NOTES & REFERENCES

Module 7

GENERATOR PROTECTION

OBJECTIVES:

After completing this module you will be able to:

Page 2 ⇔ 7.1 Describe Class A, B, C, and D turbine generator protection trips.

7.2 Explain how each of the following protection schemes could be used to provide protection of a generator:

Pages 2–4 ⇔ a) Generator differential protection,

Pages 4–6 ⇔ b) Generator ground fault protection,

Page 7 ⇔ c) Generator phase unbalance,

Page 7 ⇔ d) Generator loss of field,

Page 9 ⇔ e) Overexcitation,

Page 9 ⇔ f) Generator underfrequency,

Page 10 ⇔ g) Generator out of step,

Pages 10–11 ⇔ h) Excitation rectifier overcurrent,

Pages 11–12 ⇔ i) Motoring.

Pages 4–11 ⇔ 7.3 For each of the schemes listed in 7.2, give an example of a fault requiring the protection scheme to operate and the consequence to the generator if the protection scheme failed to operate.

* * *

INSTRUCTIONAL TEXT

INTRODUCTION

This module concentrates on the protection schemes used for the protection of generators and the consequences of their failure to operate. A brief discussion will also be given on **the operation of the various types of protective relays, but you will not be required to memorize this information.**

NOTES & REFERENCES

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

CLASSES OF TURBINE GENERATOR TRIPS

Obj. 7.1 ⇔

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) are discussed below.

Class A trips will completely separate the generator from the grid, and shut down the turbine generator (ie. 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 which 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 overexcitation trips, and are activated only if the generator is not connected to the grid (it may still be supplying the unit loads). Typical causes of this overexcitation 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 (motoring is discussed in the 234 Turbine and Auxiliaries course). 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.

GENERATOR DIFFERENTIAL PROTECTION

Obj. 7.2 a)⇔

Differential protection, as described in Module 3, 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 7.1 which 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 & REFERENCES

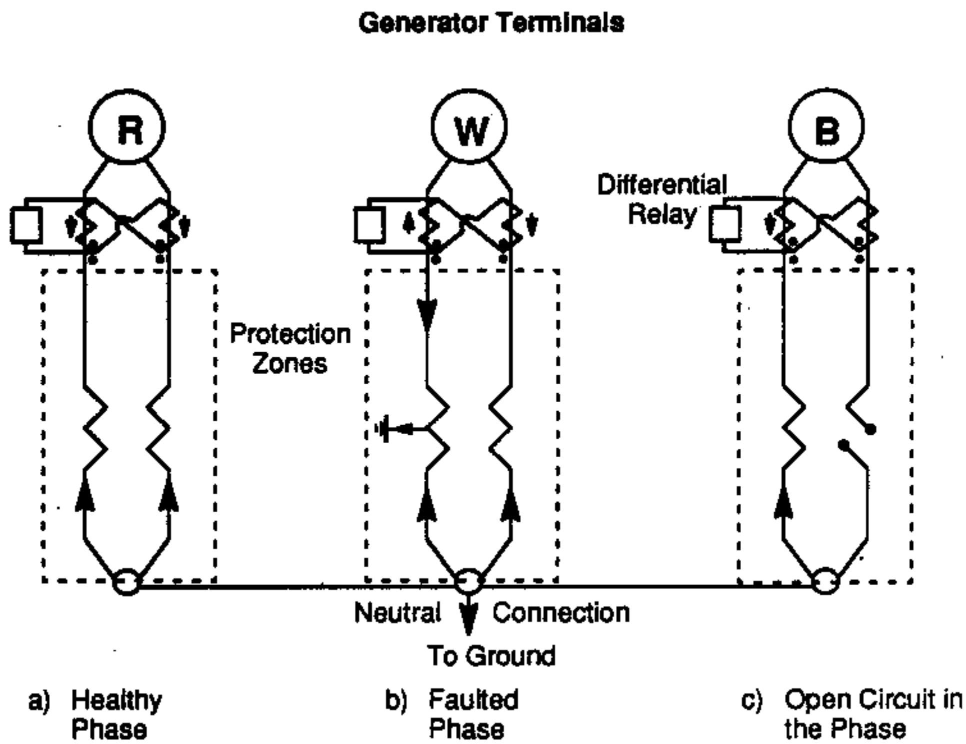

Figure 7.1: Differential Protection for Generator Windings (Split Phase Protection)

In Figure 7.1 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 7.1 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 7.1 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, differential protection could be used across each end of the windings.

