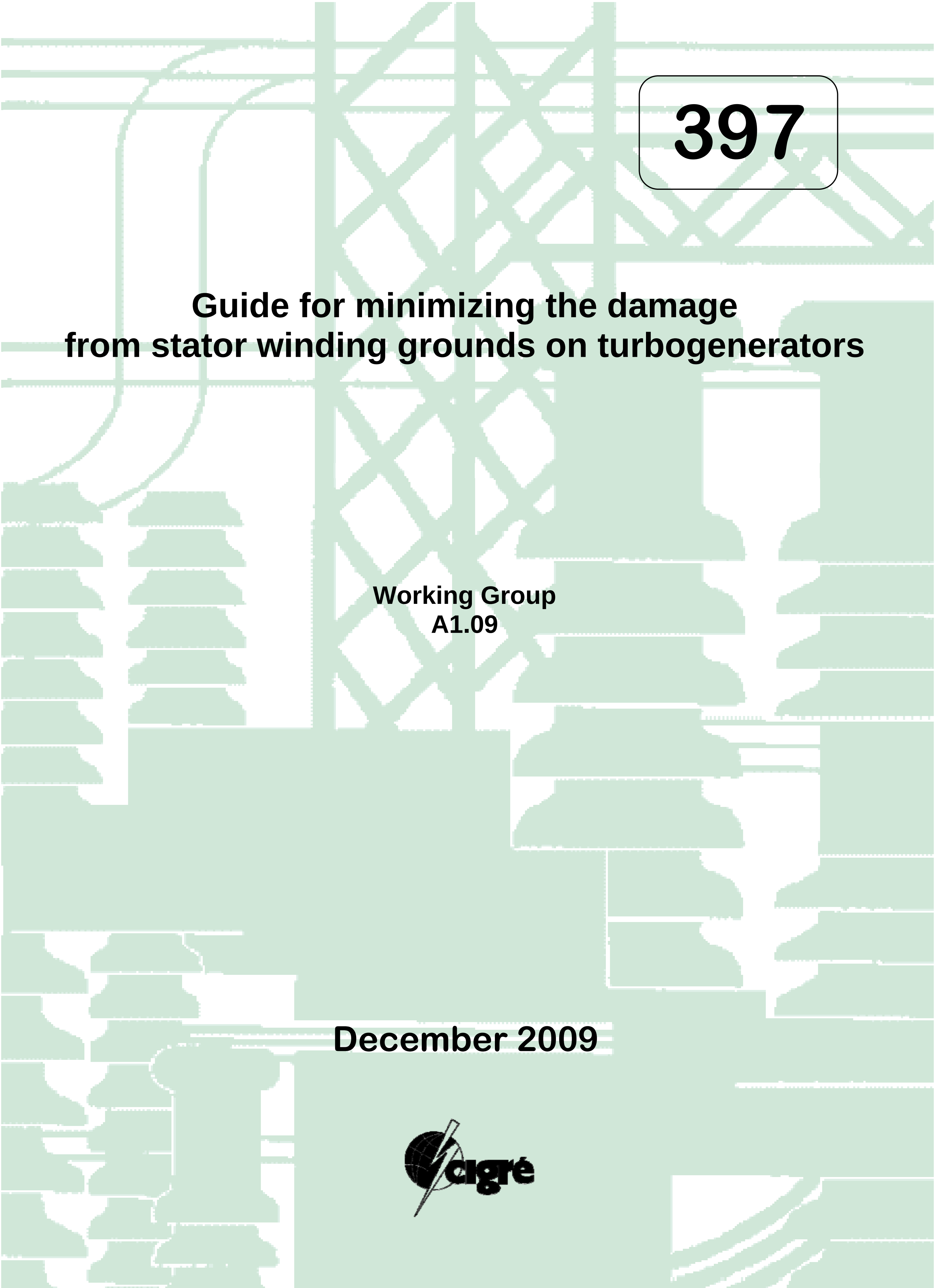

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Guide for minimizing the damage from stator winding grounds on turbogenerators

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Guide for minimizing the damage from stator winding grounds on turbogenerators

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1 EXECUTIVE SUMMARY

Stator ground faults are the most common winding failure in generators, and this kind of fault occurs due to stator winding insulation breakdown and electrical contact between the active phase winding and the grounded stator core.

Protection relays must trip the generator as soon as possible, tripping the main breaker, disconnecting the excitation supply and tripping the prime mover. However, the fault current will not disappear immediately, because of the finite time taken to discharge the stored energy in the field circuit.

Following a stator ground fault and protection relay trip, the generator performance and the damage caused to the stator core, depend on how the stator winding neutral point is grounded.

The propose of this guide is to review the effect of phase-to-ground fault on generator and to analyze the different stator winding ground schemes and protection systems. Calculation criteria for stator winding grounding will be proposed, in order to reduce damages.

1.1 Effects of stator phase-to-ground fault

A stator phase-to-ground fault produces two effects: overcurrent on the affected phase and an overvoltage on the undamaged phases.

During stator ground faults, short circuit current flows from the damaged phase to ground through the stator core. Depending on the amount of power dissipated during phase-to-ground fault (kI^2), damage to the core may be very extensive, with a lengthy and costly process of dismantling and rebuilding of the stator.
There is a relationship between phase-to-ground fault current and the severity of generator damage, and experience has shown that stator ground fault damages are proportional to the dissipated power (kI^2) and depend on the fault duration.

Stator winding ground protection operates in less than 1 second, typically in 500 ms. It trips the main breaker, shuts down the excitation and usually trips the prime mover at the same time. When the main breaker is tripped and the field breaker opens the excitation winding circuit, an overvoltage will appear across the rotor winding due to its inductive impedance, and the stored energy must be discharged through the field discharge systems. As a consequence, an overvoltage will be induced on stator windings in the rotor winding. The induced stator voltage will sustain the stator-to-ground fault current for a few seconds depending on the time constant of the field discharge system. The field discharge system must be specified to get a fast reduction in field current induction in order to reduce the transient stator-to-ground fault current and to limit machine damage. This way, transient of stator-to-ground current will develop for a few seconds, depending on field discharge system design, typically less than 5 seconds.

During phase-to-ground fault, short circuit current will circulate to ground through stator core, returning through grounding resistor (resistive component) and through capacitive insulation of the power system. Capacitive current is produced for all the capacitances in the generator area such as: stator winding, busbars, connection leads and low voltage transformer winding capacitances. The resistive current magnitude depends on the resistor value, and will be controlled in order to decrease total short circuit current, maintaining phase-to-ground fault current under a limiting value.
This report will recommend to limit phase-to-ground fault current to below 20 A for a non-severe damage level.

