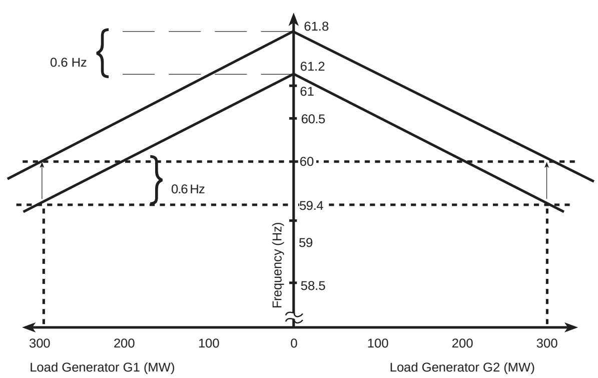

Figure 29
Frequency Restoration

Having now looked at the separate scenarios of AVR control and Governor control under various system conditions, we can put them together for a more complete picture.

Notes

4.13 COMBINED AVR/GOVERNOR CONTROL

The changes in the electrical parameters while varying steam input or excitation level can be best viewed by keeping one constant and varying the other and then combining the effect when considering system stability. We will initially assume the generator is connected to an infinite system. As such the generator will have little effect on the overall voltage or frequency.

4.13.1 Adjusting Steam Flow without Changing Excitation

Suppose the steam flow is increased, by raising the speed droop set-point on the governor. We can predict the effects (referring to Figure 30) as follows:

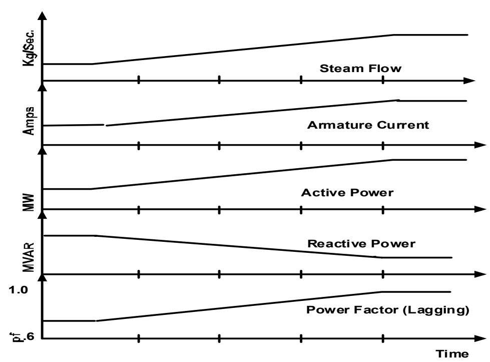

Figure 30
Increasing Steam Flow at Constant Excitation

- The initiating condition is that the steam flow increases.
- The excitation is constant, so the field is unchanged
- The active power The MW component of stator current increases, while the MVAR component of (MW) increases because the steam flow increases. The frequency maintains constant.
- With the increase in MW output, the armature reaction increases. The generator is now under-excited (leading) and the generator load angle increases. The typical 0.85 lagging power factor moves toward unity power factor and so the MVAR output decreases towards zero.
- The MW component of stator current increases, while the MVAR component of stator current decreases. However the change in MW component will be greater than the change in

Notes

MVAR component (near unity PF), so the net effect is that the stator current increases.

4.13.2 Adjusting Excitation without Changing the Steam Flow

Now we will look at increasing the excitation by increasing the AVR voltage setting while maintaining constant steam input. Refer to Figure 31 below.

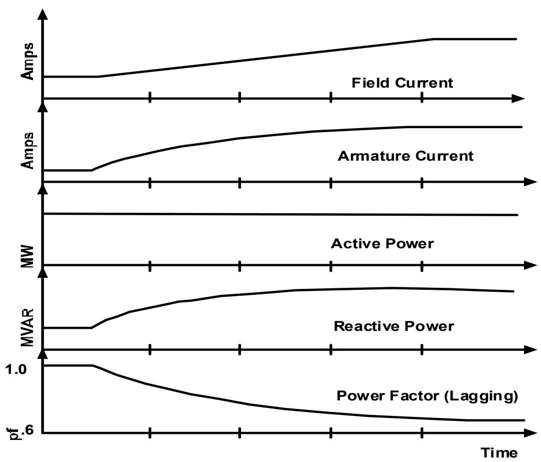

Figure 31
Effect Over Time of Increasing Excitation at Constant Steam Flow

- The initiating condition is that the excitation increases and this is done by increasing the field current (AVR voltage set-point).
- The steam flow is constant.
- The increase in excitation without a change in MW flow means that the generator is now overexcited for the level of armature reaction. Therefore the generator moves in the lagging direction and the load angle decreases. Since we initially started at 1.0 power factor, the generator becomes lagging and starts to put out MVAR. The MW component of stator current did not change, but the MVAR component of stator current increases. Therefore the magnitude of the stator current increases.
- The active power is constant, because the steam flow did not change.
- Following from the argument already made, the generator is now overexcited for the level of armature reaction. Therefore it

Notes

moves in the lagging direction from the original 1.0 power factor and starts putting out MVAR.

4.14 GENERATOR STABILITY

We will now look at the steady state and transient stability for a generator with both the AVR and governor in service (the normal situation). It can be shown that the power delivered to a load by a generator (see Figure 32) is roughly proportional to the square of the Terminal Voltage and inversely proportional to the impedance between the generator and the system it is supplying.

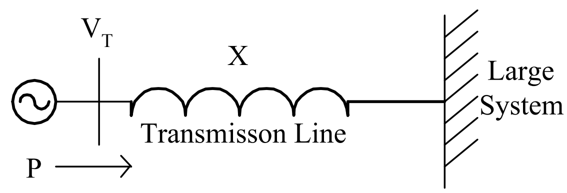

Figure 32
Generator Power Transfer

When we plot a generator's electrical power output capability as compared to how much it is leading the power system (load angle), it turns out to be a sinusoidal curve. This is termed the power transfer curve of a generator. A sample curve is demonstrated in Figure 33.

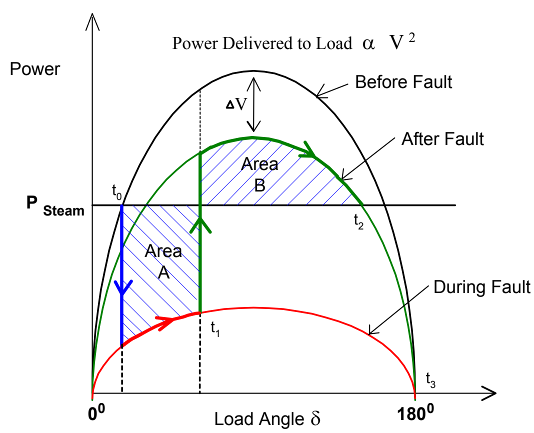

Figure 33
Generator Power Transfer Curve

The power transmitter through an inductor is proportional to the voltages on either side of the inductor, the sine of the angle between the voltages and inversely proportional to inductive reactance of the inductor.

Notes

$$P = \frac{V_1 V_2}{X_L}\sin\delta$$

A power transfer curve is the plot of this equation for fixed values of $V_{1,}$ V_2 and X_L. It is a plot of load angle vs. power transfer of the machine for a certain system configuration. If the conditions of the system change, so will the power transfer and the load angle of the machine.

One way to describe the power transfer curve is to imagine if a generator were allowed to run unsynchronized while still connected to the large system by a large reactive spring. The generator would oscillate about the large system, being completely out of phase at 180^0 and in back in phase at 360^0. In actual practice, the time required for a generator to oscillate in such a manner would be about 2 seconds. Hence, the time for the load angle to go from 0^0 to 180^0 is about 1 second.

If a generator with input P_{steam} were connected to the large system, we could show it on the curve as straight horizontal line because the steam valves operation would take longer than one second to operate.

Ideally the generator loading (P_{steam}) should be at 90^0 where the maximum power transfer would occur. However, this is a very unstable position.

On the curve, imagine that a transmission line fault occurs at time t_0. Because of the depressed voltage, the power transfer capability drops dramatically and the turbine starts to speed up. The fault is cleared at time t_1. The voltage recovers, but usually never to the original value, because the reactance X is now slightly higher due to lost elements.

During this time (t_0 to t_1) the turbine has trapped (see Area A) steam energy. It expends this energy in Area B of the curve. If it cannot transfer this energy to the connected load by time t2, the generator will quickly proceed down the curve towards 180^0 and go out of step with the system.

4.15 GENERATOR OUT OF STEP

The effects of pole slipping are so severe that it is necessary to give additional consideration to it. When the load angle of a generator increases, due either to the generator being loaded up too much for the level of excitation or when operating at a large load angle, the resultant magnetic flux lines are stretched. Review Figure 13, which shows what these stretched magnetic flux lines look like when the load angle of a two-pole generator is at 90^o. Should the rotor continue to move

Notes

ahead of the stator revolving field, the rotor will quickly reach a load angle of 180° (zero power output). This is shown in Figure 31. At this point there is no flux linkage between the rotor and stator and no hope of the generator staying in synchronism. Pole slipping is underway and it is a certainty.

As the generator pole slip continues, the rotor angular velocity is not constant. In fact, the rotor motion is very jerky and this places enormous stresses on the windings, couplings, foundations and other components. The active power output will also surge, as described above. Figure 34 (a) shows the rotor angular position and Figure 34(b) shows the active power output both versus time during pole slipping.

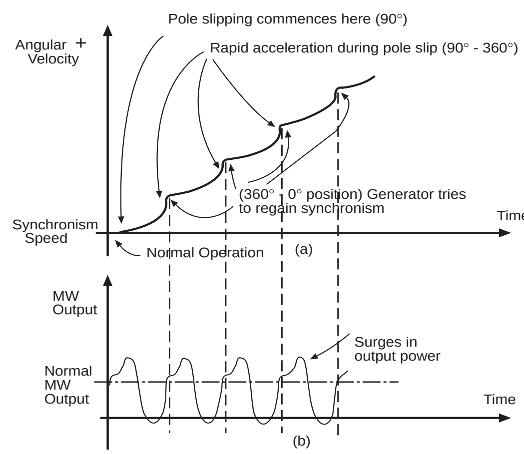

Figure 34
(a) Rotor Angular Position and (b) Generator MW Output during Pole Slipping

The normal set-point on the generator governor is such that the steam output Psteam allows for possible system instability. In calculating this operating set point, consideration also has to be given to the status of the AVRs. An AVR will detect a voltage decline and increase the excitation, boosting the terminal voltage This will increase the available transfer capability (makes the curve higher). If the AVR is on manual or a slower AVR is in service, the generating unit output will have to be decreased (de-rated) due to stability margins. It should be noted that an AVR will take at least 0.25 sec. to react and will have limited effect during a major system disturbance.

Notes

The generator voltage and frequency are set by the electrical system when it is connected to a large (infinite) bus. However, when operating as a single generator or with a small island of load both parameters have to be maintained within acceptable limits to avoid equipment damage. We have previously discussed the damaging effects due to under/over voltage and frequency and their combination (volts/hertz). Due to a major system disturbance the generator and local load may suddenly become islanded or disconnected for the main system. In which case the terminal voltage will increase rapidly and the AVR have to bring it down to rated values. Similarly the turbine speed will increase rapidly and drive the frequency above rated values. The No-Load set point of the speed governors has to be run-back rapidly to a lower value.

A turbine trip can occur at any power output and a fast run-back of the speed controller is initiated to bring the power back to zero. The most severe trip is that of a total load rejection or generator trip at full power.

The electrical system can initiate a trip to the generator breakers if due to a major system disturbance and load loss, there is too much connected generation. The entire large system would become unstable (see Figure 31) unless some generation (Psteam) were removed.

When a generator receives a trip signal:

- the generator breaker(s) are opened;
- there is rapid acceleration of the turbine generator rotor; and
- there is a large unbalance between available turbine power (Psteam) and the previous MW load.

The fast runback will lower the NL set point on the speed governor to stabilize the connected Unit Service load at 60Hz, in readiness for re-synchronization. The AVR will bring the terminal voltage down to rated values.

4.16 GENERATOR HEAT PRODUCTION AND ADVERSE CONDITIONS

Safe and efficient operation of the turbine generator is of paramount importance in station operation. One major concern is the operating limits of the equipment. That is - how far the generator can be pushed and what are the consequences of pushing it close to and beyond, its operational limits. We concentrate on the generator rather than the

Notes

turbine limit, as the turbine capacity is significantly above that of the connected generator especially when we consider it's stability.

Aside from turbine-generator stability covered previously, heating constraints pose the largest limiting factors on the generator output. Heat originates as iron/core losses and winding/copper losses in both the rotor and stator.