NOTES & REFERENCES

This latter type of differential protection scheme could be used to protect the windings of the generator and the main transformer, by optimum placement of the current transformers. Figure 7.2 shows the differential scheme with the current transformers located at the output side of the main transformer, the connection for the unit service transformer and on the generator winding at the center of the star connection. This puts the generator winding and main transformer windings within the zone of protection for this differential scheme. Note that the current transformers will require a different ratio, since the one current transformer is on the output side of the main transformer*.

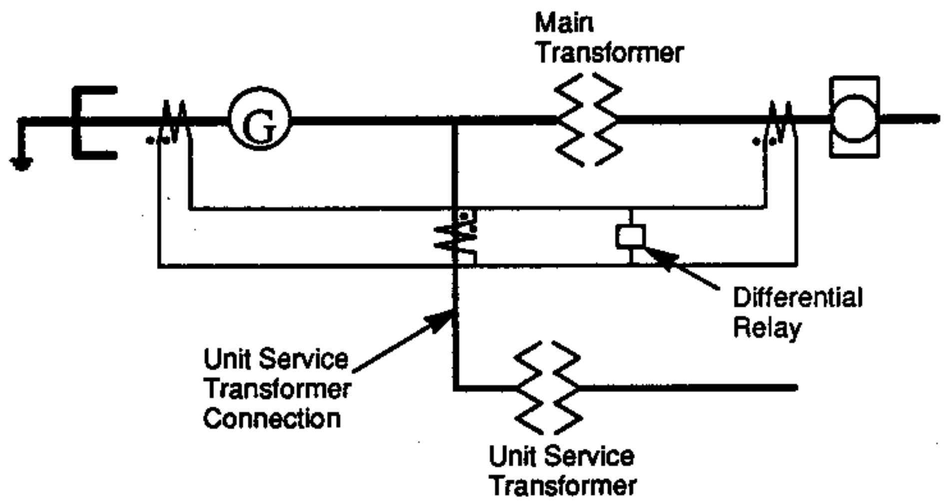

Figure 7.2: Differential Protection Scheme For The Generator (and Main Transformer)

Obj. 7.3 ⇔

If the faults listed earlier are not cleared, then the **risk of insulation damage** will occur due to overheating, as well as **damage from arcing** if the insulation has already been damaged.

GENERATOR GROUND FAULT PROTECTION

Obj. 7.2 b) ⇔

In the previous section, we have seen how differential protection can be used to protect against a ground fault in the windings of the generator itself. Another method of detecting faults is to **monitor the neutral connection for current flows.** In Figure 7.3, the grounding of the generator neutral connection is done through a neutral grounding transformer. A ground fault in the generator windings (similar to the case shown in Figure 7.1), terminals or equipment on–line will cause unbalanced current flows in the phases. This **unbalanced current flow will cause a current flow to the neutral**

* *This current will also require phase correction, since the transformation will have caused phase shifts. How this phase shift is corrected is beyond the scope of this course.*

NOTES & REFERENCES

(ground) connection. The current flowing in the neutral to ground will cause a current to be induced on the secondary side of the transformer as well. Once the voltage in the secondary side of this transformer reaches a preset level, the voltage relay will operate. The resistor seen in the diagram is sized to limit the ground fault current and thus minimize the damage to the generator stator core and winding insulation when a ground fault develops.

