Part X

GENERATOR PROTECTION

MOTOR PROTECTION

BUS PROTECTION
The generator protection system design should take into account the types of faults and abnormal operating conditions that could be present at the generating plant and provide means for detecting and acting upon these conditions. The protection system design will depend on the size of the generating unit.

These fault types and disturbance conditions are classified as:

- Overload protection, and Overcurrent (short-circuit) problems
- Stator electrical faults
- Rotor electrical faults
- Failure of prime mover (mechanical problems)
- Failure of the field circuit

Hence we must protect the generator against the effect of these faults and abnormalities using the following protection schemes:

- Overload protection, and Overcurrent protection
- Overvoltage and undervoltage protection
- Overexcitation
- Unbalanced loading (Currents) –sequence relay
- Loss of Excitation
- Loss of synchronism
- Phase Faults
- Earth Faults
- Abnormal Frequencies
- Motoring
- Overspeeding
- Excessive vibration
- Internal faults,
- Stator and rotor thermal protection, and
- Field ground.
1. Generator protection using differential protection schemes

To protect the generator against the failure of winding insulation and the failure of the field circuit as well as the primemover failures, differential protection is used with biased circulating current scheme. The theory of circulating current differential protection is discussed fully in part 7. The protection scheme is shown in Fig. 1. Normally differential protection is used for generators larger than or equal to 20MW.

![Diagram of Stator biased differential protection for generator]

**Example 1**
Figure 2 shows a biased percentage differential relay applied for the protection of synchronous generator windings. The relay has 0.1A minimum pick up current and a 10%.

(a) Fault has occurred near the grounded neutral end of the generator when the generator is carrying load. As a result, the currents flowing at each end are as shown in the figure. Would the relay operate or not?

(b) would the relay operate at the given value of fault current in (a) above if the generator was carrying no load?

(c) On the same diagram, show the relay operating characteristics and the points that represent the operating and restraining currents in the relay for the two conditions.
(a) Fault under load condition

\[ I_{S1} = 420 \times \frac{5}{500} = 4.20 \text{ A} \]
\[ I_{S2} = 400 \times \frac{5}{500} = 4.0 \text{ A} \]

The restrain coil average current \( I_r = \frac{I_{S1} + I_{S2}}{2} \)

or \( I_r = \frac{4.2 + 4.0}{2} = 4.1 \text{ A} \).

(For relay to operate, the current in the operating coil must not be less than 10% of the restrain current, i.e., \( I_{op} > \left[\frac{10}{100} \times 4.1 = 0.41 \text{ A} \right] \)).

but \( I_{op} = I_{S1} - I_{S2} = 4.2 - 4.0 = 0.2 \text{ A} \)

which is less than 0.41 A. Therefore, the relay will not operate.
(b) Generator under fault at no load:

Under no load condition, the fault current is the same as (a), hence:

\[ I_f = 4.20 - 4.00 = 0.20 \text{ A} \]

\[ I_{f5} = 20 \times \frac{5}{500} = 0.20 \text{ A} \]

which flows through the operating coil.

\[ I_{S2} = 0 \]

\[ I_{S1} = I_{f5} = 0.20 \text{ A} \]

\[ I_{op} = I_{S1} - I_{S2} \]

\[ = 0.20 - 0 = 0.20 \text{ A} \]

\[ I_{r} = \frac{I_{S1} + I_{S2}}{2} = \frac{0.20 + 0}{2} = 0.10 \text{ A} \]

since \( I_{op} > I_{r} \) hence the relay will operate.

![Graph showing relay characteristics](image-url)
Typical generator protection scheme is shown in Fig.4 below:

 Relay 51N or 51GN: Time overcurrent earth fault in the neutral

Fig.4 Generator Protection Application Simplified One-Line Diagram
GENERATOR PROTECTION APPLICATIONS
PHASE FAULT PROTECTION

Phase faults in a generator stator winding can cause thermal damage to insulation, windings, and the core, and mechanical torsional shock to shafts and couplings. Trapped flux within the machine can cause fault current to flow for many seconds after the generator is tripped and the field is disconnected.

GROUND-FAULT PROTECTION

One of the main causes of ground faults is insulation failure. The zero sequence impedance of a generator is usually lower than the positive or negative sequence impedance, and hence, for a solidly grounded generator, the single phase to ground-fault current is greater than the threephase fault current. To limit the ground-fault current, generators are usually grounded through an impedance.

