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Neutral Grounding of Generators in Utilities and Industrial Plants

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1.0 Impact of internal fault in alternator

The primary purpose of introducing resistor in generator neutral is to limit the magnitude of ground fault current that can flow in case of fault in slot region. This is to minimize the local core damage. In modern generators made by reputed companies, epoxy insulated stator winding insulation never fails by itself. Even under overload conditions, and at elevated temperatures within Class F limits, epoxy–mica insulation often exhibits higher electrical strength than at lower temperatures.

In practice, stator insulation failures are generally attributable to one or more of the following causes:

- Progressive wear of insulation due to excessive winding vibrations and consequent rubbing amongst each other or against supporting structure components in overhang region.
- Overheating of stator core due to poor core lamination insulation.
- Damage to stator winding insulation due to vibrations of protruding core laminations inside slots, say in end packet zone or near radial ventilation ducts.
- Insulation failure at stator winding exit from core due to poor semiconducting layer, and consequent damage due to corona discharges, winding bar looseness in slot accompanied with vibrations.

These issues are far more relevant in large generators, typically above 100 MW. In smaller machines—say below 20 MW—such failures are uncommon in well-designed and properly maintained units from reputable manufacturers, with the exception of damage caused by core overheating.

Core overheating or mechanical damage due to protruding, broken, or loose laminations generally affects only the upper layer of the winding and, in rare cases, may lead to a phase-to-ground fault. The core damage curves provided by manufacturers primarily address this scenario. *Also, it must be emphasized that the core damage curves, in most of the cases, supplied by vendor are more generic in nature and not for a specific machine under consideration.*

Also, from above observations, L-L-G fault within a slot is a very remote possibility and can be ignored.

2.0 Neutral grounding of large generators

For utility size generators (typically above 100MW), high resistance grounding is chosen to limit the ground fault current within 10 to 15A. This is possible in this case, as there is complete ground fault or zero sequence isolation between generator terminal and neighboring equipment. Refer Fig 1. Generator is connected to external system through Generator Transformer (GT). The vector group of GT is Delta – Star with Delta towards generator side. Auxiliary power is drawn through Unit Auxiliary Transformers (UAT). The vector group of UAT is also Delta -Star with Delta towards generator side.

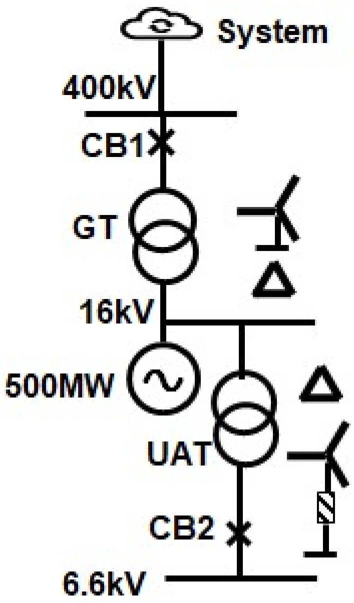

Figure 1

In this case. it is possible to use high resistance in generator neutral to limit ground fault within say 10A. There is no need to coordinate ground fault relays on alternator with external system as there is complete zero sequence isolation from rest of the system due to presence of Delta windings on GT and UAT. System contribution for ground fault in generator is practically nil.

The only significant capacitances are generator winding capacitance and surge capacitance connected at generator terminals. Also, there is insignificant resistance between generator and GT / UAT which are connected by bus ducts of negligible resistance. In this scenario, high resistance provided in generator neutral comes into play only for faults within generator. This is primarilly to provide damping so that sustained arcing faults do not occur.

For ground fault within generator, fault isolation is *not done at Generator end* but by breaker at EHV level (CB1 in Fig 1). Transient Recovery Voltage (TRV) of EHV circuit breaker is not relevant as the fault is electrically away due to presence of GT. Generator circuit breakers (GCBs) are used only in a limited number of installations and are therefore not discussed here

Beyond limiting core damage, the key objective of neutral grounding in this case is to minimize arcing during ground faults by introducing resistance in the presence of winding and surge capacitances. The resistance value is selected such that the resistive current is approximately equal to the capacitive charging current. Refer Fig 2.