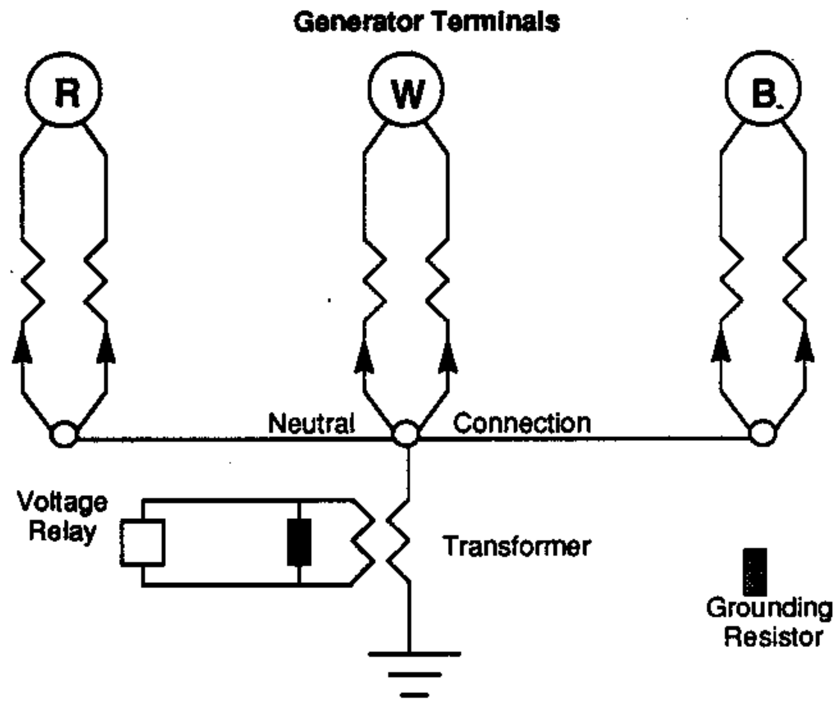

Figure 7.3: Ground Protection for Generator Windings

Obj. 7.3 ⇔

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.

ROTOR GROUND FAULT PROTECTION

Obj. 7.3 ⇔

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.

NOTES & REFERENCES

Obj. 7.2 b) ⇔

A means of **detecting the first ground fault** provides protection against the effects of a second fault to ground on the rotor. Figure 7.4 shows a simplified excitation system with a ground fault detection (GFD) circuit*. The GFD is connected to the positive side of the exciter source.

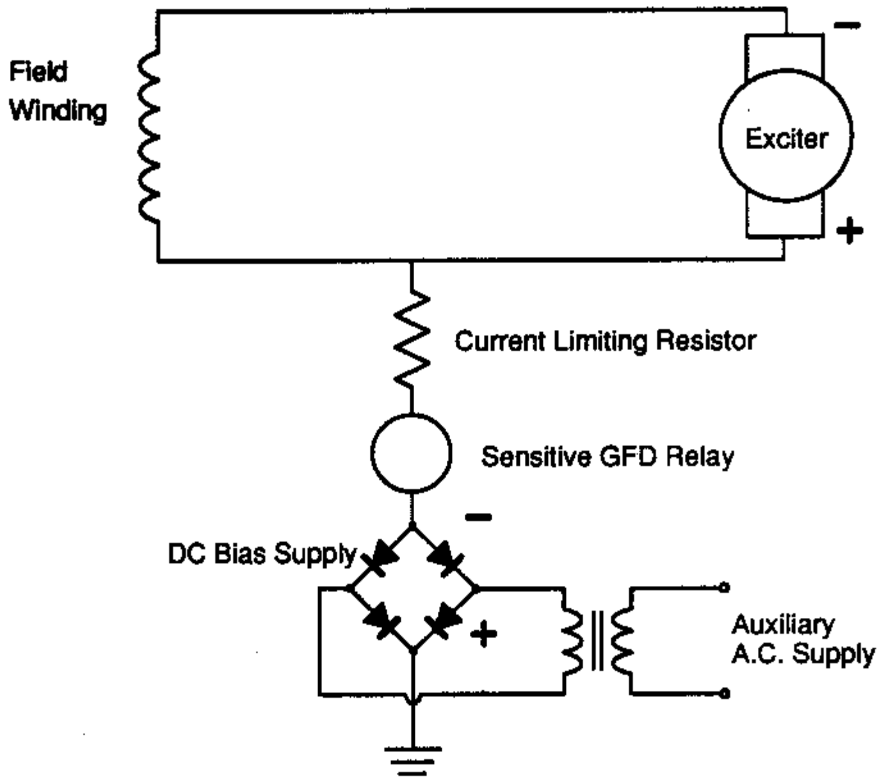

Figure 7.4: Ground Fault Detection on Excitation System

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.