During a single phase-to-ground fault, phase-to-ground voltages are unbalanced. Depending on the type of stator winding grounding system, phase-to-ground voltages on phases not affected by the fault could be increased over nominal phase-to-ground nominal voltage. Depending on the position of the fault in the winding, voltages on undamaged phases and neutral voltage can be very high. A phase-to-ground fault usually occurs on a generator when the winding insulation is in poor condition, and the insulation condition is usually similar on all three phases. Thus when a phase-to-ground fault occurs on one phase, the uncontrolled overvoltage on undamaged phases could produce a new fault, creating a double phase-to-ground fault. During a double phase-to-ground fault, the fault current is higher than in a single phase-to-ground fault because it is not limited by the grounding impedance. The damage during a double phase-to-ground fault of this type is much higher than in case of a single phase-to-ground fault. According to this, stator winding grounding system must be designed in order to avoid uncontrolled voltage increases on phases not affected by fault.

1.2 Stator Winding Grounding Systems

This report compares the four common schemes of generator grounding.
Normally, the neutrals of modern turbogenerators are grounded through resistors, and depending on the connected system design conditions, the stator winding grounding system will be:

- Direct resistor.
- Neutral grounding transformer with secondary resistor.

It is possible that the neutral point of the turbogenerator is not connected to ground. In that case, the grounding system is installed on generator busbars in two different ways by:

- Grounding Transformer on busbars.
- Neutral grounding on a unit transformer.

Advantages and disadvantages of these four grounding systems are evaluated in this guide.

1.3 Phase-to-ground fault protection

Phase-to-ground faults must be detected in any part of the generation voltage area, including stator windings and generator bus. It is recommended to install a main and a back-up protection that detect the fault in a different way, metering fault conditions in a different point of the generator voltage area, in order to ensure the fault detection.

It is recommended to install a main protection on the neutral point of the generator, in order to avoid un-adverted trips, and a back-up delayed relay on busbars. Stator phase-to-ground protection schemes are designed and set according to the stator grounding system. The chosen ground protection scheme will be based on the detection of the current in the resistor or the zero sequence voltage between the neutral-point to ground.

There are two main types of generator stator winding ground fault protection. One covering only 95% of the winding down from the line terminal and the other one, covering 100% of the winding. Both schemes will be evaluated and compared in this report.

Generator bus ground protection is a back up relay against phase-to-ground fault in generator voltage area, including stator winding and generator bus, and will be evaluated in this document.

1.4 Calculation of stator winding grounding

This document will explain that the grounding resistor must be designed in order to reduce phase-to-ground fault current, controling the overvoltage on undamaged phases.
The phase-to-ground fault current will flow to ground through the stator core, returning through the grounding resistor and the winding earth capacitance, and it will be shown that the resistive current must exceed the capacitive component..
The fault current flowing through resistor must be higher than a minimum value, in order to be detected by stator ground fault protection. At the same time, depending on resistor value, resistive current must be reduced in order to decrease total short circuit current. Taking into consideration that the tripping time of

the stator earth fault protection, this document will recommend a mimimum current limit to under 10 A where possible but certainly under 15 A.

Thus the grounding resistor has to be designed in order to keep phase-to-ground fault current in the range between 5 to 10 A.

1.5 Conclusions

This guide has provided a basis for calculation of stator grounding systems on turbogenerators. Different stator grounding schemes has been considered and compared , and has been reviewed the actual configurations of phase-to-ground protections related with them.

2 EFFECTS OF STATOR PHASE-TO-GROUND FAULT

A stator phase-to-ground fault produces two effects: overcurrent on the affected phase and an overvoltage on the undamaged phases.

2.1 Overcurrent

During stator ground faults, short circuit current flows from the damaged phase to ground through the stator core.

Depending on the amount of power dissipated during phase-to-ground fault (kI^2), damage to the core may be very extensive, with a lengthy and costly process of dismantling and rebuilding of the stator. Previous work has shown [Ref. 2], that there is a relationship between phase-to-ground fault current and the severity of generator damage. This can be represented as shown in Figure 1.

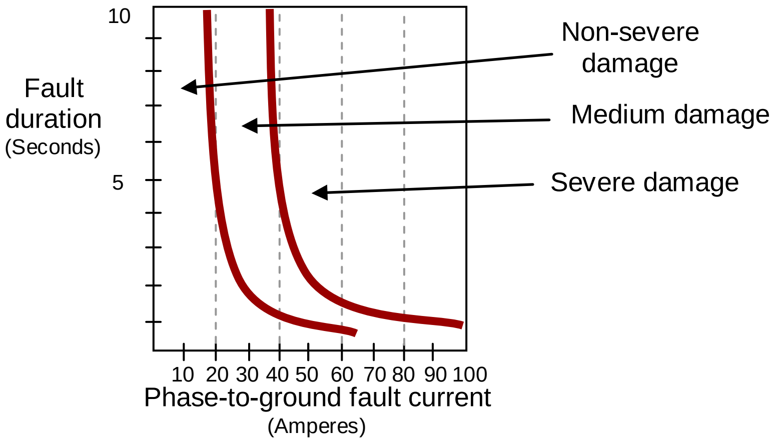


Figure 1 – Relationship Phase-to-ground fault current /Fault duration / Generator damages

Experience has shown that stator ground fault damages:

- are proportional to the dissipated power (kI^2) and,
- depend on the fault duration.

2.1.1 Fault duration

Stator winding ground protection operates in less than 1 second, typically in 500 ms. It trips the main breaker, shuts down the excitation and usually trips the prime mover at the same time.

Although a generator that is connected to the network through a delta-wye step-up transformer will not see any zero sequence current coming from the network into the phase-to-ground fault, the main breaker will be tripped to isolate the generator.

When the field breaker opens the excitation winding circuit, an overvoltage will appear across the rotor winding due to its inductive impedance, and the stored energy must be discharged through the field discharge systems (resistors, crowbar, anti-parallel discharge system, etc…)

As a consequence, an overvoltage will be induced on stator windings by the magnetic field due to the transient current flowing in the rotor winding. The induced stator voltage will sustain the stator-to-ground fault current for a few seconds depending on the time constant of the field discharge system. The field discharge system must be specified to get a fast reduction in field current induction (e') in order to reduce the transient stator-to-ground fault current and to limit machine damage.