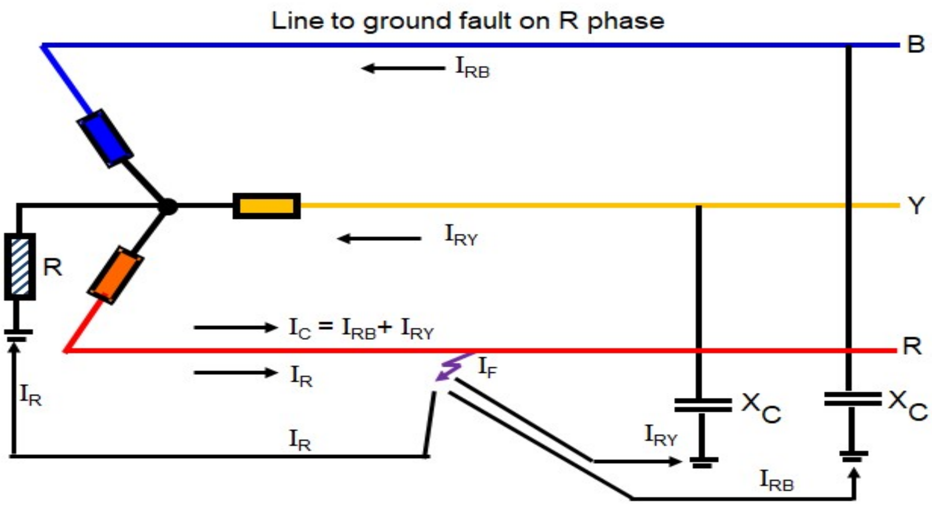

Figure 2

A common question is whether introducing resistance increases the fault current at the point of fault. For example, consider $I_R = I_C = 10A$. At the point of fault, fault current $I_F = \mathrm{Sqrt}\,(I_C^2 + I_R^2) \approx 14A$. Though magnitude of I_F is greater than I_C, power factor of I_F is 0.7, whilst that of I_C is 0. It implies during arcing faults when current is interrupted at natural zero, the voltage is maximum when breaking I_C, while it is less (70%) when breaking I_F. Refer Fig 3. Since voltage available in the ionization path is less, there is less chance of restrike in resistance grounded system.

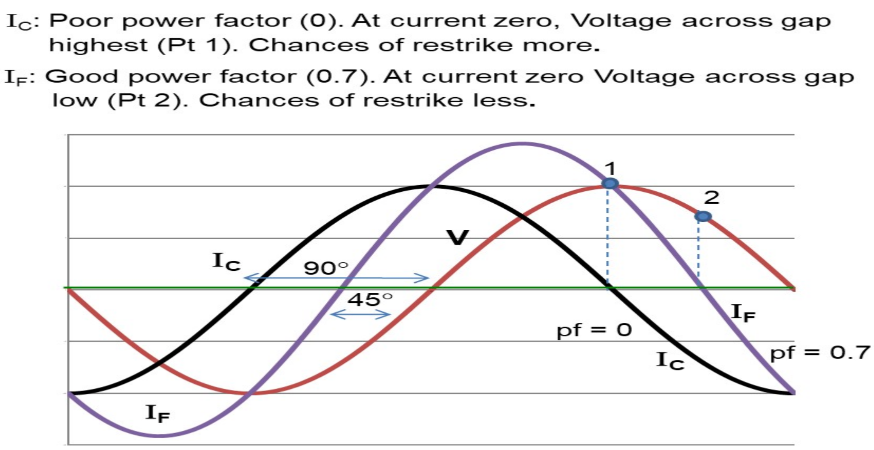

Figure 3

Typical values of capacitances for a 600MW, 20kV generator are given below:

- Generator Capacitance, C_G = 0.213μF
- Iso phaseduct Capacitance, C_{IPB} = 0.01048μF
- Generator Transformer Capacitance, C_{GT} = 0.012μF
- Unit Transformer Capacitance, C_{UT} = 0.027μF
- Surge Capacitance, C_S = 0.125μF
- System Capacitance = C = $C_G + C_{IPB} + C_{GT} + C_{UT} + C_S$ = 0.38748 μF/phase

It can be seen that generator winding capacitance and surge capacitance are the dominant factors. In fact, surge capacitance value can be as high as 0.25μF in many cases. Hence, inaccuracies in the value of bus duct or transformer winding capacitances are not of serious concern. Winding capacitance (C_G) data is usually given in data sheet of generator manufacturer. Default value of Surge capacitance value can be assumed as 0.25μF. Rest of capacitances can be ignored, if no data is available, as their influence on final value of NGR chosen is insignificant.