Iron losses are flux related: recall that magnetic flux is proportional to applied voltage and inversely proportional to frequency:

$(\phi \propto V/f)$

Because of thermal heating and mechanical stresses, manufacturers state that the flux in a generator core must not be kept at a value greater than 10% above normal for more than a few minutes

Winding losses are proportional to the square of the current in the winding. We know from basic electrical theory that: the power dissipated in electrical heating is active or real power and can be shown as:

$P_{heat} = I^2 R$ Megawatts

And since V=IR

$P_{heat} = V^2/R$ Megawatts

4.16.1 Rotor Heating Limitations

Rotor heating can arise due to two operating conditions. First, at high loading levels a high field current is required to overcome the armature reaction of the generator. Second, even at low loading levels and particularly at high loading levels, a requirement for MVAR from the generator means that the generator has to operate in an overexcited mode. This cause core losses due to excessive amount of core magnetic flux. Over-fluxing the generator (recall Figure 6) can quickly cause excessive heating in the rotor and stator core with possible damage to the generator.

Exceeding the rotor temperature will shorten the life of the insulation. Also differential expansion, due to excessive temperature differences between the rotor copper and rotor iron components, may cause cracking of the rotor copper or insulation.

Generator manufacturers specify the maximum value of field current for the generator. This limitation is imposed by rotor conductor $I_F^2R_F$ heating and by the slip rings and brushes, which are unable to carry larger currents to the rotor.

Notes

4.16.2 Stator Heating Limitations

Stator losses are mainly copper losses (**I_a^2R**). However, at very high and very low values of excitation, there is excessive core losses. At high values of excitation (lagging PF) the losses are as described for the rotor. At low values of excitation, the stator core ends over-heat due to the elongated flux patterns.

If the generator had no losses, the total generator output could be described as a circle (Figure 33). We do not show the left hand part of the circle because the generator is not intended to operate constantly in the motoring mode.

4.16.3 generator heating limits

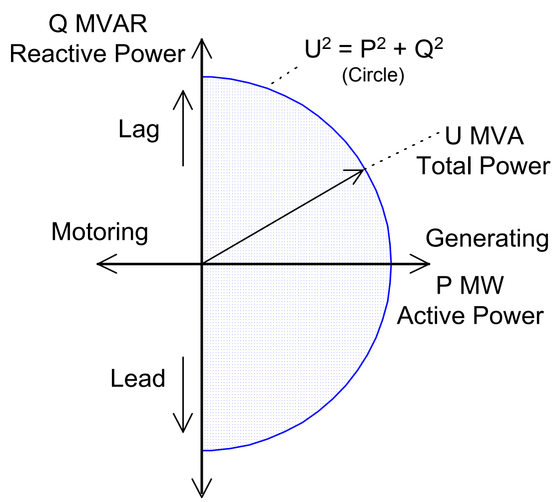

Figure 35
Basic Q-P Diagram

Observing Figure 35, the total generator output termed apparent power has the components Active and Reactive power as indicated below:

$U^2_{RATED} = P^2 + Q^2$

OR

$MVA^2 = MW^2 + MVAR^2$

We can easily indicate the effect of heat on the generator output limits, by superimposing on Figure 35 to create Figure 36 below.

Notes

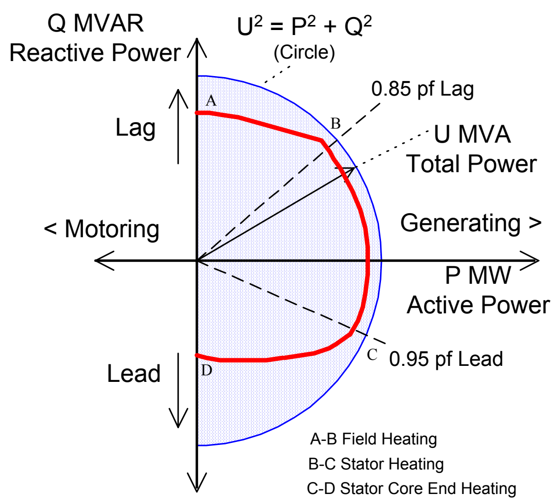

Figure 36
Q-P Diagram with Heating Limits

Stator winding heating is a copper loss, which we have shown is constant for as long as the voltage remains constant:

$P_{heat} = I^2 R = V^2/R$

Stator winding heat is the main limitation near unity power factor when the reactive current is low. This is indicated in the region B-C on the diagram.

- In the Lagging Power Factor region (A-B), the generator is over-excited. You might wish to refer back to the previous V-Curve in Figure 20 to see the effect of power factor on excitation current. There is high I^2R heating in the rotor field windings as well as high flux in the rotor and stator cores. Hence heating in the rotor conductors and rotor/stator cores is a limiting factor in this region.

- In the Leading Power Factor region (C-D), the generator is under-excited. You might wish to refer again back to the previous V-Curve in Figure 20. When the generator is under excited, there are some unusual magnetic flux patterns in the end turns of the stator windings as the flux starts to weaken and stretch. These unusual flux patterns cause heating in the metal end of the stator. Therefore stator end turn heating is a limitation in the leading power factor region.

- There is one more limiting factor to be considered in the extreme region of the leading power factor when generator is highly under excited. This means that the load angle is large and the rotor flux is stretching to its limit. Should the generator

Notes

undergo a substantial disturbance when the load angle is large, it could pull out of synchronism and pole slipping will occur. The extent of the stability limitation in the under excited region depends on a number of factors including the response of the exciter and the transmission line arrangements associated with the generator. This limitation has been superimposed on the Q-P diagram in Figure 37 below.

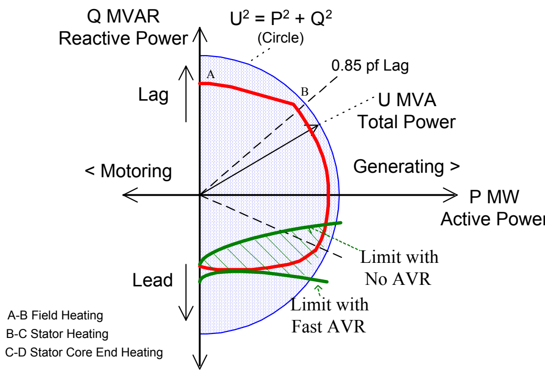

Figure 37
Q-P Diagram including Stability

The stability limits with and without a fast acting AVR have been shown in Figure 35. As you can recall from the previous section on Power Transfer, the facility for field forcing has to be available with leading power factor angle, as the rotor flux becomes more and more stretched to it's limit. The AVR counteracts any drop in voltage due to load and strengthens the field.

4.16.4 Generator Rotor and Stator Cooling

Not to over–complicate the issue of limitations on the generator output, there is one more thing that has to be included. That is the cooling level that is applied to the stator and rotor.

The stator winding is cooled by circulating water through the hollow copper conductors. The rotor is cooled by forcing hydrogen (H_2) through the sealed rotor/stator compartment (Figure 37). The hydrogen flows through special slots cut in the rotor core and through the gap between the rotor and stator. The hydrogen of course cools by expansion and thus the cooling effectiveness is proportional to the differential pressure drop. Each 7kPa of hydrogen pressure gives an additional 1% gain in output. The lines of H_2 pressure are included in Figure 36 to yield a complete although somewhat cluttered QP diagram.

Notes

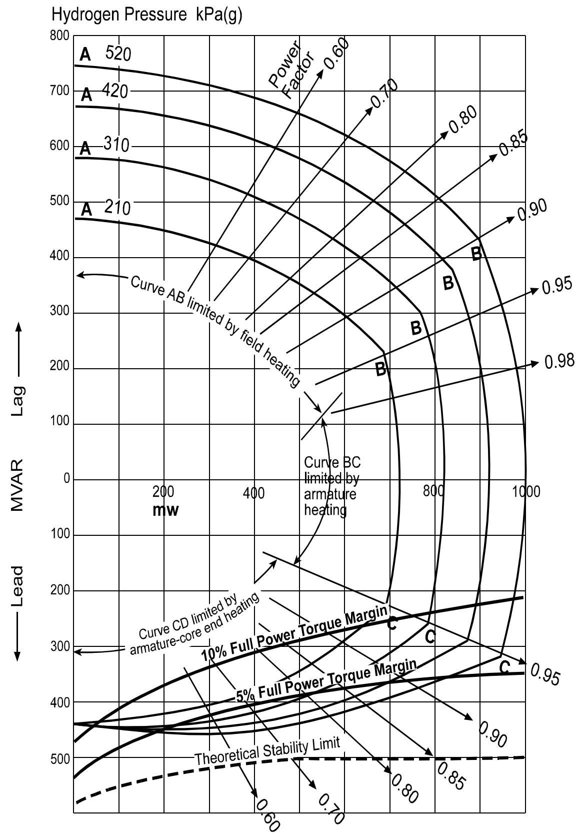

Figure 38
Q-P Diagram with Lines of H_2 Pressure

As we have stated, the stator is cooled directly by water flowing through the windings and also to some extent by the hydrogen flowing around the windings. Plastic hoses are used to connect the water lines to the stator windings. It is essential that water of low electrical conductivity be used to minimize the losses due to leakage current flow. If the conductivity limit is exceeded, electrical current will flow through the water inside the windings causing an increase in heating of the windings and decrease in output power.

Notes

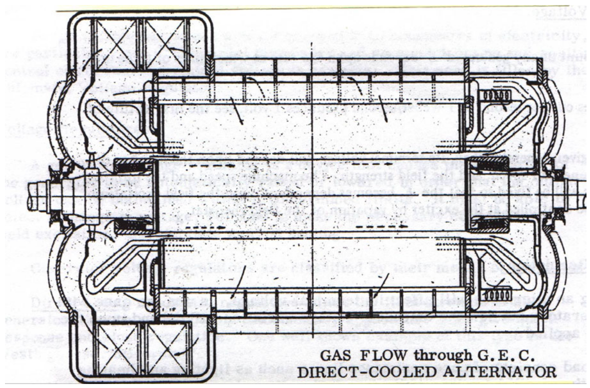

Figure 39

Cutaway Section of Generator

Hydrogen gas is used as the cooling medium for two main reasons:

- High thermal conductivity (six times that of air) and therefore will transmit heat rapidly.

- Low density (one-fourteenth that of air) and has minimal windage or braking effect to the spinning rotor.

An extra advantage of the hydrogen cooling is that it is enclosed in a dirt and moisture proof casing that reduces wear on the machine and hence reduces maintenance.

A disadvantage o the hydrogen is that it is explosive within the limits of 4% to 74% hydrogen to air ratio. That poses no problem during normal operation as long as the purity of the hydrogen is maintained at a nominal 95% or above. During maintenance, Carbon Dioxide (CO_2) is used as a buffer gas to purge the Hydrogen out of the casing and then air is used to purge the CO_2.. The process is performed in reverse to load the hydrogen. The CO_2 is injected first and purged by hydrogen.

Care must be taken to maintain the purity of the hydrogen for several reasons:

- Air will decrease the cooling capability and increase the friction (windage) as described previously. Aside from the temperature increase, remember also that a 74% hydrogen to air ratio is explosive.

- Moisture will also decrease the cooling capability and increase the windage losses. It has a more dangerous effect of decreasing the insulation capabilities between the electrical

Notes

windings and the core on both the rotor and stator. This could lead to winding faults and damage to the generator.

4.17 GENERATOR SHUTDOWN

In this module we have examined all the aspects of run-up and operation of a generator. We will now conclude by looking briefly on the actions required to safely shutdown a generator.

To take a turbine-generator off line in a system involving two or more generators, the driving torque of the prime mover (steam) must be reduced until the generator has zero current output. This is for two main reasons:

The rotor will over-speed when taken off line

Abrupt removal of generation will cause a surge of power from other connected generators to pick up the load. This will cause a bump to the electrical system as these generator governors react to fill the lost generation.

At this point the generator breaker can be opened to disconnect the generator from the system. The output voltage can then reduced to zero by removing the rotor field excitation and the prime mover (steam) can be reduced to zero. After the turbine has shutdown, the turbine-generator is placed on turning gear to revolve at a slow rate to prevent sagging or hogging of the shaft due to the heat still contained in the turbine blades, shaft, rotor and stator cores and conductors.