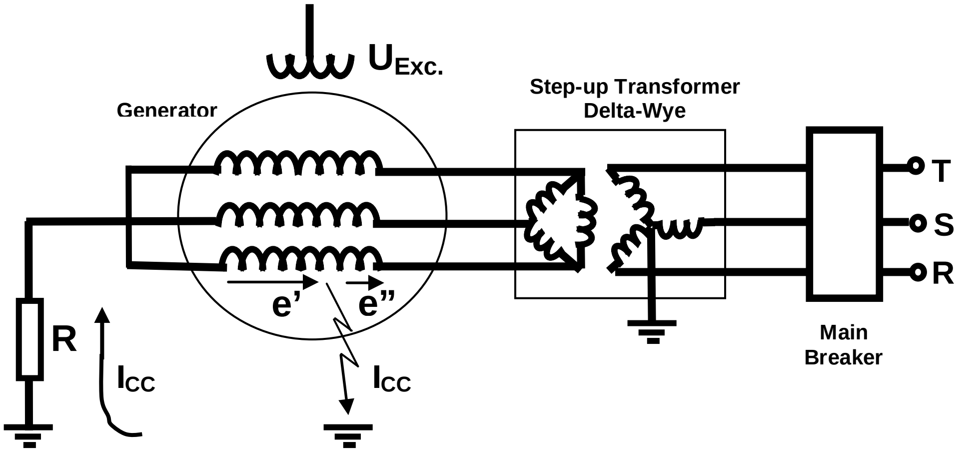


Figure 2 – Stator ground fault

This way, transient of stator-to-ground current will develop for a few seconds, depending on field discharge system design, typically less than 5 seconds.

2.1.2 Current components

During phase-to-ground fault (Figure 3), short circuit current (I_{CC}) will circulate to ground through stator core, returning by two ways:

- Through grounding resistor (I_R).
- Through capacitive insulation of the power system(I_C).

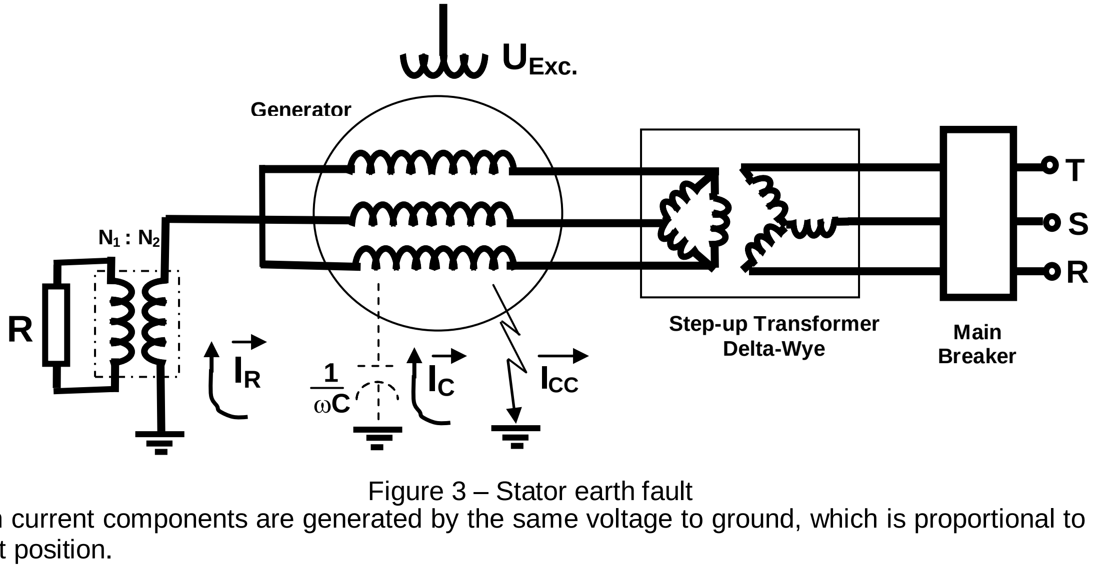


Figure 3 – Stator earth fault

Both current components are generated by the same voltage to ground, which is proportional to the fault point position.

Those resistive and capacitive currents are 90º out of phase. (Figure 4)

Capacitive current is produced for all the capacitances in the generator area such as: stator winding, busbars, connection leads and low voltage transformer winding capacitances. The value of the stator winding insulation capacitance is usually bigger than the rest of these components. But in case of a generator with surge capacitors, the equivalent capacitance value of the system can be evaluated according to the parallel of stator winding capacitance and surge capacitor value, depending on the weight of their magnitudes.

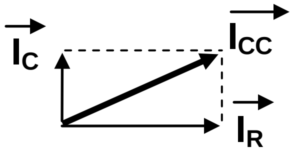


Figure 4 – Short circuit current components

The resistive current magnitude (I_R) depends on the resistor value, and will be controlled in order to decrease total short circuit current (I_{CC}), maintaining phase-to-ground fault current under a limiting value.

In order that intermittent faults do not create an increasing stator voltage it is essential that I_R is larger than I_C. This ensures that any electrostatic charge left on the winding when an intermittent fault extinguishes will decay to zero before the fault re-strikes. This is sometimes known as Petersen's rule [Ref-4 & 5].

2.1.3 Current limits

As seen above, the phase-to-ground fault current flows from the damaged winding to ground through the stator core and returns to the winding through the grounding impedance which must be designed to keep the damage at the non-severe level.

As shown in Figure 1, it is recommend to limit phase-to-ground fault current (I_{CC}) to below 20 A for a non-severe damage level.

2.2 Overvoltage

During a single phase-to-ground fault (Figure 5), phase-to-ground voltages are unbalanced.

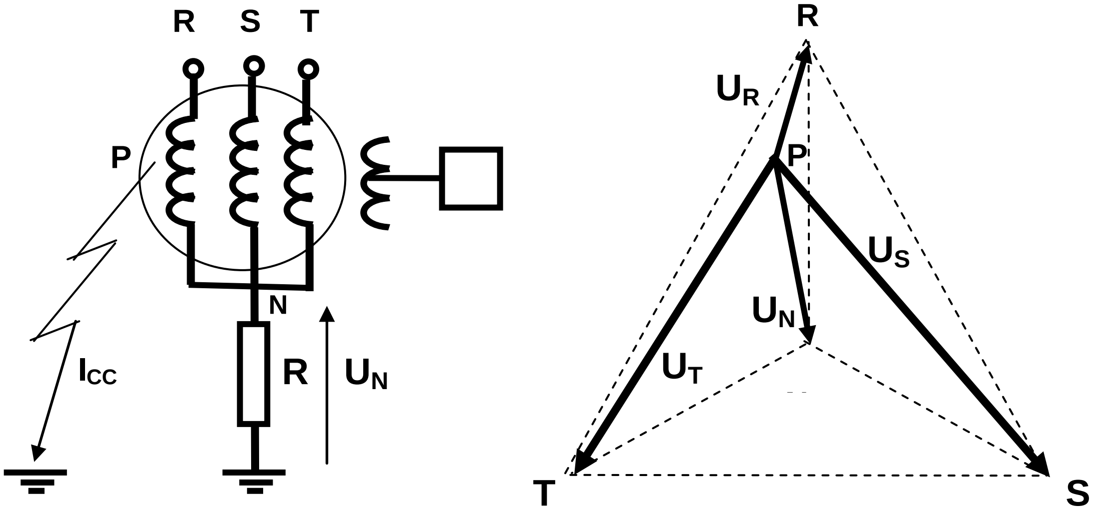


Figure 5 – Unbalanced phase-to-ground voltages during stator earth fault.