Continuing further the calculations,

Capacitive Reactance / Phase $X_{CG} = 1 / (2 \pi f C)$ = 8214.8Ω

Phase Voltage $V_P = 20 / \sqrt{3}$ = 11.54kV

Capacitive Charging Current $I_C = 3V_P / X_{CG}$ = 3 x 11540 / 8214.8 = 4.21A

The loading resistor (R'_L) is selected so that the resistive current is slightly greater than capacitive current. It is ensured by using a safety factor of say 1.1.

The resistive current , I_R = 1.1 x I_C = 1.1 x 4.21 = 4.63A

Required value of resistance, $R'_L = V_P / I_R$ = 11540 / 4.63 = 2489Ω.

In high resistance grounding, it is very uneconomical to design resistance of such high value like 2 to 5kΩ at MV levels like 6.6kV or 11kV. The standard practice is to use step down Neutral Grounding Transformer (NGT) and connect a very small resistance (<1Ω) to obtain the same effect. When a ground fault occurs in high resistance grounded system, which is almost like ugrounded system, the Neutral rises to phase voltage. Hence the primary voltage of NGT conneted between neutral and ground is chosen above phase voltage. The secondary voltage of NGT is usually selected as 240V. Choose NGT voltage ratio as 15 / 0.24kV. Refer Fig 4.

Turns Ratio TR = 15 / 0.24 = 62.5

Loading resistance, $R_L = R'_L / TR^2 = 2489 / 62.5^2 = 0.64\Omega$

The voltage ratio of NGT should be selected in such a way that the resulting value of loading resistor R_L is not too small. It is recommended that the loading resistor should preferably be greater than 0.5Ω, to ensure proper operation of 100% stator earth fault protection with 20Hz voltage injection method. In this case, R_L is above 0.5Ω. If the surge capacitance value C_S is 0.25μF instead of 0.125μF, repeating the above calculations, the value of R_L is 0.48Ω. If the primary voltage of NGT is chosen as 14kV instead of 15kV (14 / 024kV), the value of R_L is 0.55Ω, which is above minimum desired value of 0.5Ω.

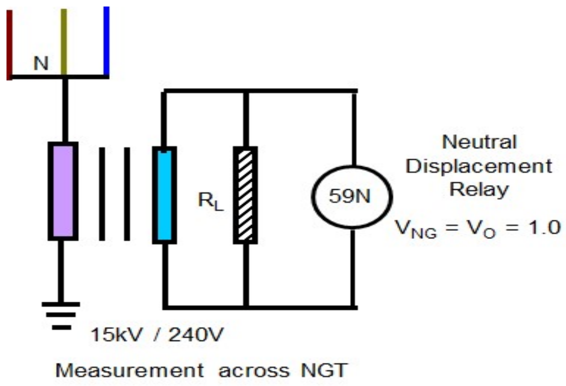

Figure 4

2.1 95% Stator earth fault protection

The handle to detect ground fault within generator is only voltage (95% stator Earth Fault detection) and not current as its magnitude is too small to sense. The principle of operation is that during an earth fault, the voltage of the faulted phase reduces to zero, while the voltage between neutral and ground rises to phase voltage.

The displacement voltage is measured across the neutral grounding transformer as shown in Fig 4. In some schemes, it is measured across open delta PT at generator terminals. In both cases the displacement voltage detected by the protection relay (59N) is of fundamental frequency (50Hz).

A challenge arises in arcing faults either within slot portion or at generator bushing terminals, where the sensing voltage may intermittently exceed the relay pickup level but not persist long enough to satisfy the time delay requirement. This can lead to repeated pickup and dropout without a trip, allowing the fault to persist and cause severe damage. Refer Fig 5.

To overcome the above, modern numerical relays provide an elegant solution with 'Timer Hold Facility' option. With the proper reset timer setting, it is possible to 'accumulate' the voltage excursion times and issue the trip command after the cumulative time has elapsed. For example, if ($T_1 + T_2 + T_3 + T_4 + T_5$) > T_{SET}, the relay issues trip command. Typical setting of T_{SET} is 0.3 to 0.5 second.