4.18 REVIEW QUESTIONS GENERATOR

Notes

1. Explain what happens in a generator if the AVR is in service with a normal set point and excitation is applied to the machine when the speed is low.
2. State four (4) electrical parameters that must be matched before a generator is connected to an electrical system. State the consequence of not having these parameters matched.
3. A synchroscope identifies the magnitude and direction of mismatch between 2 of the 4 electrical parameters required for synchronization. State the two parameters measured by the synchroscope and explain how these are displayed on the instrument.
4. Briefly describe what will happen to the output of a generator (MW and MVAR), the field current and the governor valve opening when it is connected to a dead bus with an inductive load connected. Assume that the AVR and governor of the generator are functioning correctly.
5. If possible when generators are connected to dead buses the loads are disconnected from the buses. The load is then added slowly to the bus over a time period. Explain why this is done.
6. Define the terms finite and infinite bus.
7. Briefly describe how the automatic voltage regulator controls the voltage output of a large generator.
8. Explain the function of the turbine governor when the machine is not connected to an electrical system and when it is synchronized to an infinite bus.
9. A large turbine generator set has an output of 500 MW and a power factor of .9 lagging. Describe what happens to the output, power, reactive power; terminal voltage and frequency if the governor valves are opened to allow about 5% more steam flow into the turbine. Assume the machine is connected to an infinite bus through an inductor (a transformer) and that the governor and AVR are both fully functional.
10. State the five factors that affect the steady state stability of a generator. What is the relationship between them?
11. Two major limits on generator operation are the power output and the voltage/frequency ratio. Explain why each is a limit and the consequence of exceeding the limits.

Notes

12. Define the term load rejection and briefly describe the changes in generator parameters of power, reactive power, power factor, speed, and terminal voltage when the unit undergoes a load rejection.
13. Heat is generated in the stator iron, the stator winding, the rotor winding, and hydrogen atmosphere in the generator. Explain how heat is generated in each of these places.
14. There are two heat removal systems associated with the generator. Name the two systems and state, which of the heat sources (from the previous question) they are designed to remove.
15. It is important the conductivity of the cooling system for the I^2R losses in the stator be kept low. Explain why this is so and the consequences of failing to do so.
16. The hydrogen in the hydrogen cooling system must be kept pure. The ingress of air and water must be prevented. Explain the negative consequences of air and moisture in the hydrogen cooling system.

Notes

5 ELECTRICAL PROTECTION

5.1 INTRODUCTION

On November 9th 1965, 80,000 square miles in Ontario and USA plus 30 million people went into a darkness that lasted more than half a day. That was the infamous power blackout that changed protection philosophy forever and resulted in most of the protections you see today. We won't get deeply into the reasons for the occurrence. Suffice to say that it started at the Sir Adam Beck Hydro plants because of improperly designed protection schemes that were in place throughout all of Canada and our neighbour to the south. The sequence of events started with a relay set too low for the output that the generating station. Due to many of the design items (or rather lack thereof) that we will discuss in this module it cascaded catastrophically. At that time there was little thought given to protection speed, selectivity or any of the other factors that you will soon, through this module, know and understand quite well.

In generating stations, all electrical circuits and machines are subject to faults. A fault is generally caused by the breakdown of insulation between a conductor and ground or between conductors due to a variety of reasons. The result is a flow of excess current through a relatively low resistance resulting in severe damage unless cleared quickly.

The majority of systems and devices in our stations are three phase which can experience faults of categories:

- phase to ground
- phase to phase
- three phase, with or without ground.

In this module, we will discuss the purpose and essential qualities of electrical protection schemes, the types of faults that can be expected and various means of protecting equipment against them.

5.2 PURPOSE OF ELECTRICAL PROTECTION

The function of protective relaying is to ensure the prompt removal from service of a faulty electrical system component, thereby protecting that part and the remainder of the electrical system from damage and electrical instability.

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Every item of electrical equipment must have some form of electrical protection, which will remove electrical power from the equipment in the event of it becoming faulty or overloaded.

This is necessary to ensure that:

- **Damage is minimized** on the faulty equipment and any damage is not allowed to spread to other equipment. For example, if a fault occurs in a motor, we want to isolate the motor before damage occurs to the bus supplying the motor.

- **Unaffected equipment remains in service.** Continuing on the previous example when a fault occurs in a motor, we only want the motor to trip (not the entire bus), while still providing power to the unaffected equipment on that same bus.

- **Equipment operating limits are maintained**. Again using the motor as an example, most motors are designed to run in an overload condition for at least a short duration without experiencing damage. However, we must remove the electrical power when the overload gets too great, preventing damage to the equipment.

- **Electrical system stability is maintained**. As discussed in the previous module on generators, an un-cleared or slow-clearing fault will make the electrical system unstable. Instability will cause the break-up of the electrical system until stability is obtained. Inevitably there is loss of generation capability and disruption to large amounts of electrical equipment.

5.3 ESSENTIAL QUALITIES OF ELECTRICAL PROTECTIONS

Having looked at the fundamental purpose of electrical protection, we should cover the four main building blocks that are used to meet these requirements:

5.3.1 Speed

When electrical faults or short circuits occur, the damage produced is largely dependent upon the time the fault persists. Therefore, it is desirable that electrical faults be interrupted as quickly as possible. Since 1965, great strides have been made in this area. High-speed fault detecting relays can now operate in as little time as 10 milliseconds and output relaying in 2 milliseconds. The use of protection zones, that will be discussed later, minimized the requirement for time-delayed relaying.

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5.3.2 Reliability

The protective system must function whenever it is called upon to operate, since the consequences of non-operation can be very severe. This is accomplished by duplicate A and B protections and duplicate power supplies.

5.3.3 Security

Protections must isolate only the faulted equipment, with no over-tripping of unaffected equipment. This is accomplished by the use of over-lapping protection zones.

5.3.4 Sensitivity

The protection must be able to distinguish between healthy and fault conditions, i.e., to detect, operate and initiate tripping before a fault reaches a dangerous condition. On the other hand, the protection must not be too sensitive and operate unnecessarily. Some loads take large inrush starting currents, which must be accommodated to prevent unnecessary tripping while still tripping for fault conditions. The ability of relaying to fulfil the sensitivity requirement is improved through the use of protection zones.

5.4 PROTECTION ZONES

The basic idea behind the use of protection zones is that every component in an electrical system (i.e., bus, transformer, motor, and generator) has distinct characteristics. Protections can be made to perform faster (speed), with increased security and increased sensitivity if it deals with only that one element.

As we start to look at the electrical system in view of protection zones, we have to get a clear picture of where the boundaries of these zones will normally be in any electrical system.

For simple systems such as a motor in the diagram below, the fuse or thermal circuit breaker would be the boundary of the zone. The ratings of the fuse would be designed to protect that motor only.

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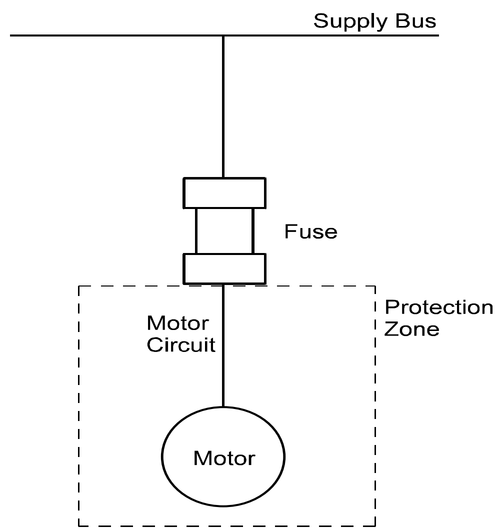

Figure 1
Simple Protection Zone

The fuse is a very rudimentary form of protection. For most protection systems, the current and potential has to be brought down to lower level though the use of Current Transformers (CTs) and Potential Transformers (PTS). An illustration of a protection ac sensing input is provided in Figure 2 below.

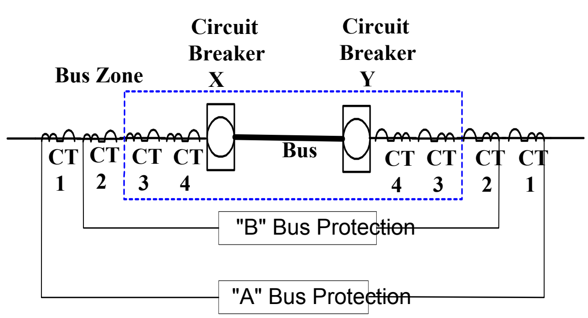

Figure 2
Protection Zone for a Bus

Although we will be describing bus protections in more detail in the next section, it is important to note that CT1 and CT2 of circuit breakers X and Y supply the currents for the bus protection zone. The equipment that is inside the protected zone is:

- The Bus
- Circuit Breakers X and Y

The A and B bus protections will trip open circuit breakers X and Y for any fault that is detected on the equipment within the outlined protected zone. Also the A and B bus protections can be designed to detect and operate specifically for bus-faults only and thus be very accurate and fast. We have now accomplished the objectives of Protection Speed, Security and Sensitivity. Protection Reliability will be covered later in duplicate protections as indicated by the multiple CTs.

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We can get an overall picture of how the zones inter-connect from Figure 3. The diagram illustrates the separation of an electrical system into the standard protective zones.

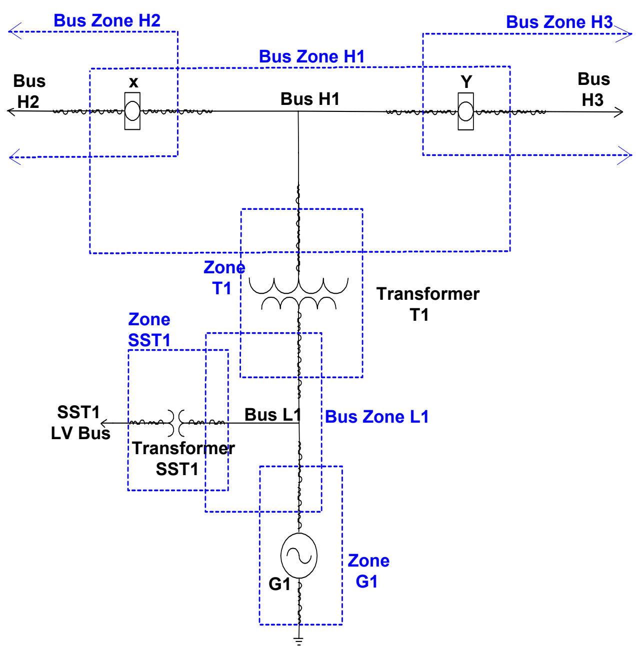

Figure 3
Overlapping Zones

There are a number of important items to note from the above diagram.

- Each individual piece of equipment has a separate specialized protection zone. As we have indicated this increases speed, security and sensitivity.
- Zones overlap so there is no equipment un-protected. This increases the security.
- The boundary of the zones is the CTs. Current transformers provide the protection with the magnitude and phase angle of current at that location on the electrical system. This allows the protection to be very selective on how it operates (as will be

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seen in following sections of specific protections). By being more selective in its operation, the speed and sensitivity of the protection can be increased while maintaining security against over-tripping.

- The protection zones can be tailored to have specialized outputs, for example generator loss of field, transformer ground fault, etc. This increases the speed, sensitivity

- The CTs are duplicated and supply duplicate A and B protections. This increases the reliability a will be discussed later.

5.5 BREAKER FAILURE PROTECTION

The separation of equipment into zones will only work successfully if the outputs of the protections can be guaranteed to do their job. This makes logical sense. For the bus protection in previous Figure 2 for example, the breakers X and Y must trip on a fault, otherwise the adjacent zone providing power to the fault must be tripped. Similarly, for breaker X in Figure 3, the adjacent zone H2 would have to be tripped if breaker X did not open. However, to maintain the speed and security in protection zones the use of timed backup protections is minimized. The addition of a timed backup decreases the speed and also the larger backup zone reduces security. The solution is to add a separate protection on the breaker itself, to guarantee that it will either open correctly or removed adjacent elements from service.

Breaker failure protection is a high speed protection scheme that will trip surrounding breakers in the event that a circuit breaker fails to clear a fault. If, for example in Figure 3, breaker X fails to clear a fault, all of the equipment on bus H2 as well as bus H1 would be given a trip signal via the breaker failure protection scheme.

A breaker will be considered to have failed if, after the trip signal has been generated, the breaker has:

- not started opening within a preset time frame (determined by switches internal to the breaker),

- the breaker has not fully opened within a preset time frame (determined by switches internal to the breaker), or

- if the current has not been broken by the breaker within a preset time (determined by current measurement devices).

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Breaker failure protections are used on breakers at any voltage level, but are predominant on 13.8kV systems and above. The more impact a failed breaker will have on electrical system stability, the more necessary to use this high speed breaker failure protection. Lower voltage levels 13.8kV and below may use timed backup protections if the fault clearing time is not crucial.

5.5.1 Duplicate A and B Protections

In the previous sections we discussed the use of discrete high-speed protection zones. Invariably each one of these protection zones utilize two high-speed duplicate protections. They are often called A and B but could be named anything (i.e., C&D, R&S, Even & Odd, etc.). The alternative to using duplicate protections would be the use of a main high-speed protection and a timed backup. However, because of slower operating time, the alternative is generally only used on equipment of less electrical system impact.