* *Rotor ground fault protection was dealt with in your 335.05–1 Electrical Systems course.*

GENERATOR PHASE UNBALANCE PROTECTION

Obj. 7.3 ⇔

If the generator continues to operate with a phase imbalance, currents in the windings will increase due to 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. Possible **damage to insulation and windings** (hence, reduced machine life), and **thermal distortion** could occur.

Obj. 7.2 c) ⇔

A specialized relay to detect these circulating currents, called a Negative Sequence Current Relay (since the "induced" currents are called negative sequence currents*), is used to detect the phase imbalance within the generator during unbalanced fault conditions. A differential scheme could be used between the three phases to detect excessive variations in current caused by uneven loading.

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

Causes of phase imbalance include **unequal load distribution, grid faults and windings faults.**

GENERATOR LOSS OF FIELD PROTECTION

Obj. 7.3 ⇔

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**. More information about pole slipping will be presented later in this module, and more about stability will be presented in Module 8.

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 sliprings, or ac power loss to the exciters** (either from the station power supply or from the shaft generated excitation current).

Obj. 7.2 d) ⇔

Relays 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 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.

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* *How these currents are formed is beyond the scope of this course. You need only know that these currents circulating in the generator will cause additional heating due to I^2R losses.*

** *Trips of the turbine–generator initiated by high vibration signals are discussed in the 234 Turbines & Auxiliaries course.*

NOTES & REFERENCES

SUMMARY OF THE KEY CONCEPTS

- Class A trips will completely separate the unit from the grid, and shut down the turbine generator.
- Class B trips will disconnect the generator from the grid, but will leave the turbine generator supplying the unit loads.
- Class C trips are generator overexcitation trips.
- Class D trips will trip the turbine and then trip the generator after motoring.
- Generator differential protection can be used for protection against winding ground faults, shorts and open circuits.
- The flow of fault currents can arise from insulation damaged due to aging, overheating, moisture or mechanical damage.
- Ground faults can also be detected by current through the neutral grounding transformer.
- Ground faults on the rotor are detected by a ground fault detection system connected to the positive bus of the exciter circuit. The first ground fault is alarmed, allowing action to be taken to prevent the consequences of a second ground fault.
- Phase imbalance can be caused by unequal load distribution, grid faults and windings faults. Phase imbalance will induce circulating currents, which will result in rapid, uneven heating within the generator. This will result in damage to insulation and windings (hence, reduced machine life), and thermal distortion. Unbalanced magnetic forces within the generator will also cause excessive vibration, resulting in a possible high vibration trip.
- A negative sequence current relay can be used to detect phase imbalance conditions and initiate protective action. A differential scheme could also be used.
- Loss of field protection will prevent the generator from pole slipping, which can result in mechanical shocks to the turbine generator. This can be caused by an exciter failure, automatic voltage regulator failure, accidental tripping of the field breaker, short circuits in the field currents, poor brush contact on the sliprings, or ac power loss to the exciters.
- Loss of field can be detected by special relays that sense reactive power flow to the machine or internal impedance changes.

NOTES & REFERENCES

GENERATOR OVEREXCITATION PROTECTION

Obj. 7.3 ⇔

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 **overfluxing** 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. Overvoltage 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. At low frequencies, the field discharge resistor should prevent terminal voltage from reaching dangerous levels**). Overexcitation in these instances 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).

Obj. 7.2 e)⇔

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

GENERATOR UNDERFREQUENCY 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.

Obj. 7.3 ⇔

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.

Obj. 7.2 f) ⇔

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

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* *This is discussed in the 230.25–7 Electrical Equipment course.*

** *Course 230.25–3 Electrical Equipment discusses the excitation system.*

*** *This is discussed in the 335.01–1 and PI35.02 Electrical Systems courses.*

NOTES & REFERENCES

GENERATOR OUT OF STEP PROTECTION

Obj. 7.3 ⇔

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.**

Obj. 7.2 g) ⇔

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 (ie. trip the generator when pole slipping is imminent). This has been discussed in the loss of field section of this module.

GENERATOR RECTIFIER OVERCURRENT PROTECTION

Individual rectifiers (part of the exciters) are used to provide the DC current, which produce the field for the generator rotor. The power supply for the rectifiers can be either from a small ac generator on the shaft of the main generator, or from a station power supply *.