Depending on the type of stator winding grounding system, phase-to-ground voltages on phases not affected by the fault could be increased over nominal phase-to-ground nominal voltage. Depending on the position of the fault in the winding (P point, in phase R), voltages on undamaged phases (U_S and U_T)

and neutral voltage (U_N) can be very high. The most severe conditions will occur in case of fault in the winding terminal. (Figure 6)

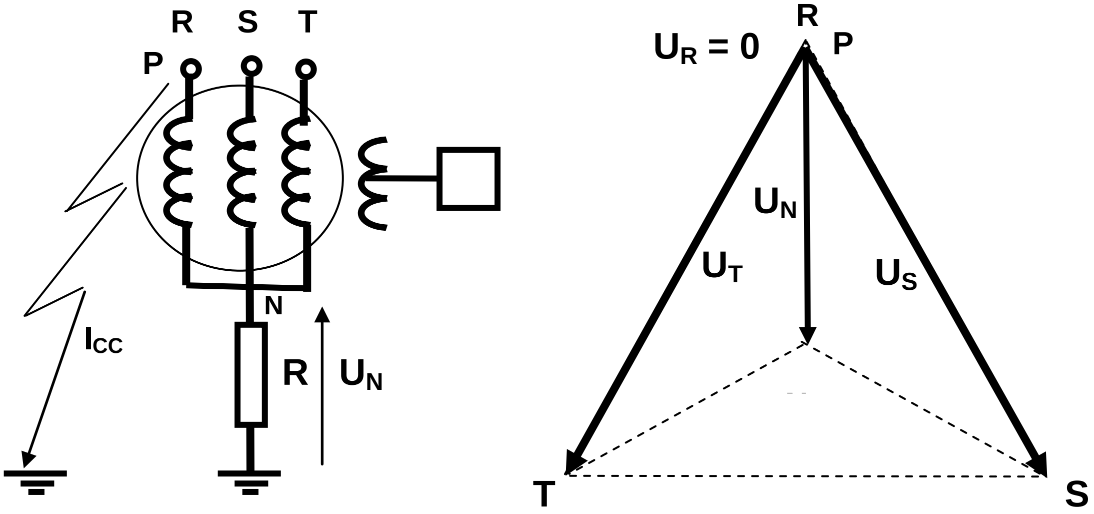


Figure 6 – Phase-to-ground fault on winding terminal.

During a phase-to-ground fault at terminal end of the winding, voltages to ground on undamaged phases (U_S and U_T) reach phase-to-phase voltage level and neutral voltage (U_N) equals phase-to-ground nominal voltage (U_F).

$$U_R = 0$$
$$U_S = U_T = U_{L-L}$$
$$U_N = U_F$$

A phase-to-ground fault usually occurs on a generator when the winding insulation is in poor condition, and the insulation condition is usually similar on all three phases. Thus when a phase-to-ground fault occurs on one phase, the uncontrolled overvoltage on undamaged phases could produce a new fault, creating a double phase-to-ground fault.

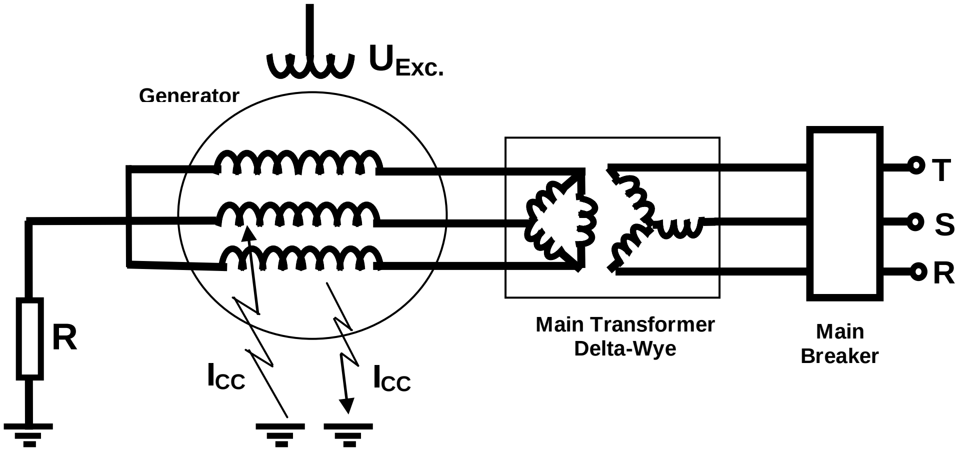


Figure 7 – Stator double phase-to-ground fault

During a double phase-to-ground fault, the fault current is higher than in a single phase-to-ground fault (Figure 7), because it is not limited by the grounding impedance. The damage during a double phase-to-ground fault of this type is much higher than in case of a single phase-to-ground fault.

According to this, stator winding grounding system must be designed in order to avoid uncontrolled voltage increases on phases not affected by fault.

Turbogenerator 336MVA, 15.75 kV, 50Hz

3 STATOR WINDING GROUNDING SYSTEMS

There are four different schemes of generator grounding possible
Normally, the neutrals of modern turbogenerators are grounded through resistors, and depending on the connected system design conditions, the stator winding grounding system will be:

- Direct resistor.
- Neutral grounding transformer with secondary resistor.

It is possible that the neutral point of the turbogenerator is not connected to ground. In that case, the grounding system is installed on generator busbars in two different ways by:

- Grounding Transformer on busbars.
- Neutral grounding on a unit transformer.

In all cases, the stator must be grounded at one point only so that phase-to-ground faults can be detected. The generation voltage area, including stator windings, busbars, low voltage windings of the step-up transformer and high voltage windings of unit transformer, must have only one connection to ground in order to be sure that all the phase-to-ground fault current flows through it. Phase-to-ground fault protection is usually installed on grounding systems. In case of two grounding points, the short circuit could not be detected because the fault current would be divided depending on the values of the grounding resistors and the capacitances of the generator area, as well as, the fault location.

3.1 Direct resistor

This method of stator grounding is to connect a resistor between neutral point and ground. (Figure 8)

As explained in chapter 2, the criteria for the grounding system are:

a) to keep the phase-to-ground current below 20 A,
b) to reduce the overvoltage on undamaged phases.

In the case of a phase-to-ground fault on the winding terminal (Figure 6), the resistor conditions will be:

$$U_N = U_F$$
$$I_{cc} = 20 \text{ A}$$

Most of turbo-generators have a nominal voltage higher than 10 kV, typically around 20kV, and in this case the design voltage of the resistor would be, for instance:

$$U_R = \frac{U_N}{\sqrt{3}} = \frac{20 \text{ kV}}{\sqrt{3}} = 11.5 \text{ kV}$$

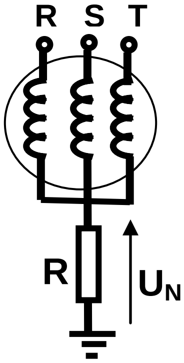


Figure 8 – Generator grounded by a direct resistor.