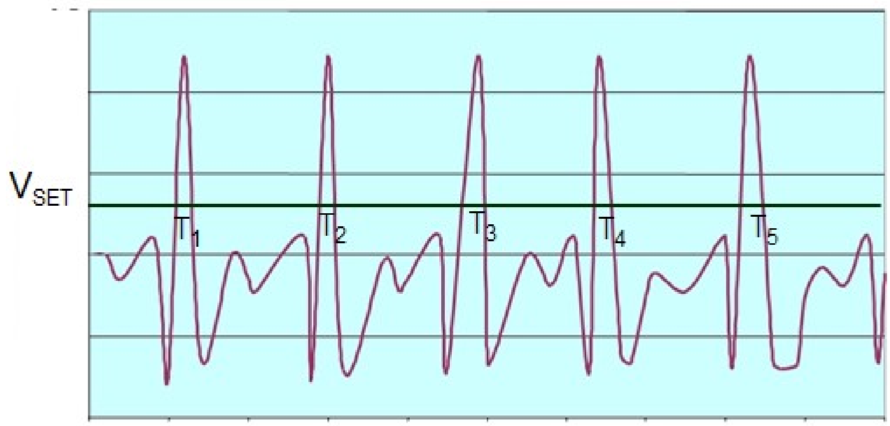

Figure 5

3.0 Neutral grounding of small generators

Generating units in industrial plants, refineries, oil platforms, etc., are typically in the range of 2 to 20 MW rated at 3.3 / 6.6kV / 11kV. Here, the generators are directly connected to external system. There is no transformer between generator and rest of the system (as in the case of utility generators) to provide ground fault or zero sequence isolation between generator and rest of the system.

Limiting ground fault current to a low value is not practical, as ground fault relays on generators *need to be coordinated* with ground fault relays in upstream feeders (CB1 with CB2 and CB3). Current sensing itself will be an issue if ground fault current is too low. Refer Fig 6.

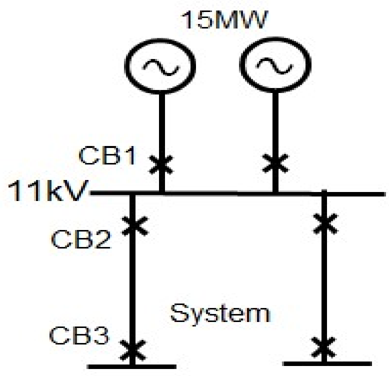

Figure 6

For these reasons, practice is evolved to limit ground fault to typically 100A, a reasonable compromise between limiting core damage and selective ground fault isolation. It is also in line with general criteria specified in Sec 1.2.8 of IEEE Std 142 – 2007 for "Grounding for Industrial and Commercial Power Systems" - 'Low Resistance grounded system: A resistance-grounded system that permits a higher ground-fault current to flow to obtain sufficient current for selective relay operation. Usually meets the criteria of R_0 / X_0 less than or equal to 2. Ground-fault current is typically between 100 A and 1000 A'.

Connected capacitance is not of relevance here as each generator has its *own circuit breaker at its terminal.* Current based protection can be applied as sensing current is relatively high (100A) compared to high resistance grounded system (< 10A).

If any internal ground fault within a slot is cleared within 100 to 150 msec, achievable in modern protection schemes with numerical relays, generator core damage is not significant. Usually, every alternator is provided with Restricted Earth Fault (REF) protection scheme to isolate earth fault within, say 100 msec. Since REF is unit protection, it does not need coordination with upstream relays. Sometimes, to provide a backup to REF, directional ground overcurrent relay (67N) is provided on generator feeder (CB1 in Fig 6) looking towards generator from 11kV bus. But this is not widely used considering robustness of well proven REF scheme. Of course, the ultimate back up is provided by Standby Earth Fault Relay (51SN) provided on generator neutral.

In resistance grounded system, to improve sensitivity of ground fault detection, NCT (Neutral CT) ratio is selected as per the magnitude ground fault current. If ground fault current is limited to 100A, NCT ratio can be selected as, say, 50/1. If the phase CT ratio is, say 500/1, then REF (64) relay is connected to 0.1:1 ICT (Interposing Current Transformer) as shown in Fig 7.