LOSS-OF-FIELD (EXCITATION) PROTECTION

Loss of excitation on a synchronous machine can be caused by operator error, excitation system failure, a short in the field leads, accidental tripping of the field breakers, or flashover of the exciter commutator. When the machine loses its excitation, the rotor accelerates and the synchronous machine operates as an induction generator. As a result, the machine draws inductive reactive power from the system instead of supplying it to the system. Also heavy currents are induced in the rotor teeth and wedges and can cause thermal damage to the machine if the machine continues to operate.

OVEREXCITATION PROTECTION

When the ratio of the voltage to frequency (volts/Hz) exceeds 1.05 pu for a generator, severe overheating can occur due to saturation of the magnetic core of the generator and the subsequent inducement of stray flux in components not designed to carry flux. Such overexcitation most often occurs during start-up or shutdown while the unit is operating at reduced frequencies, or during a complete load rejection which leaves transmission lines connected to the generating station. Failure in the excitation system can also cause overexcitation. Similar problems can occur with the connected transformer.
OVERVOLTAGE PROTECTION

Generator overvoltage may occur during a load rejection or excitation control failure. In case of hydrogenerators, upon load rejection the generator may speed up and the voltage can reach high levels without necessarily exceeding the generator’s V/Hz limit. The overvoltage relay (59) is used to protect the generator from this condition.

UNBALANCED CURRENTS

Unbalanced faults and other system conditions can cause unbalanced three-phase currents in the generator. The negative sequence components of these currents cause double-frequency currents in the rotor that can lead to severe overheating and damage. The negative sequence overcurrent function (46) is provided to protect the unit before the specified limit for the machine is reached.

ABNORMAL FREQUENCY PROTECTION

- Over Frequency Protection
  Full or partial load rejection can lead to overspeed of the generator, and hence, over frequency operation. In general, over frequency operation does not pose any serious problems and control action can be taken to reduce the generator speed and frequency to normal without tripping the generator. Generators are shipped with overspeed detectors. An over frequency relay can be used to supplement this overspeed equipment. The multifunction relays provide a two-setpoint over frequency relay (device 81O) that can be set to alarm or trip on an over frequency condition.

- Under Frequency Protection
  Overloading of a generator, perhaps due to loss of system generation and insufficient load shedding, can lead to prolonged operation of the generator at reduced frequencies. This can cause particular problems for gas or steam turbine generators, which are susceptible to damage from operation outside of their normal frequency band. The turbine is usually considered to be more restrictive than the generator at reduced frequencies because of possible mechanical resonance in the many stages of the turbine blades. If the generator speed is close to the natural frequency of any of the blades, there will be an increase in vibration. Cumulative damage to the blades due to this vibration can lead to cracking of the blade structure.
MOTOR PROTECTION

1. General

Fuses, thermal overload relay, and contactors have proved itself an effective and economical solution for small to medium-sized motors up to about 150 hp. Two basic protections are used for these motors:

- Thermal overload protection
- Short-circuit (overcurrent) protection

On larger, more expensive motors or when maximum motor utilization is required under varying operational conditions, more sophisticated flexible and accurate microprocessor protection relays should be considered. These relays typically include:

- Thermal overload protection,
- Short-circuit protection
- Start-up and running stall protection
- Phase unbalanced protection
- Single-phasing protection
- Earth fault protection
- Undercurrent protection

The present day concept is the use of microprocessor-based numerical relays for both HV and LV motors (say beyond 50 kW), as the relays come with lots of features which allow them to be interchangeable, ensures site settings, and give valuable feedback on the load details whether a trip occurs or not.

2. Typical protective settings for motors

(a) Long-time pick-up

- (1.15) times motor full load current (FLA) times motor service factor for applications, encountering 90% voltage dip on motor starting
- (1.25) times motor FLA times motor service factor for applications encountering 80% voltage dip on motor starting.

(b) Long-time delay

- Greater than motor starting time at 100% voltage and the minimum system voltage
- Less than locked rotor damage time at 100% voltage and the minimum system voltage
• On high-inertia drives, it is common for the start time to be greater than the locked rotor withstand time. Under these circumstances, set the time to permit the motor to start. Supplemental protection should be added for locked rotor protection. One example of this is a speed switch set at 25% of rated speed tripping through a timer to trip if the desired speed has not been reached in a pre-determined time.

(c) Instantaneous pick-up
• Not less than 1.7 times motor long-time pick up rated ampere (LRA) for medium-voltage motors
• Not less than 2.0 times motor LRA for low-voltage motors.