Obj. 7.3 ⇔

As the amount of current through the rectifiers increases, the generator field increases. This current must be limited to prevent **damage due to overheating.** Complete **loss of the rectifier** can occur if the protective device for the circuit operates, if the rectifier has a component fault, or if the unit has tripped on overload or high temperature (these units require cooling to dissipate heat produced). Causes of rectifier overcurrent could be overexcitation due to some **voltage regulation fault, or a grid fault** requiring higher than normal excitation.

Obj. 7.2 h) ⇔

Protection against high rectifier current varies between stations. In some stations, high rectifiers currents will initiate trips of exciters, and in others, only alarms are generated (an indication that some action will be required). Overcurrent protection can be provided by **fuses **, and by current relays** (whose details were mentioned in a previous module).

Excitation systems, as with many systems in our stations, have redundant components. For example, an exciter may have 6 rectifier sections, with only five of them required to operate the generator at full power. In this example, the loss of more than one rectifier will result in the overall capacity of the exciter being reduced. If the exciter was forced to produce the current required to produce full load, the remaining rectifiers would be overloaded,

* *Course 230.25–3 Electrical Equipment discusses the excitation system.*

** *Fuses were discussed in your 426.0–16 Electricity Course.*

and these rectifiers will also be lost. Some stations will allow continued operation with reduced number of rectifiers in service, but **generator excitation (hence load) will be limited by remaining field current capacity**. By not having the field current available to "stiffen" the generator's connection to the grid, the system stability is at risk.

The rectifiers have an overload capacity, but the duration that they can sustain this overload is limited. This overload capacity is required when grid faults result in reduced voltage, power or frequency changes. A power stabilizing system*, upon "seeing a grid problem", will call for an increase in excitation to maintain grid stability. This is known as **field forcing**. If the number of rectifiers is limited, and field forcing is required, it can/will overload the remaining rectifiers, resulting in a total loss of excitation (hence production). To prevent this, **the ability to field force is reduced** to a value dependent upon the number of rectifier sections in service. This will result in a **less secure electrical supply**.

MOTORING

Obj. 7.3 ⇔

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.

Obj. 7.2 i) ⇔

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 (see Class D trips on page 2). Figure 7.5 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.

* *The stabilizing system will detect voltage, speed and power changes that can be indicative of a grid fault. The stabilizing system will be discussed in your station specific training.*

** *Further information on turbine generator motoring can be found in the Turbine & Auxiliaries course 234.0–13.*

NOTES & REFERENCES

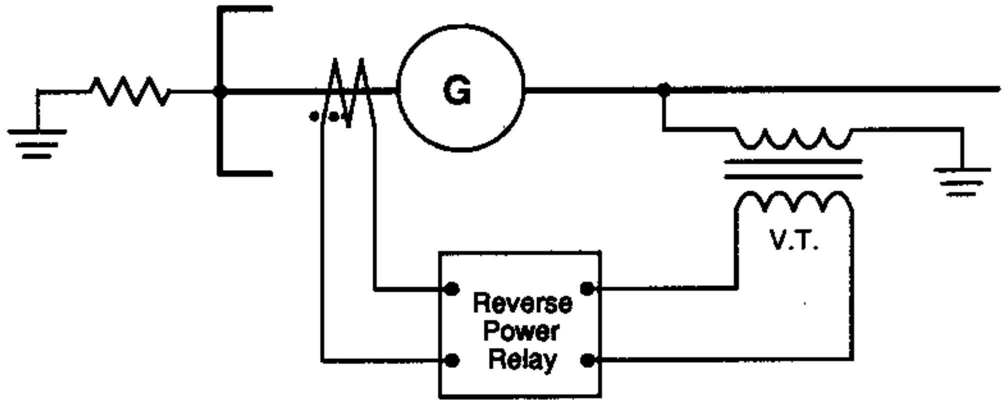

Figure 7.5: Generator Reverse Power Protection

Generator Protection Scheme	Class of Trip
Differential Protection	A
Ground Fault Protection	A
Phase Unbalance	A
Loss of Field	A
Overexcitation	A, B, C
Underfrequency	B
Out of Step	B
Excitation Rectifier Overcurrent	A*
Motoring	D

* This does not lead to a trip directly, though once excitation collapses, a loss of excitation trip will result.