This level of design voltage requires reinforced resistor insulation thus increasing resistor costs. The impedance value can be several hundred ohms and the cost of a direct grounding resistor is proportional to impedance value.

So, direct grounding resistor is not recommended in case of generators with nominal voltage higher than 10kV.

Advantages:
This earthing method is very simple with low maintenance costs.
In general, as will be explained on chapter 4, stator grounding systems are related to phase-to-ground protections. A direct resistor on the neutral point provides a very easy way of metering the zero sequence voltage, with a very low level of disturbances from the grid.
Using this arrangement, the main stator winding ground protection (64G) can be installed separately from a backup relay on the generator busbars (64B). This allows the main protection to detect phase-to-ground faults with a very short tripping time and the backup protection to be installed on an open delta secondary of a voltage transformer connected to the generator busbars using delayed tripping (see chapter 4). It is an advantage that the two relays monitor for faults at different locations.
Disadvantages:
As explained above, this earthing scheme requires a high value of resistance in order to limit phase-to-ground current to an acceptable value, and such resistors are very expensive. The cost and physical dimensions of the resistor can be reduced by using a neutral grounding transformer as described below.

3.2 Neutral grounding transformer with secondary resistor

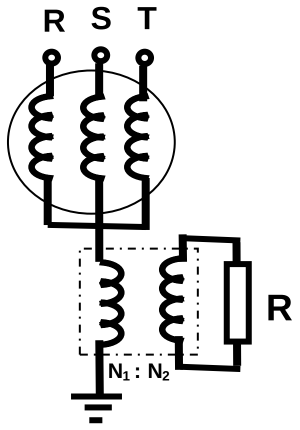


Figure 9
Grounding transformer
with a secondary resistor.

In this case the actual resistor impedance value can be reduced by using a grounding transformer (Figure 9) with a turns ratio of N_1/N_2.

Grounding transformer can be a standard dry single phase transformer with very low maintenance costs.

Resistor primary value will be:

$$R' = (N_1 / N_2)^2 \; R$$

For example, in case of a 20kV / 220 V transformer, and a required primary resistor value of 1000Ω, the actual secondary resistor value will be:

$$R = \frac{R'}{(N_1 / N_2)^2} = \frac{1000\Omega}{(20 / 0{,}22)^2} = 121\text{m}\Omega$$

The resistor impedance value is significantly lower than in the case of a direct resistor, as is the resistor cost.

In addition, the resistor design voltage and cost will be reduced:

$$U_R = \frac{U_N}{\sqrt{3}} = \frac{220\text{ V}}{\sqrt{3}} = 127\text{ V}$$

During a phase-to-ground fault, the primary voltage of the grounding transformer rises very quickly from zero to the zero sequence voltage. In the worst case, the highest voltage between neutral-point and ground will be phase-to-ground nominal voltage (Chapter 2.2).

The stator winding ground protection system monitors the transformer secondary voltage and it is important that the secondary voltage has a linear relationship to the primary voltage otherwise incorrect operation will occur (Chapter 4.1.1).

During the fault process, the neutral voltage increases suddenly from zero, and grounding transformer suffers an inrush-magnetizing transient of a few cycles. In case of a severe phase-to-ground fault, a grounding transformer with a phase-to-ground primary nominal voltage could be saturated during the inrush transient, the primary voltage reaching its nominal value in a few cycles. In this case the secondary winding would have a lower voltage level than the one it should have because of the saturation.

Thus the grounding transformer core must be designed with nominal conditions higher than phase-to-ground primary voltage. A standard primary voltage equal to phase-to-phase generator nominal voltage is recommended. The secondary nominal voltage is usually a standard such as 127 V or 220 V.

According to the standard IEEE C62.92-1989 ("Neutral grounding in electrical utility systems") overloading of neutral grounding transformer is acceptable. For example, in the case of an expected overload lasting 10 seconds, the transformer can be loaded at 10,5 times its nominal power. The stator winding ground protection (Chapter 4.1) will disconnect the generator, tripping the main breaker, with a tripping time lower than 1 second. This way, the nominal power of the grounding transformer could be 10,5 times lower than short circuit power, according to the limitation to 20A.

However in the case of any failure of the protection system or the tripping circuit during the fault disconnection, the grounding transformer will be permanently overloaded. This type of overload on a dry type grounding transformer will lead to severe damage: for example, internal short-circuits or the failure of its winding, thus disconnecting the grounding secondary resistor.
So, it is recommended that the nominal power of the grounding transformer be high enough to avoid transformer overloading.

Turbogenerator: 312 MVA, 17kV, 50Hz
Neutral grounding transformer: 12kV/240V, 25kVA, 50Hz, 10kA-1seg, 400A-1min.
Secondary grounding resistor: 525 mOhm, 400 A-1 min.

Advantages:
This grounding method is very simple with very low maintenance costs.
This method provides an easy way of metering the zero sequence voltage, with a very low level of disturbances from the grid.
Using this arrangement, the main stator winding ground protection (64G) can be installed separately from a backup relay on the generator busbars (64B). This allows the main protection to detect phase-to-ground faults with a very short tripping time and the backup protection to be installed on an open delta secondary of a voltage transformer connected to the generator busbars using delayed tripping (see chapter 4). It is an advantage that the two relays monitor for faults at different locations.
The dimensions of a secondary resistor are lower when used with a neutral grounding transformer than when fitted directly, because of the lower level of voltage on the resistor.

Disadvantages:
This earthing scheme is more expensive than using a direct resistor due to the extra cost of a neutral grounding transformer with a standard primary voltage equal to phase-to-phase generator nominal voltage.

3.3 Grounding transformer on busbars

This grounding scheme is based on a transformer connected on busbars with a resistor on its open delta secondary winding (Figure10).

The resistor is used as a load for limitation of the phase-to-ground fault current in the generation voltage area. The transformer turns ratio provides a primary resistor value that only will be on load in case of fault.

Because of the secondary open delta connection, the secondary resistor sees the summation of the three phase voltages. This summation is the zero sequence voltage, and its value is zero under normal conditions.

During a phase-to-ground fault, the induced voltage increases to a value determined by the transformer ratio, and the resistor is under voltage limiting the primary short circuit current.

This grounding system can be found in the case of small ungrounded generators but it is not recommended for large turbo-generators.

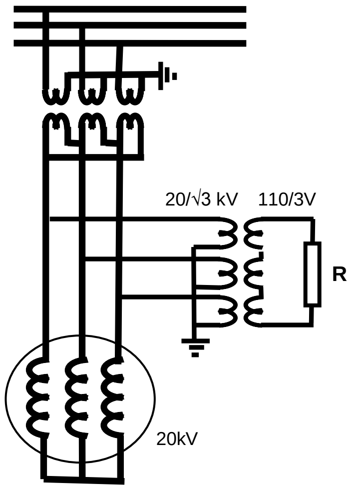


Figure 10 – Grounding transformer on busbars.