Duplicate protections are functionally identical, but not physically the same. They will have the following six common features:

- Functionally identical. The duplicate protections both fulfil the same purpose and either one could be removed from service without affecting the protection of the equipment.

- Not physically identical. They use different types of protection design or different relay types. If one of the protections were to fail due to a system problem (i.e., harmonics in the current waveform), there would be less chance of the other protection failing also. Often one protection will utilize electro-mechanical relaying and the other solid state relaying.

- Separate Battery Supplies – To maintain redundancy, separate battery supplies must be provided for each protection.

- Separate routing of wiring – Equipment and wiring are physically separated to reduce possibilities of common faults.

- Separate Inputs – The protections utilize signals from completely separate current and voltage transformers. Other equipment data that is input to the protections (i.e., pallet positions, temperature sensors, mechanical interlocks, etc.) are also duplicated.

- Separate Outputs – The protections have separate output signals to the circuit breakers or other electrical devices.

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Quite often the devices will have duplicate trip coils installed to facilitate complete separation.

Figure 4 below illustrates the philosophy of duplicate (A and B) protections.

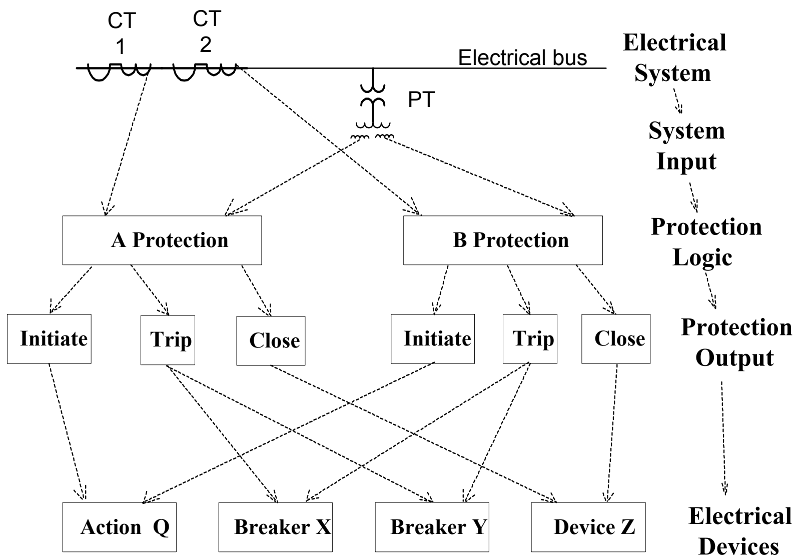

Figure 4
A and B Protection

5.6 BUS PROTECTIONS

When we examine electrical protection schemes, the best place to start is with electrical bus protections, as they are the easiest to protect. They utilize the fundamental concept of the over-current relay
(Figure 5). An over-current relay is an electromagnetic device in which current in the coil surrounding a metal core produces magnetic flux in the core. When there is a sufficient current flow, the flux will attract the armature (metal flap), which will move to close the attached contacts.

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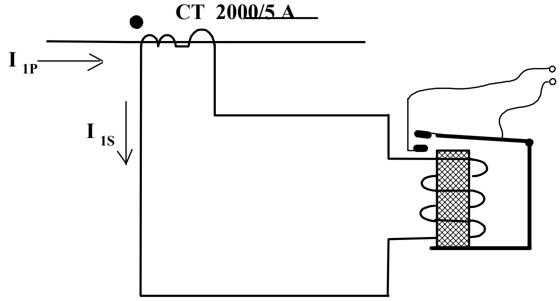

Figure 5
Over-Current Relay

Two other items are indicated in the diagram. One is the direction of CTs. If current I_{1P} flows in the primary towards the primary spot mark, simultaneously output current I_{1S} will flow out of the CT at the secondary spot mark. This is an important concept to remember. Current Transformers (CTs) transform the current in magnitude but retain the same waveform and phase relationship. One can picture the current going in as I_{1P} and out as I_{1S} instantly reduced in size by a factor of 2000/5.

The second point to note is the CT ratio (2000/5 A). This is standard notation that 2000 Amps in the primary will produce 5 Amps on the secondary.

5.6.1 Bus Differential Protection

The differential protection utilizes the over-current relay just discussed. For ease of description we will indicate only one phase of a three-phase system, as the other phases are identical.

The differential relay is fed by CTs on the outside of the protected bus. Recalling the spot convention of CTs, one can see in Figure 6 below, that if current I_{1P} flows into the bus, then an equivalent current I_{1S} will flow in the secondary winding of CT1. Similarly current I_{2P} will flow out of the bus with a corresponding I_{2S} flowing in the secondary (note direction). If the bus is healthy current in equals current out and there will be a circulating current in the secondary circuit as shown. No current will flow in the over current relay. Note that the current flow in the over-current relay is equal to the difference (where differential relay gets it's name) in the input currents. In this case they are equal and the differential current is zero.

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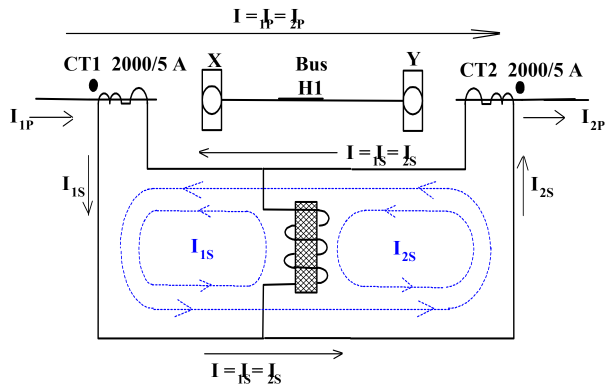

Figure 6
Differential Protection

If the bus in Figure 6 happens to fault (either phase to phase or phase to ground fault), the current entering and leaving the bus will not be the same. Hence the difference seen by the relay (I_{1S} - I_{2S}) will not be zero. If the fault is of high enough magnitude to pickup the over-current relay the differential protection will operate to trip breakers X and Y, plus block any reclosure of these breakers, initiate breaker failure protection and any other actions required by that specific protection zone.

Figure 7 shows the current directions for the most severe fault, an internal bus fault fed from both ends of the bus. If you consider the figure carefully you will notice that any number of breakers or transformers could be added to the bus. Care would have to be taken to ensure the CT ratios and spot marks were correct and that the secondary circuits were added in parallel. Figure 8 gives an example of what it would look like if a transformer were fed off the bus.

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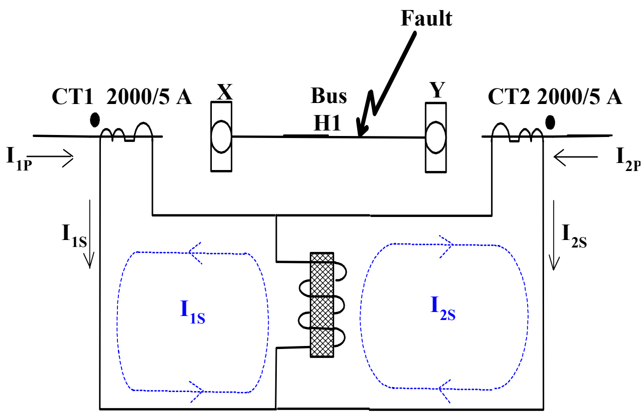

Figure 7
Differential Operation

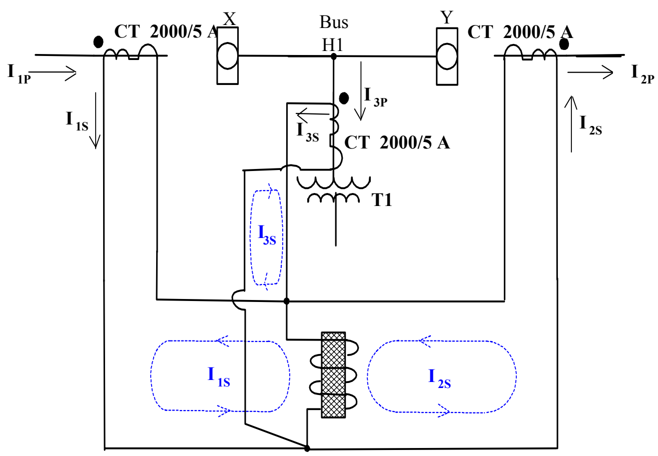

Figure 8
Ended Differential Protection

5.6.2 Bus Over-Current Backup

Normally a bus protection would be made up of two high-speed differential relays that we have just discussed. This would form a duplicated or A and B bus protection. Refer to previous Figure 2 for configuration.

For low-voltage buses (13.8kV and below) there often is no breaker failure protection provided on the breakers (X and Y in the figure above). In such a case duplicate (A and B) protections cannot be used. Zone protection with duplicate protections and no breaker failure protection will only work if the breakers never fail. Thus one of the two protections has to be made into a backup, to cover the case where the breaker might not open. This creates a larger overlapping zone as shown by Figure 9.

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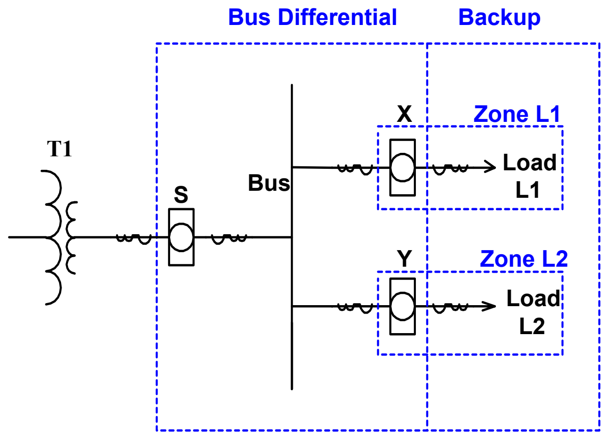

Figure 9
Bus Zones with Backup

In Figure 9, you can see the standard bus differential zone and the extra bus backup zone that includes the loads L1 and L2 supplied off the bus.

Suppose an electrical fault (phase to phase or phase to ground) or overload occurs on feeder L1. The protection for L1 should operate to trip breaker X. If breaker X does not trip within a certain time the bus backup protection will operate to open supply breaker S and remove all supply from the bus. A close-up of the bus backup protection is shown in Figure 10 below.

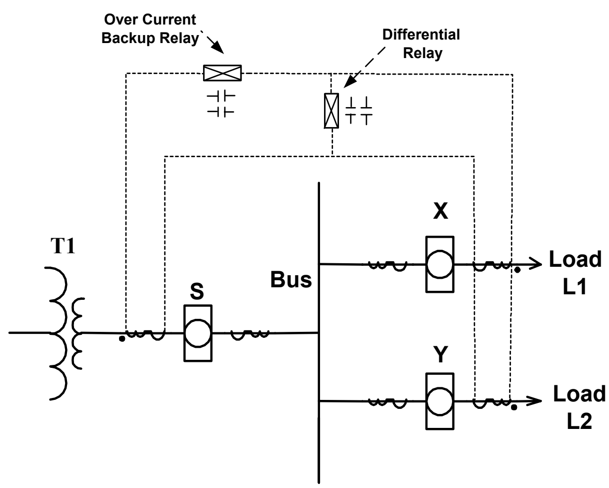

Figure 10
Over-Current Backup

The over-current backup relay will see the total current supplied to the bus, whereas the differential relay only sees the difference between supply current and load current as discussed previously. The relay settings for over-current backup protections are somewhat difficult and

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usually employ an instantaneous and timed component. After all, the objective is that breakers X and Y should clear the fault before the backup protection operates to trip the main supply breaker S.

- The instantaneous over-current setting has to be above the total expected current inrush or loading expected on the bus, but below the minimum bus fault level. For coordination, the setting also has to be also higher than any individual load setting. If this cannot be obtained the instantaneous element is blocked.

- The timed over-current setting has to coordinate with all of the loads fed from the bus to allow the separate protections (Zone L1, L2 in Figure 9) to operate first.

5.6.3 Bus Ground Faults

Bus phase to ground faults are far more common than phase to phase or three phase faults. They are generally due to breakdown of insulation by some foreign material or moisture. Due to the severe affect on the connected loads as well as structural damage, these have to be instantaneously cleared from the electrical system. The differential relay previously discussed is utilized to protect the bus against this type of fault.