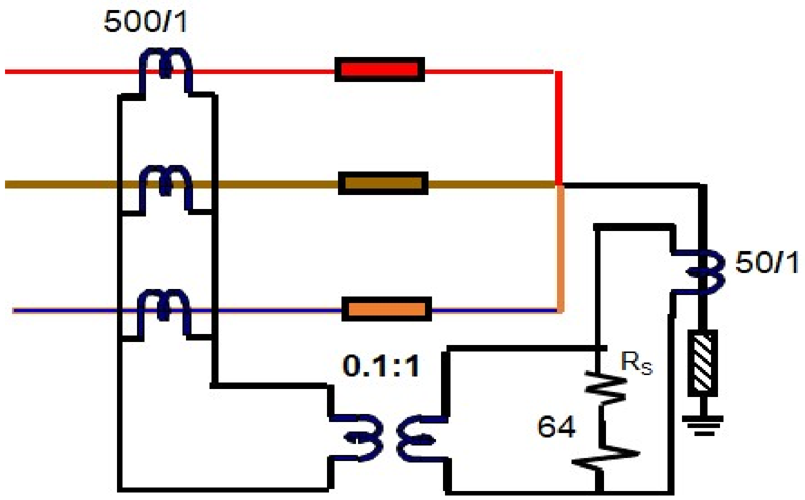

Figure 7

Some manufacturers provide CBCT on line side to obtain residual or ground fault current ($I_R + I_Y + I_B$), as shown in Fig 8.

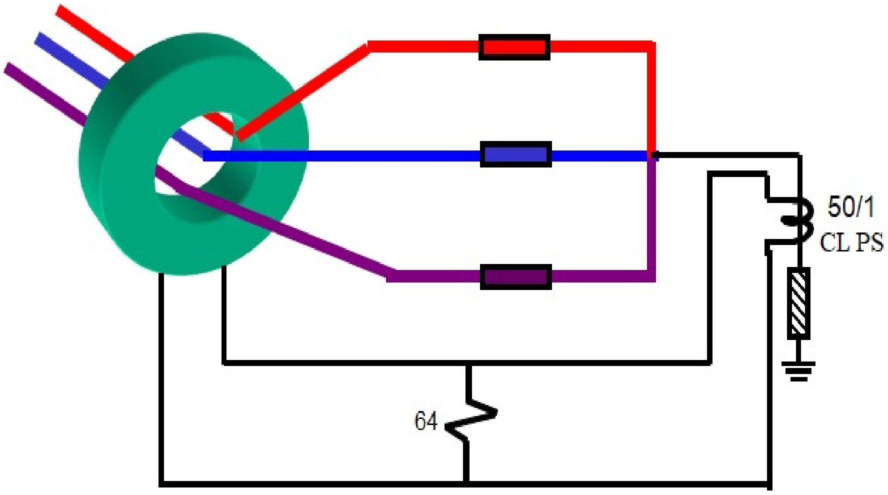

Figure 8

The above schemes fall under High Impedance REF schemes. In modern numerical relays, Low Impedance REF option is *also* available, where the NCT ratio can be equal to phase CT ratio or can be much smaller. ICT is software implemented. Relay configuration, pick up and bias setting for low impedance scheme shall be done with extreme care.

2.1 REF response for external and internal fault

Consider three generators operating in parallel. Typical current distribution for external fault F_1 is shown in Fig 9. Ground fault current is 300A with each generator contributing 100A. REF (64) will not pick up as the current through operating coil is (theoretically) zero, thus ensuring stability of the scheme.

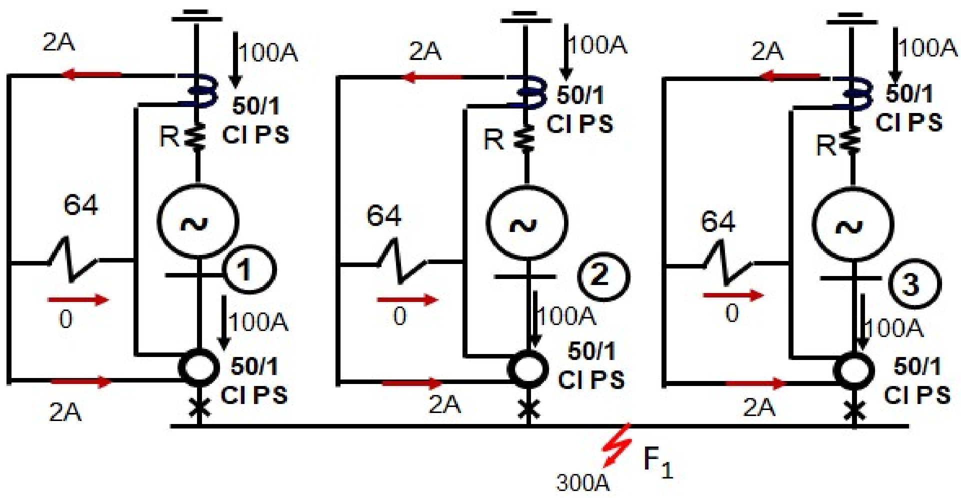

Figure 9

The current distribution for internal fault F2 is shown in Fig 10. On the faulted unit 1, substantial current flows through 64 leading to tripping of this unit. This ensures sensitivity and selectivity. On the other units, current through 64 is nearly zero ensuring stability.