The advantages of this grounding system are that it can be used in case of generators without accessibility to the neutral point of the winding, and because it eliminates third harmonic current in the delta winding. But in case of turbo-generators, the neutral is normally accessible and the third harmonic level is normally very low because of the design of the machine.

Also, this grounding system is more expensive than the scheme with a neutral grounding transformer with secondary resistor, because this scheme needs a three phase power transformer and the neutral grounding scheme only requires a single-phase transformer.

Advantages:
This scheme provides a method of grounding generators where the neutral point of the stator winding is not accessible.
With this configuration any fault on the busbars is also monitored.

Disadvantages:
The cost of this earthing scheme with a three phase grounding transformer on the busbars with a secondary resistor, is higher than the configurations mentioned before.
This method is sensitive to grid disturbances affecting the zero sequence voltage being monitored. In order to avoid inadvertent tripping, the tripping time must be longer than when the protection is installed on the generator neutral point.
It is always recommended that both main and back-up phase-to-ground fault protection schemes are used, and that the relays monitor for faults at different locations.

3.4 Neutral grounding on a unit transformer

This scheme is based on a grounding resistor installed on the neutral point of a unit transformer connected to the busbars (Figure 11). The neutral point of the unit transformer can be grounded by a direct resistor or using a secondary resistor on a grounding transformer.
This is not a very common scheme for grounding turbogenerators, but can be found in some power plants around the world.

Advantages:
This scheme provides a way of grounding in case of generators where the neutral point of the winding is not accessible. This grounding scheme does not use a specific grounding transformer. The grounding resistor is installed in the neutral connection of an existing unit transformer. The cost of the scheme is very low.

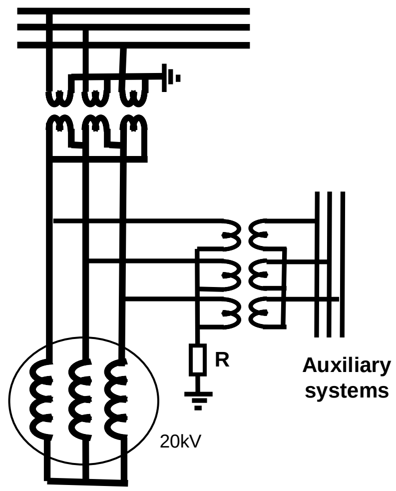


Figure 11 – Grounding on a unit transformer

Disadvantages:
As in the previous scheme, this method is sensitive to grid disturbances affecting the zero sequence voltage being monitored. In order to avoid inadvertent tripping, the tripping time must be longer than when the protection is installed on the generator neutral point.

4 PHASE-TO-GROUND FAULT PROTECTION

Phase-to-ground faults must be detected in any part of the generation voltage area, including stator windings and generator bus.

It is recommended to install a main and a back-up protection that detect the fault in a different way, metering fault conditions in a different point of the generator voltage area, in order to ensure the fault detection.

Figure 12 shows a typical phase-to-ground protection scheme of a large generator, with:

- Stator winding ground protection (64G), as the main protection relay,
- Generator bus protection (64B), as a backup protection relay.

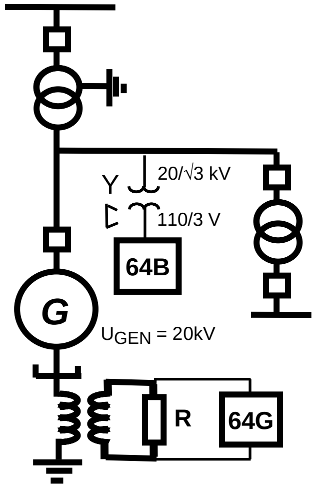


Figure 12
Scheme of stator winding ground protection

Protections on generator phases are much more influenced by voltage unbalances and inductions coming from the network.
So it is recommended to install a main protection on the neutral point of the generator, in order to avoid un-adverted trips, and a back-up delayed relay on busbars.

4.1 Stator Winding Ground Protection

Stator phase-to-ground protection schemes are designed and set according to the stator grounding system.

As previously mentioned in Chapter 3, turbogenerator stator grounding systems incorporates resistors between the neutral point and ground, using a direct resistor or a resistor connected through a grounding transformer.

The chosen ground protection scheme will be based on the detection of the current in the resistor or the zero sequence voltage between the neutral-point to ground.

There are two main types of generator stator winding ground fault protection. One covering only 95% of the winding down from the line terminal (see 4.1.1) and the other one, covering 100% of the winding (see 4.1.2).

4.1.1 Stator winding ground 64G-(95%) Relay

a) <u>Neutral-to-ground overvoltage relays</u>:

As seen in chapter 2.2, when a single stator ground fault occurs, the neutral-to-ground voltage (U_N) increases from zero to a maximum of nominal phase-to-ground voltage (U_F).

One way of detecting phase-to-ground faults is to monitor the voltage between the neutral-point and ground and the precise configuration of the protection will depend on the grounding scheme.

1) With a direct resistor (Figure 13), stator ground protection 64G must be connected to a voltage transformer monitoring the voltage across the resistor.

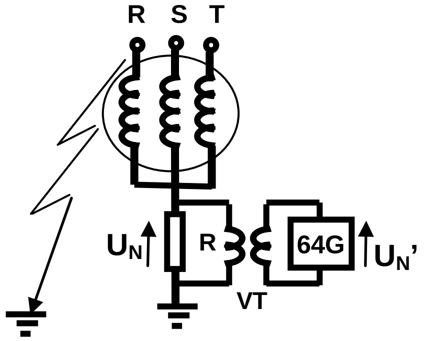


Figure 13
Stator Ground Overvoltage Relay
Direct Resistor

The nominal primary nominal voltage of this VT should be equal to the phase-to-phase generator nominal voltage, because of inrush transient during phase-to-ground fault, as it was explained in chapter 3.2.

Secondary nominal voltage of the VT is usually a standard such as 127 V or 220 V.

2) In the case of a grounding system with a grounding transformer and a secondary resistor (Figure 14), the ground protection (64G) monitors the voltage between resistor terminals, but at the lower voltage of the secondary winding.

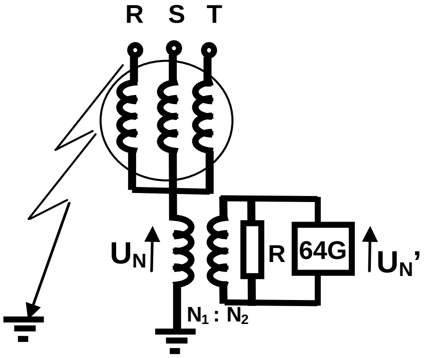


Figure 14
Stator Ground Overvoltage Relay
Grounding transformer & Resistor

As previously explained in chapter 3.2, the transformer will be phase-to-phase nominal voltage on primary winding, and 120 V or 220 V on the secondary.