5.6.4 Bus Under-Voltage Protection

Bus under-voltage protection (sometimes called no-volt trip) is supplied on many buses for two reasons:

- Many loads, especially motors, are susceptible to low voltage. As the voltage supply to a motor decreases, the motor will attempt to deliver the same amount of torque for a given load and will draw higher currents to do this. This will result in excessive heating of the motor windings, resulting in insulation damage and reduced machine life

- Another benefit of this type of protection is to prevent all loads from automatically restarting at the same time, when voltage to a system is restored. Loads are usually introduced slowly to allow the generator to stabilize its power production before more loads are placed on the generator (there are thermal limits on rates of loading/unloading of turbine-generators anyway, which help in this situation). If the loads are all automatically reconnected at once to a re-energized bus, the voltage on that bus will likely drop and the loads will likely trip again on under-voltage. Another danger of automatic re-loading if the

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voltage is quickly restored is that the supply and load voltages will be out of phase, resulting in current surges and mechanical stresses on the machine.

Under-voltage protection can be achieved by an electromagnetic relay (an example is shown in Figure 11). This relay holds the armature to the coil as long as the voltage remains above the desired amount, keeping the normally open contacts of the relay closed.

If voltage drops, the coil can no longer hold the armature and the relay contacts will open. In this type of protection, there will also be a time delay built in (usually by a timer) to prevent operation during voltage transients (i.e., if the voltage is quickly restored, the trip will not occur). The voltage drop and time delay are chosen such that re-energizing the load will not result in excessive demands on the system.

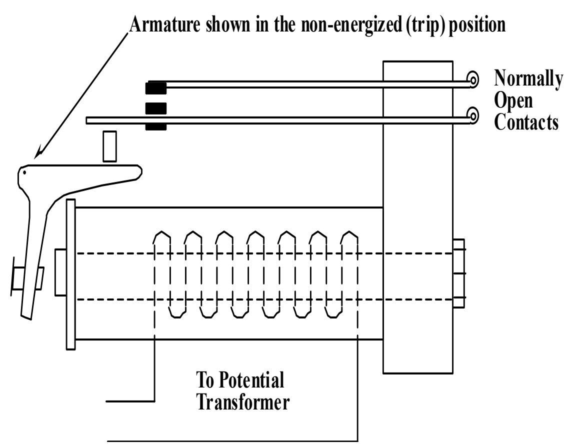

Figure 11
Under-Voltage Relay Protection

5.7 TRANSFORMER PROTECTION

Transformers, of course, are somewhat more difficult to provide electrical protection than a section of solid electrical bus.

- Transformers have high magnetizing inrush currents when energized.
- Transformers can vary the ratio of input to output current via off-load and under-load tap-changers.
- The input and output current is often not the same phase relationship (sometimes has **Y–Δ** transformation)

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- Transformers will be affected by over-fluxing (high volts/hertz).

- Transformers will be affected by over-temperature.

To examine transformer protections, we will build on the similarity to bus protections just discussed. Transformers utilize duplicate protections and the protection zone (similar to buses) can been seen in Figure 12 below.

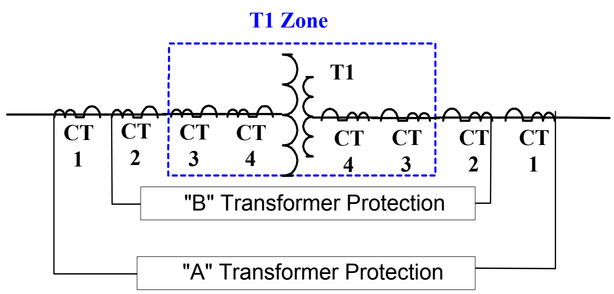

Figure 12
Transformer Protection Zone

5.7.1 Transformer Instantaneous Over-Current Protection

Instantaneous over-current is usually the result of fault conditions in which current flow will greatly exceed normal. These faults (phase to phase, phase to ground) can be in the form of inter-winding faults or winding to core/case faults. Catastrophic damage associated with large fault currents can occur without this type of protection.

These types of faults can be rapidly detected by differential protection schemes. In these situations, fast acting electromagnetic relays will be used to trip the affected transformer.

5.7.2 Transformer Differential Protection

Similar to bus protections, transformers are protected by differential relays. Inter-winding faults (short circuits) and ground faults within power transformers can be detected by this protection scheme. Failure to detect these faults and quickly isolate the transformer may cause serious damage to the device.

Remember that a differential relay is basically an instantaneous over current relay that operates on the difference of current flowing into and out of the protected zone. For transformers the differential protection (Figure 13) is basically the same as that for a bus but there are certain differences that we will look more closely at. These differences are a direct result of three characteristics or a transformer.

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- A transformer has a turns ratio so the current in is not really equal to the current out. The current transformers are not likely exactly matched to the transformer turns ratio so there will always be an unbalance current in the operating coil of a transformer differential relay.

- Transformers require magnetising current. There will be a small current flow in the transformer primary even if the secondary is open circuited.

- A transformer has an inrush current. There is a time period after a transformer is energized until the magnetic field in the core in alternating symmetrically. The size and the length of this inrush depends on the residual field in the core and the point in the ac cycle the transformer is re-energized. In large trans formers in might be ten or twenty times the full-load current initially and it might take several minutes to reduce to negligible values.

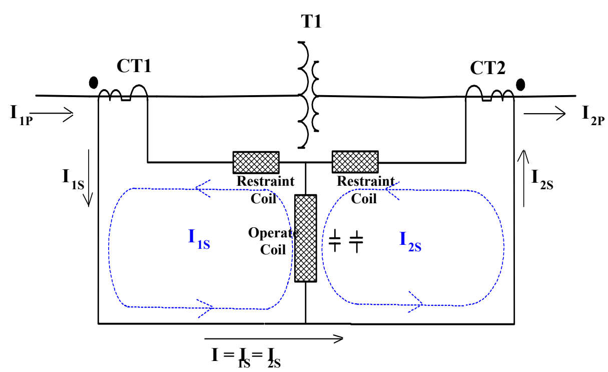

Figure 13
Transformer Differential Protection

Transformer differential relays have restraint coils as indicated in Figure 13. The value of the operate current has to be a certain set percentage higher than the current flowing in the restraint coils. For this reason transformer differential relays are said to percentage-differential relays. Referring again to Figure 13, you will notice that when the transformer is first energized, there will not be any current flowing in CT2. The CT1 secondary current I_{1S} flows through both the restraint and operate coils and prevents operation unless the current is very high. The restraint coils also prevent relay operation due to tap-changes, where the ratio of transformer input to output current can continuously vary.

One other item included in transformer differential relays but not shown in the diagram, is second harmonic restraint.

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When transformers are first energized there is over-fluxing (saturation) of the core and the large inrush energizing current has a distorted waveform. This waveform is described as having high second harmonic content. The transformer differential relays make use of this known fact and add in extra restraint when it detects this second harmonic. This extra feature prevents the transformer from tripping due to magnetizing current when being energized, but does not add any time delay.

Because the differential relay will not operate with load current or faults outside the protected zones (through faults), it can be set to operate at a low value of current thereby giving rapid operation when a fault occurs. There is no need to time delay the operation of the relay and therefore a fast acting type of relay can be used.

5.7.3 Transformer Gas Relay

The transformer gas relay is a protective device installed on the top of oil-filled transformers. It performs two functions. It detects the slow accumulation of gases, providing an alarm after a given amount of gas has been collected. Also, it responds to a sudden pressure change that accompanies a high rate of gas production (from a major internal fault), promptly initiating disconnection of the transformer.

An incipient fault or developing fault, usually causes slow formation of gas (the process of gas formation is discussed later in this section). Examples of incipient faults are:

- current flow through defective supporting and insulating structures;
- defective joints at winding terminals causing heating;
- minor tap changer troubles; and
- core faults.

A major fault is one that results in a fast formation of a large volume of gases. Examples of such faults are:

- shorts between turns and windings; and
- open circuits, which result in severe arcing.

Failure to disconnect the transformer under fault conditions can result in severe equipment damage from high gas and oil pressures and the effect of the electrical fault.

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5.7.4 Generation of Gas Due to Faults

Internal transformer electrical faults result in the production of ionized gases. A significant volume of gas is frequently generated in the early stages of a fault by rapid oil breakdown. The generated gases rise through the oil to the top of the equipment and collect in the gas relay. Once a sufficient volume of gas has accumulated, an alarm is generated by contacts within the gas relay.

In the event of a gas alarm, it is necessary to sample and analyze the gas being generated. This analysis, together with knowledge of the rate at which gas is accumulating, will determine the proper course of action. If a fault is thought to be developing, the device must be removed from service. Ignoring this early warning sign can lead to severe equipment damage as the fault progresses.

Operation of a Transformer Gas Relay

A typical transformer gas relay consists of two chambers, each performing a distinctive function. A simplified cross-section of a gas relay is shown in Figure 14.

The relay assembly consists of a gas accumulation chamber mounted directly over a pressure chamber. The accumulation chamber collects slowly produced gases. A float located in this partially oil-filled chamber moves as the gas volume increases. It operates an alarm switch when the amount of gas collected reaches a specified level. An indicator coupled to the float also provides a means to monitor the rate at which gas is being generated.

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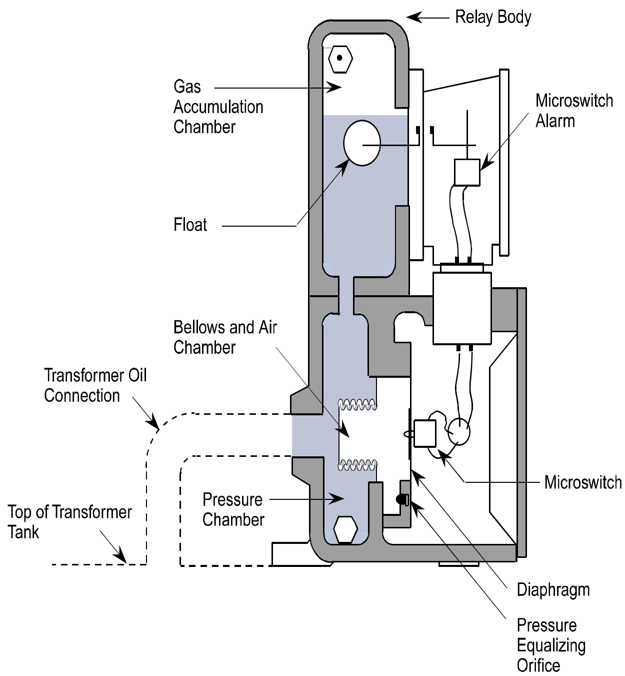

Figure 14
Typical Transformer Gas Relay

The second chamber, a pressure chamber, connects directly to the transformer oil circuit. It connects vertically to the accumulation chamber, providing a path for the rising gas. An air-filled bellows within the pressure chamber acts as the pressure change detector. A sudden pressure surge in the oil compresses the bellows and forces the air within to move a diaphragm. The moving diaphragm actuates a switch that initiates tripping of the transformer.

Sudden pressures, such as oil circulating pump surges, are normal operating events and the relay must be set to ride through them. In practice, it is necessary to make sure the relay is set to operate at about 7 KPa (1 psi) above the maximum oil circulating pump surge pressure.

Dangerously high pressure increases from major faults are relieved by an explosion vent on the top of the transformer tank. This is basically a diaphragm sealed pipe with its open end directed away from the transformer. A significant increase in pressure bursts the diaphragm and discharges gases and hot oil with a possibility of resulting fire.

5.7.5 Transformer Thermal Overload

Heat is generated in a power transformer by current flow in the primary and the secondary windings as well as internal connections due to I^2R losses. At low loads, the quantity of heat produced will be small. But, as the load increases, the amount of heat becomes

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significant. At full load, the windings will be operating at or near their design temperature. The nameplate on a transformer will provide information on the maximum allowable in-service temperature rise for its windings and connections and will indicate what method of cooling is employed to remove the heat generated under load. A temperature of about 105°C is considered to be the normal maximum working value for large power transformers, based on an assumed maximum ambient temperature of 40°C.

The winding temperature is sensed and indicated by a winding temperature gauge/alarm assembly. Figure 15 shows a typical arrangement. The purpose of this gauge is to provide a thermal image of the hottest point within the transformer. The sensing bulb of the assembly is placed in a well located near the top of the transformer tank. The well is immersed in the hot transformer oil. A heating coil, supplied from a load sensing current transformer, is installed around the sensing bulb to provide a local temperature rise above the general oil temperature. The affect of the heating coil, coupled with the heat of the oil on the bulb, allows the gauge to simulate the winding temperature hot spots.