Table 7.1: Summary of Generator Protection Schemes and Trip Classes

NOTES & REFERENCES

SUMMARY OF THE KEY CONCEPTS

- Overexcitation, caused by generator voltage regulation problems or operator error, will result in overfluxing of the generator stator iron and the transformers. This may result in overheating to these components. Exceeding insulation voltage can lead to breakdown/arcing.
- Underfrequency protection prevents damage to the generator stator and transformers from overfluxing due to the application of excessive excitation when the grid frequency falls.
- Generator out of step protection prevents continued operation while pole slipping and prevents mechanical damage due to the impacts of slipping in/out of synchronism.
- Rectifier overcurrents could result from a voltage regulation problem or a grid fault requiring higher than normal excitation (excessive field forcing).
- Rectifier overcurrent protection prevents damage to the rectifiers due to overheating. Without protection or annunciation, the remaining rectifiers will be overloaded and trip. Loss of field will occur, causing total loss of production. Power production and/or field forcing limitations may be required (which may affect stability).
- A reverse power relay detects the flow of power into a generator. It can provide an alarm, as occurs before turbine generator motoring, or initiate a protective trip, as is the case with standby generators.

Pages 13–18 ⇔

You can now do **assignment questions 1–19.**

NOTES & REFERENCES

ASSIGNMENT

1. Discuss each of the four classes of turbine generator protection trips.

   Class A: ______________________________

   ____

   ____

   Class B: ______________________________

   ____

   ____

   Class C: ______________________________

   ____

   ____

   Class D: ______________________________

   ____

   ____

2. Explain how differential protection is used for the protection of a generator (in your explanation include consequences to station equipment if this protection fails to operate):

   ____

   ____

   ____

   ____

   ____

3. Faults that can be detected by generator differential protection are:

   a) ______________________________

   b) ______________________________

   c) ______________________________

NOTES & REFERENCES

4. Explain how ground fault protection is used for the windings of a generator (in your explanation include consequences to station equipment if this protection fails to operate):

5. Possible causes of ground faults are:

   a)

   b)

   c)

6. Explain how ground fault protection is provided for a generator rotor (in your explanation include consequences to station equipment if this protection fails to operate):

7. Explain how phase unbalance protection is used for a generator (in your explanation include consequences to station equipment if this protection fails to operate):

NOTES & REFERENCES

8. Two possible causes of phase unbalance are:

   a) ______________________________

   b) ______________________________

9. Explain how loss of field protection is used for a generator (in your explanation include consequences to station equipment if this protection fails to operate):

   ____

   ____

   ____

   ____

   ____

10. Four possible causes of generator loss of field are:

    a) ______________________________

    b) ______________________________

    c) ______________________________

    d) ______________________________

11. Explain how overexcitation protection is used for a generator (in your explanation include consequences to station equipment if this protection fails to operate):

    ____

    ____

    ____

    ____

    ____

12. A possible cause of overexcitation is:

    ____

NOTES & REFERENCES

13. Explain how underfrequency protection is used for a generator (in your explanation include consequences to station equipment if this protection fails to operate):

____

____

____

____

____

14. Two possible causes of excitation being applied during underfrequency conditions are:

    a) ____

    b) ____

15. Explain how out of step protection is used for a generator (in your explanation include consequences to station equipment if this protection fails to operate):

____

____

____

____

____

16. Three possible reasons that of out of step operation could occur are:

    a) ____

    b) ____

    c) ____

NOTES & REFERENCES

17. Explain how rectifier overcurrent protection is used (in your explanation include consequences to station equipment if this protection fails to operate):

    ____

    ____

    ____

    ____

    ____

    ____

18. Two possible causes of rectifier overcurrent are:

    a) ____________________________________

    b) ____________________________________

19. The flow of power **into** a generator can be detected by a ______________________________.

Before you move on to the next module, **review the objectives** and make sure that you can meet their requirements.

Prepared by: Nick Ritter, WNTD

Revised by: Paul Bird, WNTD

Revision date: July, 1992