In both cases, the voltages on the relays are directly proportional to neutral-to-ground voltage according to the transformer ratio (U_N').

As seen in chapter 2.2, the voltage between the winding neutral and ground (U_N) will depend on the position of the fault in the stator winding, the most severe condition occurring when the fault is at the winding terminal. In that case, U_N will be equal to the phase-to ground voltage.

When the fault occurs in the middle of one phase of the stator winding, at the 50% of the winding, voltage induced between the neutral-point and ground will be a half of a phase-to ground nominal voltage. In the limiting case with a fault at 99% of a phase stator winding, at only 1% from neutral point, the voltage at the neutral point will be only 1% of the phase-to ground voltage.

In this way, the lower the trip setting of the overvoltage relay 64G is, the bigger is the protected area from the winding terminal to the neutral point.

However, it is not recommended to set this overvoltage function too low because any neutral-point to ground voltage transient of a few volts could produce an inadvertent protection trip for several different reasons:

- induced voltages,
- minor unbalance in the stator winding,
- phase-to-ground short circuit currents on the grid system, through capacitive coupling between the windings of the step-up transformer,

A 5% of the phase-to-ground voltage (U_F') is the lowest trip setting recommended. In this way, 95% of the stator winding from terminals will be protected.

Tripping time must be less than 1 second, typically in a value of 500 ms; tripping the main breaker, disconnecting the field and tripping the prime mover at the same time.

b) <u>Stator-to-ground overcurrent relays</u>:

As seen in chapter 2.1, short circuit current flows through grounding resistor to ground during a phase-to-ground fault and this current is limited to 20 A by the resistor.
In this cases, the stator winding ground protection (64G) must be connected to a current transformer with a standard ratio (i.e. 100/5 or 200/5).

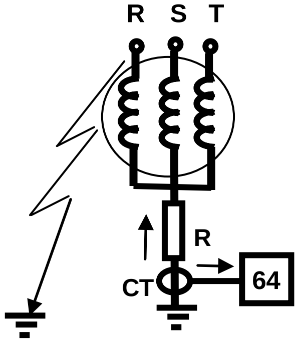


Figure 15
Stator Ground Overcurrent Relay

A trip setting in the range of 20% to 40% of the limited fault current of 20A is recommended. Sometimes this is a fixed setting in the relay.
As previously mentioned, it is not recommended to use a too low setting because any inducted current or any transient could produce an inadvertent trip of the relay.

Trip time must be also less than 1 second, typically 500 ms.

4.1.2 Stator winding ground 64G-(100%) Relay

The ground fault 64G-(95%) scheme described in chapter 4.1.1, will detect a phase-to-ground fault in the major part of the generator winding, up to 95% of the stator winding from terminals. If a phase-to-ground fault occurs in the 5% of phase stator winding from neutral point, the neutral-to-ground voltage (U_N) will be lower than trip setting of the 64G-(95%) protection, and the fault will not be tripped.

Under this condition the phase-to-ground voltages on the undamaged phases will be only slightly increased, and fault current will be very low. Experience shows that any core damage is likely to be acceptable. However, the continued operation of the turbogenerator under unbalanced phase-to-ground voltages can produce permanent unwanted effects such as unbalanced stator currents, increased vibrations, and a slight increase of voltage in the un-damaged phases.

Thus if it is required to detect faults located at any position in the winding a 100% protection scheme is required. There are two different types of 100% stator winding protection available:

a) Third harmonic stator ground fault protection:

The third harmonic voltage is present in each of the three windings of the generator due to the non-linearity's in the magnetic circuits of the generator design. Theoretically, the third harmonic voltage is produced by the capacitive coupling of the generator windings to earth (Figure 16), and in general, under normal operation conditions, third harmonic voltage will change in magnitude according to the load of the generator and depending on MW and MVAR conditions.

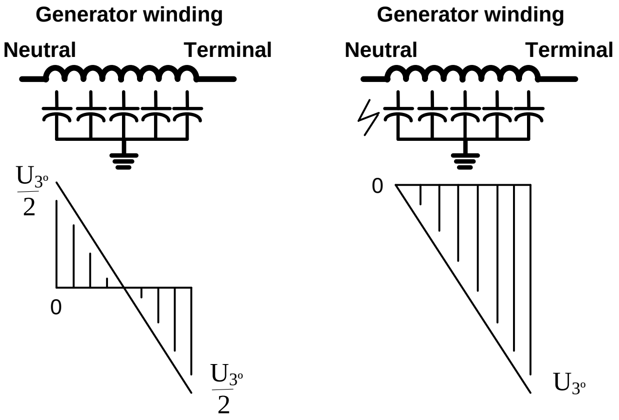


Figure 16 – Third harmonic voltage behaviour.

In case of phase-to-ground fault, the third harmonic voltage at the neutral point decreases, and this effect can be detected by a third harmonic undervoltage relay (Figure 16).

This stator ground fault protection has a connection scheme similar to Figure 14, but with a third harmonic filtered relay which trips in case of third harmonic voltage decreases below a predetermined level. Before using this protection scheme, it must be checked that third harmonic voltage level in the generator under any operation conditions is large enough to exceed a minimum trip level.

As third harmonic voltage reduction occurs between the neutral point and the ground during a fault near to the neutral point, this relay helps to protect the 100% of the stator windings. This protection should be an additional relay to the conventional stator earth fault 64G (95%) protection.

The third harmonic voltage tripping level must be adjusted according to the manufacturer's design criteria and depends on the third harmonic voltage level measured between the neutral point and ground. This option can sometimes provide practical difficulties in setting this protection.

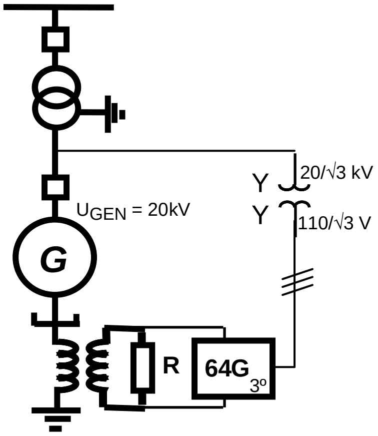


Figure 17
Differential third harmonic voltage relay

Sometimes third harmonic voltage variations can lead to false operation of the protection and for that purpose a compensation scheme is recommended.
This compensation can be done in two different ways: by measurement of the load current or by comparing the third harmonic voltage at the two ends of the winding.
In case of compensation by the load current, the protective function is only in operation with load on the generator, that is the reason why the comparison of a third harmonic voltage is recommended for large generators.

A comparator system is based on a measurement of the differential third harmonic voltage between neutral point and terminal voltages (Figure 17).