Operation of the transformer above its rated voltage by even 10% can cause a significant temperature rise, initiating an over-temperature alarm. Over voltage operation may be a result of tap changer or voltage regulation problems. Such over-temperature operation can lead to physical insulation damage reducing the useful life of the insulation and thus the life of the unit.

A temperature rise of 8 -- 10°C beyond the normal maximum working value, if sustained, will halve the life of the unit.

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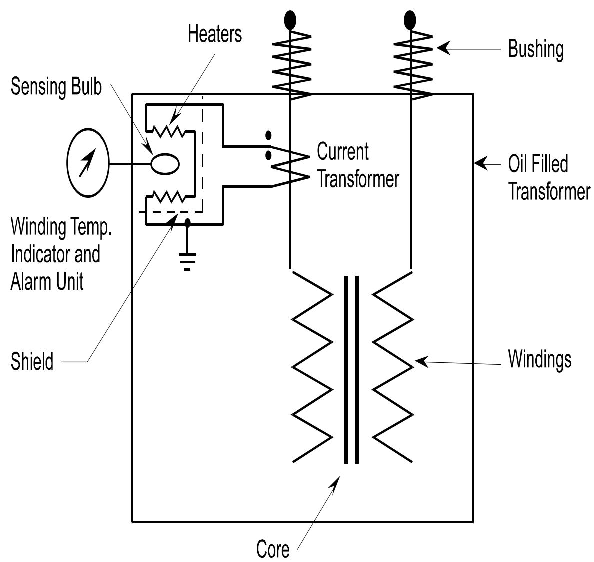

Figure 15
Transformer Winding Temperature Sensor

5.7.6 Transformer Ground Fault Protection

The majority of the power transformers are connected as Wye–Wye (Y-Y) or Wye–Delta (Y-Δ). If the transformer has a grounded Wye connection as per Figure 16, it becomes a source for ground current (I_N) to the electrical system. Ground currents can arise from electrical phase to ground faults, high resistances or open phase connections anywhere on the system. Under normal circumstances the fault or problem causing the ground current is cleared in short order by the protections on the apparatus itself (i.e., bus, motor, feeder, etc.). If the problem remains, it will cause over-current and unbalanced loading in the transformer feeding this current. This would create extra stress and heating of the core and windings. The transformer differential protection will not detect the ground current coming up the neutral and out the bus. In Figure 16 you can observe that the current would go intoCT3 and out CT2 and thus be outside the differential zone.

To solve this problem, Wye grounded transformers have an extra external CT connected between the Star Point and ground. Any current in this CT will pickup up the ground backup timed over-current relay, which will trip the circuit breakers supplying the transformers.

Notes

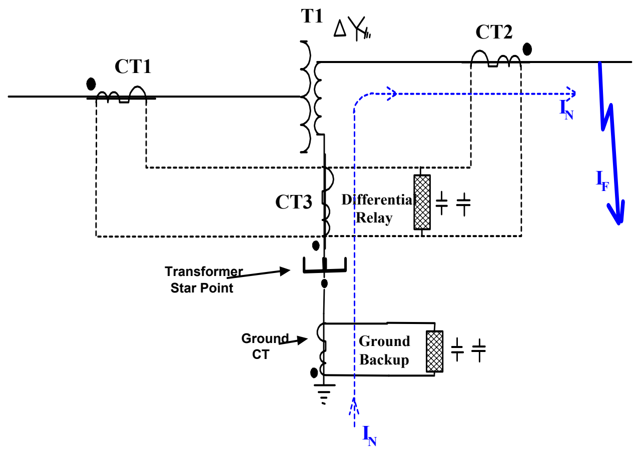

Figure 16
Ground Fault Protection for a Star Winding

5.8 MOTOR PROTECTION

Motor protections vary widely depending on the size of the motor and voltage level involved, thus only the more common ones are discussed in this section.

5.8.1 Motor Instantaneous Over-current Protection

Instantaneous over-current is usually the result of fault conditions (phase to phase, phase to ground), in which current flow will greatly exceed normal values. Damage due to winding overheating and burning damage associated with large fault currents can occur without this type of protection.

These types of faults can be rapidly detected by a differential protection scheme using Core Balance CTs as will be discussed later and cleared before major damage results. In these situations, fast acting electromagnetic relays will be used to trip the affected motor.

5.8.2 Motor Timed Over-Current Protection

Continuous operation of an electric motor at currents marginally above its rated value can result in thermal damage to the motor. The insulation can be degraded, resulting in reduced motor life through eventual internal motor faults. Typically, an electric motor has a service factor rating listed on its nameplate. This number represents the continuous allowable load limit that can be maintained without sustaining damage to the motor. For example, a typical electric motor is designed to withstand a continuous overload of about 15% without sustaining damage and has a service factor = 115%. Continuous operation at or above this value will result in thermal damage. To protect against motor damage, we must ensure that this condition is not

Notes

reached, hence we must trip the motor before the overload limit (service factor) is reached.

The relay most commonly used for this purpose is the induction disc relay. In this relay (Figure 17), the current in two coils produces opposing magnetic fluxes, which create a torque on a disc. As the motor current increases, so does the torque on the disc.

When the torque overcomes the spring torque, the disc begins to rotate. When the moving contact meets the stationary contact on the disc, the trip will operate.

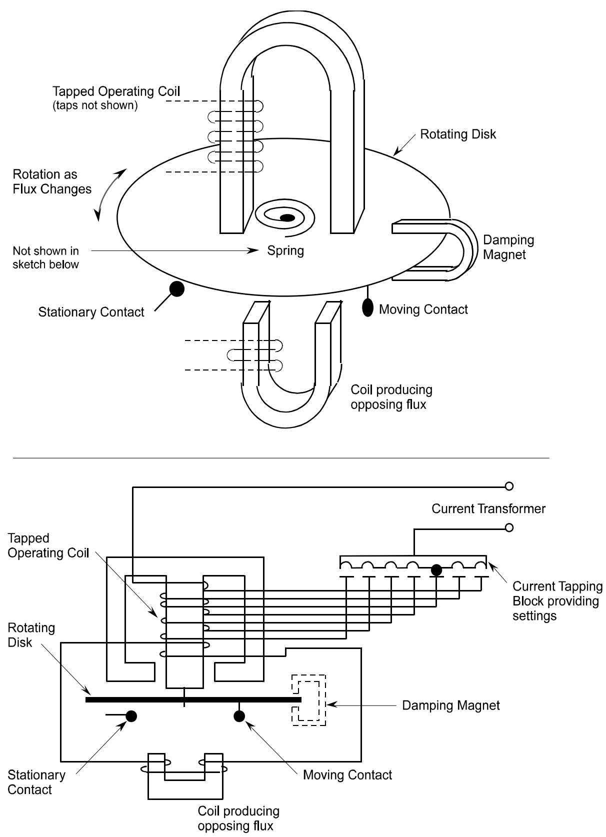

Figure 17
Induction Disc Relay

Tap settings and time characteristic adjustments can be made to alter the time delay of the relay. The major benefit of the induction disk timed over current relay is that the speed of rotation is proportional to the motor current. Hence major over-current conditions will trip the supply breaker almost instantaneously, while currents just above rated load will cause operation after several seconds (or minutes).

Notes

5.8.3 Thermal OverLoad

Another common type of relay used for timed overload protection is a thermal overload relay. In this type of relay, the motor current or a fraction of the current through a current transformer is connected to an in-line heater. Figure 18 shows a simplified thermal overload relay.

The heater (heated by I^2R action) is used to heat a bimetallic strip, which causes the displacement of a relay contact. A bimetallic strip consists of two different materials bonded together, each having different thermal expansion properties. As the materials are heated, one side will lengthen more than the other, causing bending.

Normal operating currents or short duration overload conditions, will not cause the bimetallic element to bend enough to change the relay contact positions.

Excessive currents will cause increased heating of the bimetallic strip, which will cause relay contacts to open and/or close, tripping the motor.

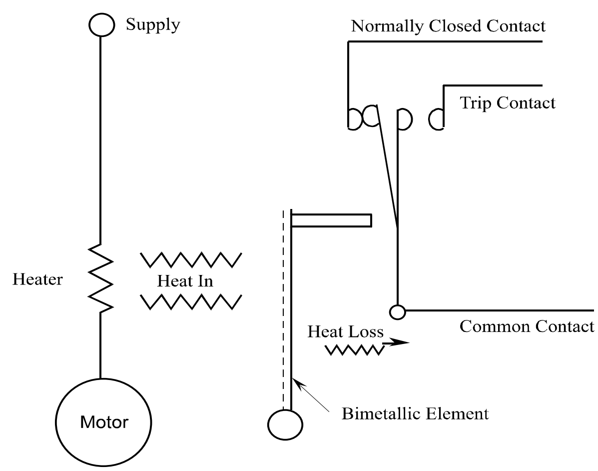

Figure 18
Thermal Overload Relay

The thermal overload relay has an inherent reaction time, since the heater and bimetallic element take time to heat. Care must be taken to match the current heating characteristics of the motor or else the motor could be damaged during the locked rotor starting conditions.

This type of relay can be used for direct protection against excessive motor current caused by electrical faults and motor overloads. Also, it is often used in combination with the timed over-current protection. Thermal overload relays using in-line heaters and bimetallic strips, provide an alarm in the case of continuous overload. This provides an opportunity for the operator to correct the problem before it reaches trip level magnitude.

Notes

As we have stated, thermal over-load trips can occur during repetitive starts on a motor or during motor over-loading. Thermal overload trips will seal-in to prevent the motor contactor from closing. This lock-out will require manual reset before the motor can be re-started. The operator or attendant will have to physically confirm that the motor has had sufficient time to cool down and that the cause for the overload has been removed. If the operator is confident that there is not a permanent fault on the motor the relay can be reset.

Note however, that if an instantaneous over-current trip has occurred, no attempt at closing the motor contactor should be made. An instantaneous trip will only occur if there is a fault in the motor or supply cable and this must be corrected before any attempt to reset the relay.

5.8.4 Motor Ground Fault Protection

In the detection of ground faults, as with the detection of instantaneous over-currents, it is extremely important that the fault be detected and cleared quickly to prevent equipment damage. Insulation damaged by heat (from extended overload operation), brittleness of insulation (due to aging), wet insulation or mechanically damaged insulation can cause ground faults.

Ground fault protection schemes use differential protection to detect and clear the faulted equipment. For motors, the common method is to use a Core-Balance CT as illustrated in Figure 19. The output of the core-balance CT will be the difference or imbalance of current between the three phases. If no ground fault is present, no current imbalance is present; hence no current will flow in the protection circuit.

If a ground fault develops, a current imbalance will be present and a current will flow in the protection circuit, causing it to operate to trip the supply breaker. Figure 20 shows a similar protection scheme, with each of the windings of the motor protected individually (this scheme is not normally installed in small motors, but may appear in the protection of very large motors).

Notes

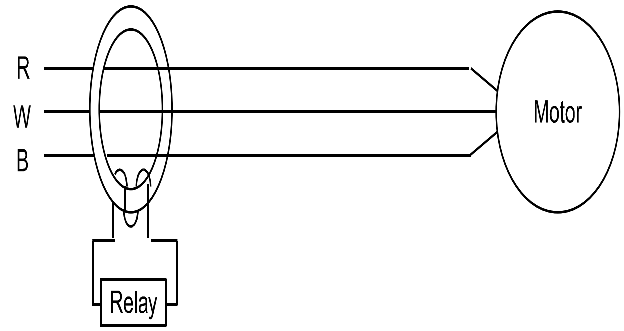

Figure 19
Three Phase Ground Fault Protection

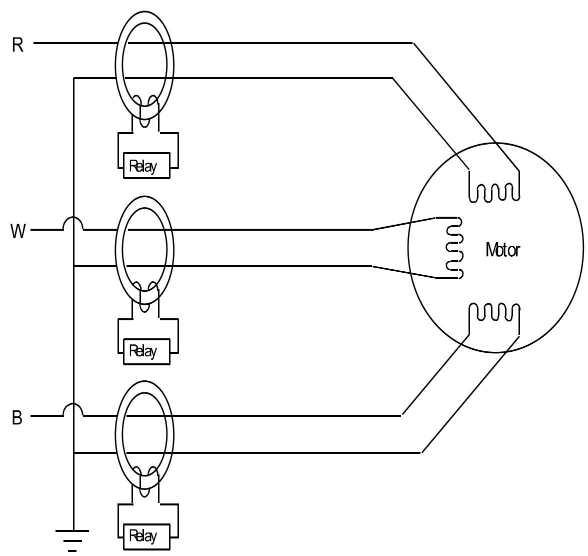

Figure 20
Single Phase Ground Fault Protection

5.8.5 Motor Stall Protection

Stalling or locking the rotor, is a situation in which the circuits of a motor are energized but the rotor is not turning. Motors are particularly susceptible to overheating during starts, due to high currents combined with low cooling air flows (due to the low speed of the motor, cooling fans are delivering only small amounts of air). This is also why some larger motors have a limit on the number of attempted motor starts before a cooling off period is required. However, stall conditions can occur during normal operation. For example, mechanical faults such as a seized bearing, heavy loading or some type of foreign object caught in a pump could be possible causes of motor stalling. The loss of a single phase while the motor is not rotating or under high load, is another situation in which a motor may stall.