(d) Earth-fault protection
• Minimum pick-up and minimum time delay for static trip units
• Core-balance CT and 50 relays set at minimum for medium-voltage, low-resistance grounded systems
• Residually connected CT, and 50/51 for medium voltage, solidly grounded systems. Minimum tap and time dial equals 1 for 51 relay
• Minimum tap (not less than 5 A) for 50 relay.

Motor protective device

- Molded Case Circuit Breakers (MCCB) are used for low voltage motors of high ratings.
- Miniature circuit breakers (MCB) for small motors.
- Fuses + contactor + thermal relay for L.V motors.
- For high voltage motor: H.V. circuit breaker and differential protection.
Example

A 100 hp, 480 V, 0.85 p.f., 85% efficiency motor has starting up to 5.9 times rated current up to 85% with voltage dip of 80% during starting. Select protection means for this motor.

Solution:

\[ \eta = \frac{P_o}{P_{in}} \quad \therefore P_{in} = \frac{P_o}{\eta} = \frac{100 \times 746}{0.85} = 87.764 \text{ kW} \]

\[ I_{\text{rated}} = \frac{P_{in}}{\sqrt{3} \times V \times X \times p.f.} = \frac{87764}{\sqrt{3} \times 480 \times 0.85} = 124 \text{ A} \]

Choose Moulded case circuit breaker with both thermal and magnetic trips:

1. **Thermal setting of MCCB:**
   - Thermal pick up setting \((100 - 12.5\%) \times I_{\text{rated}}\)
   - Choose 125%.
   - **Thermal setting =** \(1.25 \times 124 = 155 \text{ A}\).

2. **Magnetic Trip =** \(6.75 \times I_{\text{tho}} = 6.75 \times 124 = 837 \text{ A}\).

3. **Circuit breaker rating =** \(2 \times I_{\text{rated}} = 2 \times 124 = 248 \text{ A}\)

Choose MCCB TP 250 A/150 A.
Motors protection by fuses

In several industrial applications, fuses are used for protecting small and medium size motors. To determine the fuse size for a motor, one should refer to Fig. 1 which shows typical fuse time/current characteristics. These characteristics represent fuse operation where the current is insufficient to operate the fuse in the first 1/4-cycle, or 0.005 s in a 50 Hz system.

If the starting current of the motor is say 500 A and the run-up time 10s, then a 125 A fuse would be required. Examination of the fuse time/current characteristic shows that at 500 A the 125 A fuse would operate in 15 s. The fuse one size lower, 100 A, would operate in 4 s at 500 A and is, therefore, not suitable. The full-load current of the motor would be, say, 83 A and although a 100 A fuse would deal with this current it could not deal with the starting current for the duration of the starting time. The fuse does not protect the motor against overload as the rating of the fuse is always two to three times the full load current.
To summarize

1. The fuse must be adequately rated to supply normal current to the circuit.
2. The rating must take into account any normal healthy overload conditions e.g. the starting of motors.
3. An allowance must be made if an overload occurs frequently.
4. There must be an adequate margin if discrimination between fuses is required.
5. The fuse must protect any equipment which is not rated at the full short-circuit rating of the power system, e.g. contactors, cables, switches, etc.

Example of fuse selection
A 415 V distribution system is shown in Fig. 3.

Lighting load - 20 kW

\[ I = \frac{20 \times 1000}{\sqrt{3} \times 415} = 27.8 \text{ A} \]

Select a 32 A fuse.
Heating load - 30 kW

\[ I = \frac{30 \times 1000}{\sqrt{3} \times 415} = 41.7 \text{ A} \]

Select a 50 A fuse.

Motor 30 kW

Note that, whereas the lighting and heating loads are rated at the input power, the motor is rated at the output power. The motor input power is output power/efficiency, i.e. for 92% efficiency:

Input power = \( \frac{30}{0.92} = 32.6 \text{ kW} \)

Also the heating and lighting loads are at unity power factor whereas the motor power factor is, say, 0.83.

Therefore the motor full load current is

\[ I = \frac{32.6 \times 1000}{\sqrt{3} \times 415 \times 0.83} = 54.7 \text{ A} \]

The starting current of, say, 7 x full load current for 10 s is 7 x 54.7 = 383 A.
From the time/current curve, Fig. 4, an 80A fuse would withstand 383 A for only 6 s. Therefore a 100 A fuse, which would withstand 383 A for longer than 10s, would be necessary.

To provide discrimination the fuse at A must meet the following requirements.