For any case of third harmonic stator ground protection, tripping time must be less than 1 second, typically 500 ms.

b) <u>Stator ground fault protection with a pulse voltage injection</u>:

This protection is based on the injection of a pulse voltage wave into the generator winding. The voltage has a sub-harmonic frequency of 12.5. Hz or 20Hz

Voltage injection is done in a part of the grounding resistor (R_1) by an independent source of frequency. (Figure 18) The injected pulse voltage produces a pulse waveform current from windings to ground through insulation, and returns through the grounding resistor. The relay works by monitoring the voltage induced in the rest of the grounding resistor (R_2)

In normal operation conditions, the pulse current ratio is related to insulation conditions. In case of phase-to-ground fault, the pulse current increases rapidly through the fault and the protection trips.

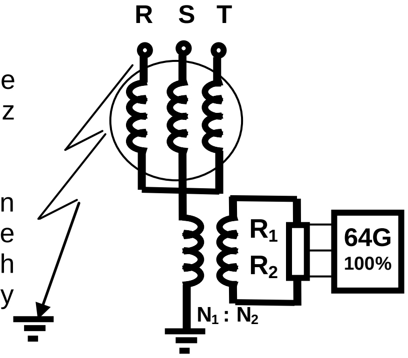


Figure 18
Stator Ground Fault
64G-(100%) Relay
with a pulse voltage injection

Stator ground fault protection with a pulse voltage injection continuously monitors both the stator and bus insulation. As voltage injection is done by an independent source included in the relay, phase-to- ground faults can be detected without the generator being excited, for example during stand-by or start-up operations. This system operates with the same sensitivity for a fault at any point in the winding, providing 100% ground fault protection.

Trip adjustment is usually expressed in ohms, and trip time must be less than 1 second, typically in a value of 500 ms, too.

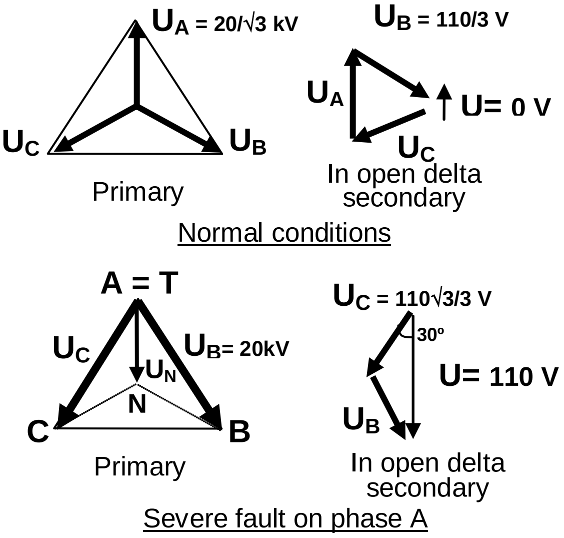
4.2 Generator bus ground protection

Generator bus ground protection is a back up relay against phase-to-ground fault in generator voltage area, including stator winding and generator bus.

This protection meters the induced voltage in the open delta secondary of a voltage transformer connected to the generator bus.

Considering the example of the generator on figure 8, the voltage monitored by the protection is the summation of the three phase voltages. This summation is the zero sequence voltage, and its value is zero in normal conditions (Figure 19).

In case of a phase-to-ground fault, the induced voltage increases to a value determined by the transformer ratio. Generator bus ground protection is an overvoltage relay, and the recommended trip setting is 5% of the phase-to-ground nominal voltage. The operation time must be coordinated with stator ground fault relay, with a value in the range of 1 to 2 seconds.



<u>Normal conditions</u>

<u>Severe fault on phase A</u>

Figure 19- Bus ground protection.Voltages.

5 CALCULATION OF STATOR WINDING GROUNDING

As seen in chapter 2, the grounding resistor must be designed in order to:

- Reduce phase-to-ground fault current
- Control the overvoltage on undamaged phases

5.1 Current criteria

As mentioned in chapter 2, the phase-to-ground fault current (I_{CC}) will flow to ground through the stator core, returning through the grounding resistor (I_R), and the winding earth capacitance (I_C). (Figure 3)

Also, as explained in Chapter 2.1.2, it is essential that I_R exceeds I_C to comply with Petersen's Rule, ensuring that any electrostatic charge left on stator windings when an intermittent fault extinguishes is reduced to zero before the next fault conditions.

The fault current flowing through resistor must be higher than a minimum value, in order to be detected by stator ground fault protection. As previously explained on chapter 4, this kind of relay usually detects the fault by an overcurrent function installed between neutral point and ground in the secondary of a current transformer, or by an overvoltage relay metering voltage on the grounding resistor. A short circuit current I_{CC} higher than 5 A standard current is recommended to ensure that the fault is detected properly.

Depending on resistor value, resistive current I_R must be reduced in order to decrease total short circuit current I_{CC}, maintaining phase-to-ground fault current under 20 A. Taking into consideration that the tripping time of the stator earth fault protection can be as high as 1 second, considering the opening time of the main breaker and depending on the constant time of the field discharge system, it is recommended to reduce the maximum current limit to under 10 A where possible but certainly under 15 A.

Thus the grounding resistor has to be designed in order to keep phase-to-ground fault current in the range of:

$$I_{CC} \in (5,10) \text{ A}$$

5.2 Impedance criteria

The current criteria given above and Petersen's Rule can be complied with by the following impedance criteria.

It is recommended that:

$$\boxed{R \leq \frac{1}{3\,\omega C}}$$

R: Direct resistor between neutral-point to ground.
C: Phase-to-ground insulation winding capacitance.

It may be necessary to obtain the capacitance value by measurement between a phase to ground. If so, any additional capacitive items as listed in Section 2.1.2 must be included.

In case of a grounding transformer with secondary resistor, the resistor primary value will be:

$$R' = (N_1 / N_2)^2 \; R$$

thus:

$$\boxed{R \leq \frac{1}{3\,\omega (N_1 / N_2)^2 \, C}}$$

R: Grounding resistor in grounding transformer secondary.
N_1 / N_2 : Grounding transformer relation
C: Phase-to-ground insulation winding capacitance.

6 REFERENCES

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EPRI EL-5036 Volume 8, in particular pages 8-19 through 8-22 that deal with the same subject.

[Ref-1] This guide includes comments from: Australia, Brasil, Israel, Poland, Spain, Sweden, South Africa, United Kingdom and United States of America.

[Ref-2]: “Lecture Notes of Generator Protection Relay Course” BBC-March 1975.

[Ref-3]:CIGRE WG34.05 “Guide for the protection of synchronous generators”. Chapter IV 3.1.b. 1996.

[Ref-4]: “Suppression of Arcing Grounds through Neutral Resistors and Lightning Arrestors” W Petersen. Published on E.T.Z. 39 (1918).

[Ref-5]: ““Neutral Grounding in High Voltage Transmission Systems” by R Willheim and M Waters. Elsevier Publishing Company. 1956.

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