Notes

The typical starting time of a motor is less than ten seconds. As long as this start time is not exceeded, no damage to a motor will occur due to overheating from the high currents. During operation, a motor could typically stall for twenty seconds or more without resulting in excessive insulation deterioration.

We use a stalling relay to protect motors during starts, since a standard thermal relay has too much time delay. A stalling relay will allow the motor to draw normal starting currents (which are several times normal load current) for a short time, but will trip the motor for excessive time at high currents. A stalling relay uses the operating principle of a thermal overload relay, but operates faster than a standard thermal relay.

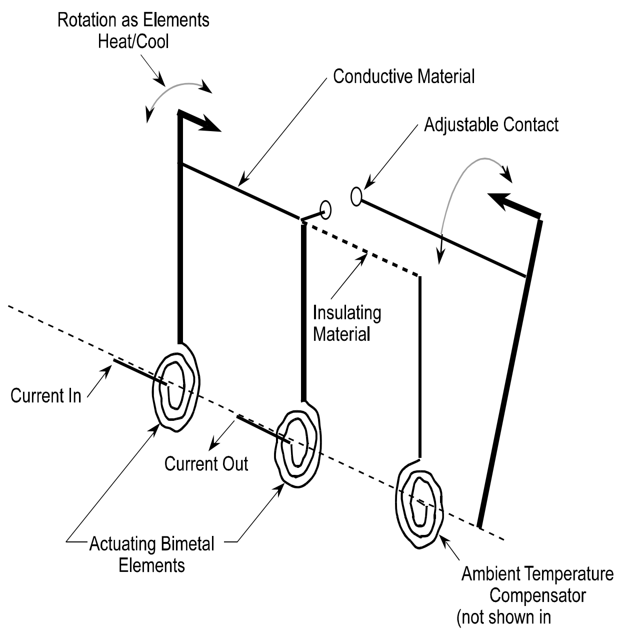

Figure 21
Stalling Relay

A schematic representation of a stalling relay has be been provided in Figure 21 for reference. By passing a portion of the motor current directly through the bimetallic elements in this relay, the heating is immediate, just as would be experienced within the windings of the motor.

This type of relay is usually operational only when the motor current is above 3 times the normal operating current and is switched out when the current is below 2 times the normal operating current. This switching in/out is achieved by the use of an additional relay contact. When the motor is operating normally, the current in this protection

Notes

scheme passes through the resistor and bypasses the bimetallic elements.

5.8.6 Motor Over-Fluxing Protection

As you can recall from the module on motor theory, the current drawn by a motor is roughly proportional to the core flux required to produce rotation. Moreover, the flux in the core is roughly proportional to the square of the slip speed.

$$I \; \alpha \; f \; \alpha \; s^2$$

Obviously over-fluxing is most severe during the locked rotor or stall condition when the slip is at the maximum. The stall relay previously discussed protects against this. However, there is another condition where we can enter into a state of over-fluxing the motor.

If one of the three phases of the supply has high resistance or is open circuit (due to a blown fuse, loose connection, etc.), then the magnetic flux becomes unbalanced and the rotor will begin to slip further away from the stator field speed. The rotor (shaft) speed will decrease while the supply current will increase causing winding over-heating as well as core iron heating. Also intense vibration due to unbalanced magnetic forces can cause damage to the motor windings and bearings.

This open-phase condition is oddly enough called single phasing of the motor, even though two phases are still connected.

If the motor continues to operate with an open supply line, the current in the remaining two healthy leads will exceed twice the current normally seen for a given load. This will result in rapid, uneven heating within the motor and damage to insulation, windings, reduced machine life and thermal distortion.

If torque required by the load exceeds the amount of torque produced, the motor will stall. The motor will draw locked rotor current ratings, which are, on average, 3-6 times full load current. This will lead to excessive heating of the windings and will cause the insulation to be damaged. If the open circuit is present before the motor start is attempted, it is unlikely that the motor will be able to start rotating.

The phase-unbalance relay used to protect against this scenario is similar in design to the stall relay, but is set for about 20% of the full load current. A rough representation of the operation of the relay is included in Figures 22a and 22b for reference only. If any one of the phases in the motor loses power, the heater will cool down. The

Notes

bimetallic strip will turn, causing the unbalance contacts to close and the motor to be tripped. This relay will also protect against thermal overload, as the heaters cause the bimetallic strips to close the overload trip contact. You will also see a compensating bimetal element, which will compensate for ambient temperature changes, thus preventing unnecessary trips.

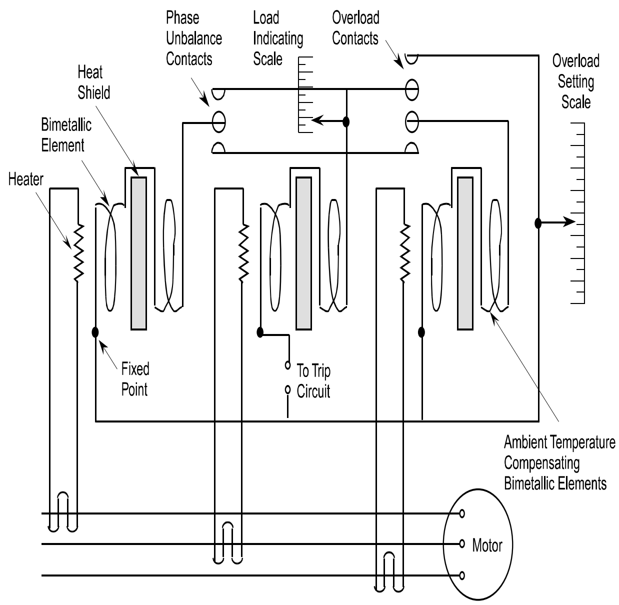

Figure 22a
Phase Unbalance and Overload Protection

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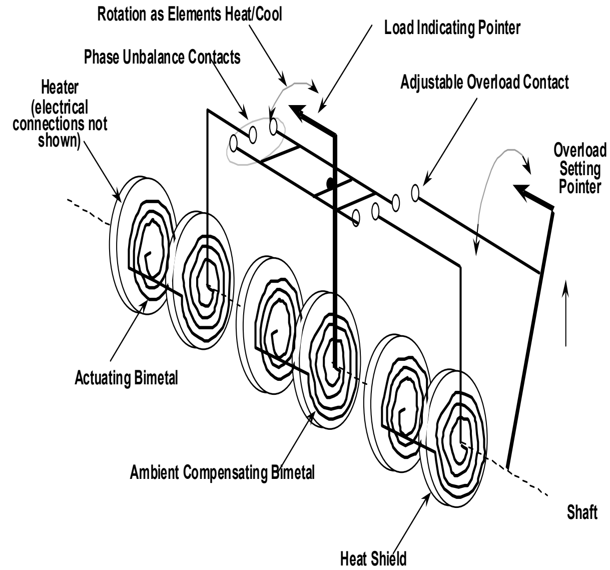

Figure 22b
Phase Unbalance and Overload Protection

5.9 GENERATOR PROTECTION

As with electrical motor protection, generator protection schemes have some similarities and overlap. This is advantageous, since not all generators have all of the protection schemes listed in this section. In fact, there are many protection schemes available; only the more common ones are discussed here.

5.9.1 Classes of Turbine Generator Trips

There are different classes of protective trips for generators, each with different actions, depending on the cause and potential for damage. Each of the four Classes of trip (A, B, C, &D) is discussed below.

Class A trips will disconnect the generator from the grid and shut down the turbine-generator (i.e., it will trip the turbine and the field breaker). Typical causes could be generator electrical protection, main transformer electrical protection, ground faults or any other cause that may directly affect the unit's safe electrical output.

Class B trips will disconnect the generator from the grid, but will leave the turbine generator supplying the unit load. Typical initiation of this event is a grid problem, thus resulting in this loss of load.

Class C trips are generator over-excitation trips and are activated only if the generator is not connected to the grid (it may still be supplying the unit loads).

Notes

Typical causes of this over-excitation are manually applying too much excitation or applying excitation current below synchronous speed (this will be discussed later in this module).

Class D trips the turbine and then trips the generator after motoring. The causes of this type of trip are associated with mechanical problems with the turbine generator set.

Each of these trips, along with their causes and exact effects, will be discussed further in your station specific training.

5.9.2 Generator Over-Current

As discussed in the previous sections, over-currents in the windings due to over-loads or faults will cause extensive damage. The generator must be separated from the electrical system and field excitation removed as quickly as possible to reduce this damage to a minimum.

During run-up and shutdown, the field may accidentally be applied while the frequency is below 60Hz. Under these conditions normal protections may not work or may not be sensitive enough. A sensitive over-current protection called supplementary start over-current is usually provided when the frequency is less than about 56Hz.

5.9.3 Generator Differential Protection

Differential protection can be used to detect internal faults in the windings of generators, including ground faults, short circuits and open circuits. Possible causes of faults are damaged insulation due to aging, overheating, over-voltage, wet insulation and mechanical damage.

Examples of the application of differential protection are shown in Figure 23 that considers a generator winding arrangement with multiple windings, two per phase (this type of differential protection is also called split phase protection for this reason).

Notes

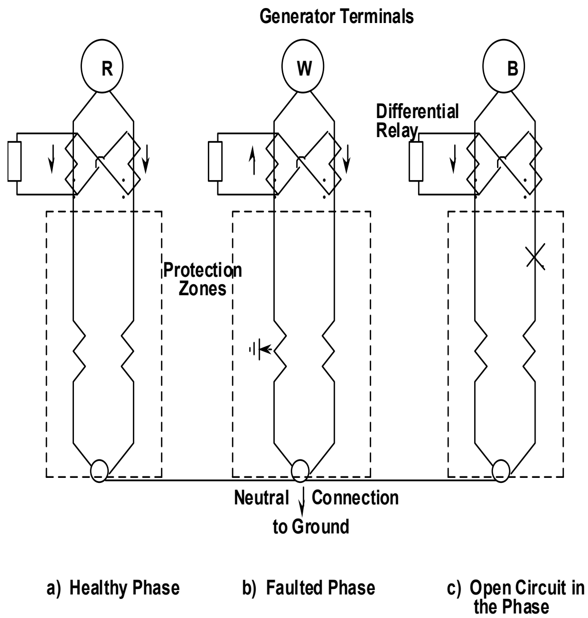

Figure 23
Split Phase Differential Protection

In Figure 23 a), the currents in the two windings will be balanced, causing the currents in the protection circuit to be balanced. Hence in this case, the differential relay will not operate.

In Figure 23 b), a ground fault is shown on one of the windings. In this case the fault current direction is shown and it will be unbalanced. This will result in unbalanced secondary currents in the protection circuit, causing the differential relay to operate. Similarly, a short circuit within a winding will cause the two winding currents to be unmatched, causing the differential relay to operate.

In Figure 23 c), an open circuit is shown, resulting in no current in the one winding. Again, the unbalanced currents will cause the differential relay to operate.

In generators with single windings per phase, the differential protection (Figure 24) is similar to the transformer protection previously discussed. This arrangement will provide high-speed tripping of the generator and field breaker plus shutdown of the turbine (class A trip). This minimizes insulation damage due to overheating, as well as damage from arcing if the insulation has already been damaged.