1 - It must carry the normal load

\[ 27.8 + 41.7 + 54.7 = 124.2 \text{ A} \]

2- It must carry the load plus the starting current of the motor:

\[ 27.8 + 41.7 + 383 = 452.5 \text{ A for 10 s} \]

From Fig. 4 a 125 A fuse would withstand 452.5 A for more than 10s.
3- The pre-arcing $\int i^2 t$ must be greater than the total $\int i^2 t$ of the 100 A fuse. Figure 5 shows that a 160 A fuse would be required.
Bus Bars Protection

Bus Protection Schemes
Bus protection is used to protect switches, disconnects, instrument transformers, circuit breakers, and other bus equipment as well as the bus itself.

There are several methods of bus protection:
- Basic Differential Protection
- Differential Protection with Overcurrent Relays
- Percentage Differential Protection
- High-Impedance Voltage Differential Protection
- Bus Partial Differential Protection

All these methods are based on KCL, namely, that the sum of all current entering a node must be zero. Consider the two situations for simple bus shown in Fig. 1.

![Fig. 1 Simple bus arrangement](image)

- For external fault: \( I_f = I_6 = I_1 + I_2 + I_3 + I_4 + I_5 \)
- For internal fault: \( I_f = I_1 + I_2 + I_3 + I_4 + I_5 + I_6 \)
Bus differential relaying Schemes:

1. Basic differential system

A basic differential system is shown in Fig.2. All CTs must have same ratio and polarity such that the current circulate amongst them is zero ($I_d=0$) for all external faults. For internal fault current $I_d=I_f$ will flow through the relay.

![Diagram of External and Internal Faults](image)

**Fig.2**

2. Bus Differential Protection with Overcurrent Relays

If the CTs behaved ideally, the differential system shown in Fig.2 would be very easy to implement using a simple overcurrent relay as shown in Fig.3.

![Diagram of Overcurrent Relays](image)

**Fig.3**
3. Bus Protection with Percentage Differential Relays
A percentage restrain differential relay takes the fact that there may be error current in differential circuit. A simple percentage restrain differential relay is shown in Fig.4.

![Fig.4](image)

Consider a load bus with three outgoing feeders as shown in Fig.5. This bus is protected by differential relay with three restrain coil. The protection scheme shown for one phase only.

![Fig.5](image)
• When there is no fault (internal fault):

\[ I_1 + I_2 = I_3 \]
\[ I_1' + I_2' - I_3' = 0 = I_{op}. \] The relay will not operate.

• When there is fault:

\[ I_1' + I_2' - I_3' \neq 0 \] The relay will operate.

Example 1: for the system shown (bus protection by differential current relay) an external fault has occurred on feeder no.3, find whether the differential relay will operate or not.

**Solution:**

\[ I_f = I_{F1} + I_{F2} = 6000 + 10000 = 16000 \text{ A}. \]
\[ I_1' = 6000 \times \frac{5}{600} = 50 \text{ A}. \]
\[ I_2' = 10000 \times \frac{5}{600} = 83.4 \text{ A}. \]
\[ I_3' = 16000 \times \frac{5}{600} = 133.4 \text{ A}. \]

\[ I_{op} = I_1' + I_2' + I_3' = 50 + 83.4 - 133.4 = 0. \] Hence the relay will not operate.
Example 2: repeat example 1, if the feeder no.3 supplies 7000A current infeed to the bus and an internal fault occurs on the bus itself.

\[
\text{Solution:}
\]

\[I_f = I_{F1} + I_{F2} + I_{F3} = 6000 + 10000 + 7000 = 23000 \text{ A}.
\]
\[I_{1}' = 6000 \times \frac{5}{600} = 50 \text{ A}
\]
\[I_{2}' = 10000 \times \frac{5}{600} = 83.4 \text{ A}
\]
\[I_{3}' = 7000 \times \frac{5}{600} = 58.3 \text{ A}
\]
\[I_{OP} = I_{1}' + I_{2}' + I_{3}' = 50 + 83.4 + 58.3 = 191.7 \text{ A}
\]

Hence the relay will operate.
4. Bus High-Impedance Voltage Differential Protection

5. Bus Partial Differential Protection

- A partial differential scheme is similar to an overcurrent differential scheme, the difference being that all breakers are not monitored. This scheme is used when there are limited sources and multiple outfeeds. This scheme is shown in Fig.7 below.

- The scheme uses an overcurrent relay fed from paralleled CTs that only monitor the sources to the bus. The overcurrent relay is set to coordinate with the feeder relays.

- Advantage: Relatively inexpensive.

- Disadvantage: Slower clearing time.