Notes

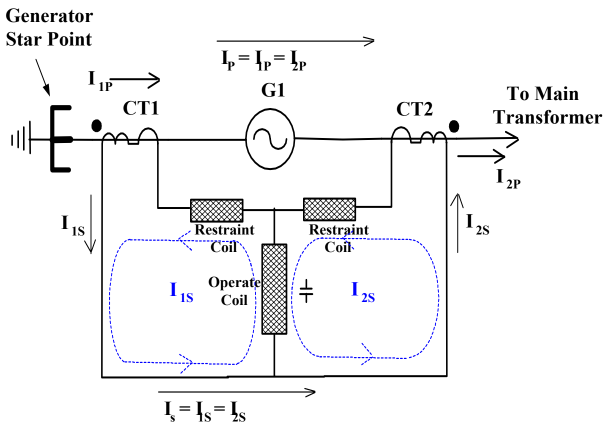

Figure 24
Generator Differential Protection

5.9.4 Generator Ground Fault Protection

Generators are usually connected to the delta winding of a delta-star main transformer. This allows the generator to produce nearly balanced three phase currents even with unbalanced loading on the primary of the main transformer. This minimizes stress, vibration and heating of the stator windings during unbalanced system conditions and electrical system faults. However, with the generator connected to a delta winding, a separate protection has to be used to protect against stator faults. Any resistance to ground will pull the delta towards ground and may initially go undetected by the differential relay. The stator ground relay will trip the generator before severe damage results. Often the ground relay has a low-set alarm included to allow possible correction before a trip condition exists.

Notes

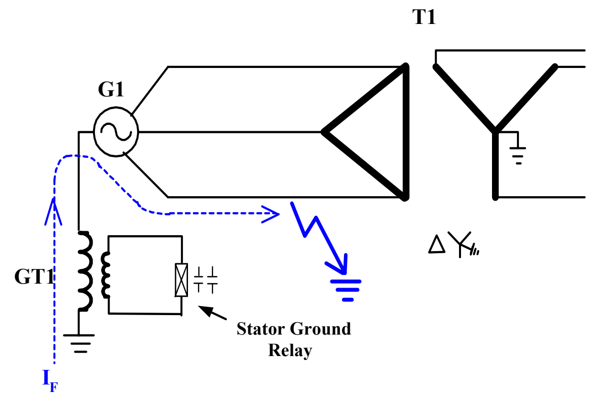

Figure 25
Generator Stator Ground Protection

Figure 25 illustrates ground protection system when the generator neutral connection is done through a neutral grounding transformer. Some locations utilize a grounding resistor and accompanying CT.

Possible causes of ground faults are insulation damage due to aging, overheating, over-voltage, wet insulation and mechanical damage. If the faults are not cleared, then the risk of insulation damage will occur due to overheating (as a result of high currents) or damage from arcing if the insulation has already been damaged.

5.9.5 Rotor Ground Fault Protection

The windings on the rotor of an ac generator produce the magnetic field at the poles. In four pole generators (typical of 60 Hz, 1800 rpm units), the occurrence of a single ground fault within the rotor generally has no detrimental effects. A second ground fault, however, can have disastrous results. It can cause part of the rotor winding to be bypassed which alters the shape of the otherwise balanced flux pattern. Excessive vibration and even rotor/stator contact may result.

A means of detecting the first ground fault provides protection against the effects of a second fault to ground on the rotor. Figure 26 shows a simplified excitation system with a Ground Fault Detection (GFD) circuit. The GFD is connected to the positive side of the exciter source.

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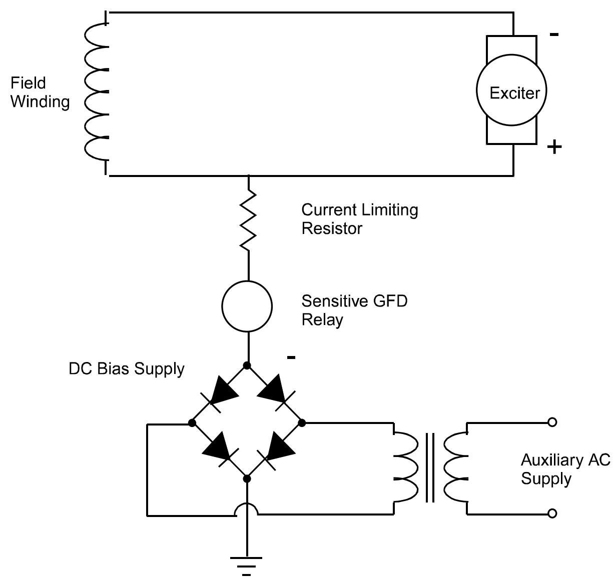

Figure 26
Rotor Ground Fault Detection

A ground fault occurring anywhere within the excitation system and rotor winding will cause current to flow through the limiting resistor (the voltage at the fault point will add to the bias voltage and cause a current flow through the GFD circuit), the GFD relay, the bias supply to ground and then back to the fault location. Current flow through the GFD relay brings in an alarm.

5.9.6 Generator Phase Unbalance Protection

If a generator is subjected to an unbalanced load or fault, the unbalance will show up as ac current in the rotor field. With the 4-pole 1800 rpm generators used in nuclear stations, this current will be at twice line frequency or 120Hz. Continued operation with a phase imbalance will cause rapid over-heating of the rotor due to the additional induced circulating currents (these currents will also cause heating of other internal components of the generator). This will result in rapid and uneven heating within the generator and subsequent damage to insulation and windings (hence, reduced machine life) and thermal distortion could occur.

Also the unbalanced magnetic forces within the generator due to these currents will cause excessive vibration. This may result in bearing wear/damage and reduced machine life and may result in a high vibration trip.

A specialized relay to detect these circulating currents, called a negative sequence current relay, is used to detect the phase imbalance within the generator. The term negative sequence is just a

Notes

mathematical term to describe the effects of unbalancing a symmetrical three phase system.

The most critical phase unbalance would come from an open circuit in one of the windings and may not be detected by any other protection. Other causes of phase imbalance include unequal load distribution, grid faults and windings faults.

5.9.7 Generator Loss of Field Protection

When a generator develops insufficient excitation for a given load, the terminal voltage will decrease and the generator will operate at a more leading power factor with a larger load angle. If the load angle becomes too large, loss of stability and pole slipping will occur and the turbine generator will rapidly go into over-speed with heavy ac currents flowing in the rotor.

A loss of field could be caused by an exciter or rectifier failure, automatic voltage regulator failure, accidental tripping of the field breaker, short circuits in the field currents, poor brush contact on the slip-rings or ac power loss to the exciters (either from the station power supply or from the shaft generated excitation current).

A relay that sense conditions resulting from a loss of field, such as reactive power flow to the machine, internal impedance changes as a result of field changes or field voltage decreases, may be used for the detection of the loss of field. A field breaker limit switch indicating that the breaker is open also gives an indication that there is no field to the generator.

5.9.8 Generator Over-Excitation Protection

If the generator is required to produce greater than rated voltage at rated speed (or rated voltage below rated speed), the field current must be increased above normal (generated voltage is proportional to frequency and flux). The excess current in the rotor and generated voltage will result in over-fluxing of the generator stator iron and the iron cores of the main and unit service transformers. Damage due to overheating may result in these components. Over-voltage may also cause breakdown of insulation, resulting in faults/arcing.

This problem may occur on generators that are connected to the grid if they experience generator voltage regulation problems. It may also occur for units during start-up or re-synchronizing following a trip (the field breaker should open when the turbine is tripped). When the field breaker opens, a field discharge resistor is inserted into the rotor circuit to help prevent terminal voltage from reaching dangerous levels.

Notes

Over-excitation on start-up may be a result of equipment problems or operator error in applying excessive excitation prematurely (excitation should not be applied to the generator until it reaches near synchronous speed).

A specialized volts/hertz relay is used to detect this condition and will trip the generator if excessive volts/hertz conditions are detected.

5.9.9 Generator Under-frequency Protection

While connected to a stable grid, the grid frequency and voltage are usually constant. If the system frequency drops excessively, it indicates that there has been a significant increase in load. This could lead to a serious problem in the grid and it is of little use to supply a grid that may be about to collapse. In this case, the generator would be separated from the grid. The grid (or at least portions of it) may well collapse. The system can slowly rebuild (with system generators ready to restore power) to proper, pre-collapse operating conditions.

As mentioned above, if a generator connected to the grid has sufficient excitation applied below synchronous speed (since grid frequency has dropped) for it to produce rated voltage, the excitation level is actually higher than that required at synchronous speed. Overexcitation and the problems described above may result.

A specialized volts/hertz relay compares voltage level and frequency and will trip the generator if preset volts/hertz levels are exceeded.

5.9.10 Generator Out of Step Protection

This protects the generator from continuing operation when the generator is pole slipping. Pole slipping will result in mechanical rotational impacts to the turbine, as the generator slips in and out of synchronism. This can be the result of running in an under excited condition (see the section on loss of field) or a grid fault that has not cleared.

Relays that detect changes in impedance of the generator can be used to detect the impedance changes that will occur when the unit slips poles. Another method to provide this protection is to detect the loss of excitation, using the loss of field protection and trip the unit if excitation is too low (i.e., trip the generator when pole slipping is imminent). This has been discussed in the loss of field section of this module.

Notes

5.9.11 Generator Reverse Power Protection

Motoring refers to the process of an ac generator becoming a synchronous motor, that is, the device changing from a producer of electrical power to a consumer of it. Following a reactor trip or setback/stepback to a very low power level, it is beneficial to enter the motoring mode of turbine-generator operation. However, this is not a desirable mode of operation for standby or emergency generators. They are not designed to operate in this manner and can be seriously damaged if power is allowed to flow in the wrong direction.

A means of indicating when the transition from exporter to importer of power occurs is provided by a device known as a reverse power relay. As its name suggests, it is triggered by power flowing in a direction opposite to that which is normally desired. This can be used for generator protection, as is the case with standby generators or as a permissive alarm/interlock for turbine-generator motoring. Figure 27 shows a typical arrangement of a reverse power protection circuit employing both a CT and a Voltage Transformer (VT) to power the relay and hence, protect the generator. The relay will operate when any negative power flow is detected.

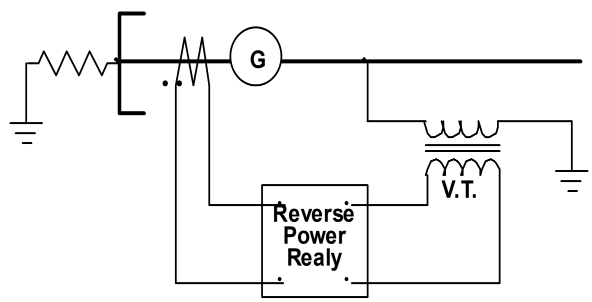

Figure 27
Reverse Power Protection

5.10 REVIEW QUESTIONS-ELECTRICAL PROTECTION

Notes

1. An electrical bus with two supplies and four feeders is protected by differential protection. Sketch the connection of the current transformers and the differential relay. Indicate the differential zone protected by the relay.
2. An electrical bus has protective relays providing the functions listed below. Explain the reasons for each of the protections.
    a. Differential
    b. Over-current back up
    c. Ground fault
    d. Under voltage
3. A transformer gas relay has two separate functions. One is a gas accumulation alarm; the other is a gas trip. Briefly, explain the types of faults detected by each function.
4. In addition to a gas relay a transformer is protect by relays providing the following functions. Briefly, explain why each function is required.
    a. Instantaneous over-current
    b. Differential
    c. Thermal overload
    d. Ground fault
5. A large induction motor has the following protections. For each explain why the reason for the protection.
    a. Instantaneous over-current
    b. Thermal overload
    c. Ground fault
    d. Stall
    e. Over-fluxing (phase unbalance)
6. In some installations, a timed over-current relay is used instead of one of the following standard motor protections. Select the protection that a timed over current might replace.

Notes

7. For each of the following protective relay functions for a generator explain the purpose of the relays.
    a. Over-current
    b. Differential
    c. Ground fault
    d. Phase imbalance
    e. Loss of field
    f. Over excitation
    g. Under frequency
    h. Pole slip
    i. Reverse power
    j. Rotor ground fault

8. The trips involved with the main generator are divided into 4 classes: A, B, C & D. Definitions for each class of trip are provided. For each of the list of conditions listed below identify which class of trip will be initiated.

    Class A trips will disconnect the generator from the grid and shut down the turbine-generator (i.e., it will trip the turbine and the field breaker).

    Class B trips will disconnect the generator from the grid, but will leave the turbine generator supplying the unit load.

    Class C trips are generator over-excitation trips and are activated only if the generator is not connected to the grid (it may still be supplying the unit loads).

    Class D trips the turbine and then trips the generator after motoring

    a. A generator differential fault (A)
    b. A mechanical fault in the turbine (D)
    c. A fault in the switch yard that causes the generator breaker is open (B)
    d. Over excitation (C)
    e. Generator load rejection (D)
    f. UST differential protection (A)