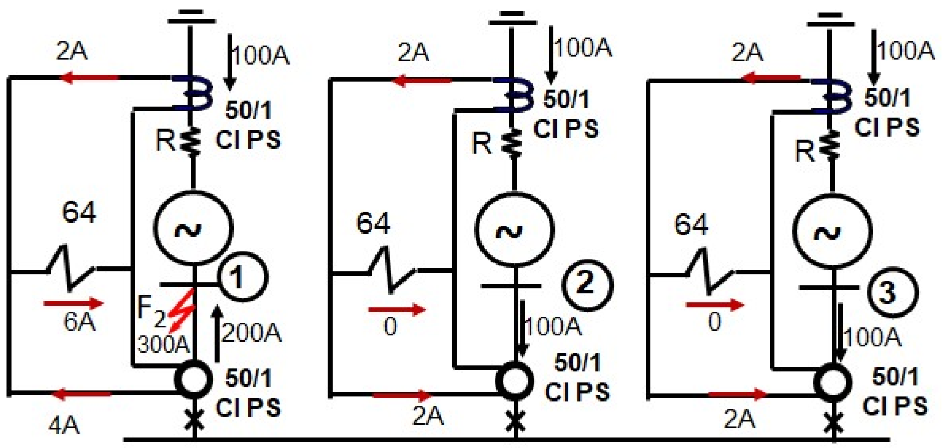

Figure 10

3.1 Impact of winding pitch of alternator for parallel operation.

A coil whose sides are separated by one pole pitch (i.e., coil span of 180º electrical) is called a full-pitch coil. With a full-pitch coil, the emfs induced in the two coil sides are exactly in phase with each other and the resultant emf is the arithmetic sum of individual emfs. One minor disadvantage of full-pitch coil is the resultant voltage waveform is not perfectly sinusoidal and contains 3^{rd}, 5^{th}, 7^{th}, etc harmonics though of minor magnitude. The dominant harmonic is 3^{rd} which is zero sequence.

One method to minimise harmonics is to adopt partial pole pitch – usually $5/6^{th}$ or $2/3^{rd}$. But for medium voltage generators at 11kV which do not supply single phase loads directly, pole pitch of $5/6^{th}$ is normally used. In either case, third harmonic voltage generated is of the order of 5%.

Also, parallel operation of units with different pole pitches needs special scrutiny for third harmonic current circulation *only* in case neutrals of generators operating on a common bus are *solidly grounded as in LV system*. But in case of 11kV systems, the neutrals of generators are connected through a resistance of say RΩ. Let the differential third harmonic or zero sequence voltage between two machines be ΔE_0. Refer Fig 11.

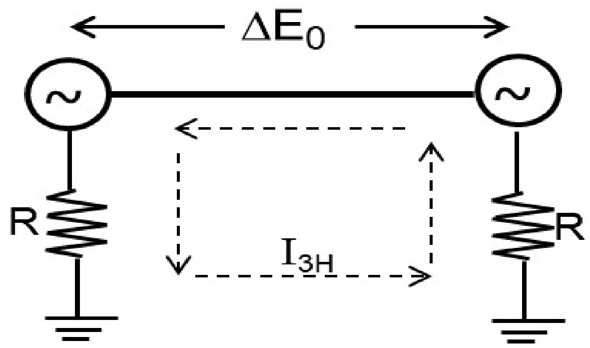

Figure 11

Example: 11kV, 10MW (12.5MVA) generator. Let X_0 = 10% = 0.1pu (typical value).

Base Impedance $Z_B = 11^2 / 12.5 = 9.68\Omega$

Base Current $I_B = 12.5 / (\sqrt{3} \times 11) = 656.1A$

Assume NGR is rated for 100A.

Resistance $R = (11kV / \sqrt{3}) / 100 = 63.5\Omega$

$R = 63.5 / 9.68 = 6.56pu$

R (6.56pu) >> X_0 (0.1pu). Hence X_0 can be ignored in further calculations.

Assume *differential* zero sequence voltage (third harmonic voltage) ΔE_0 is 10%, which is a very conservative figure.

The third harmonic circulating current I_{3H} = 0.1 / (2 x 6.56) = 0.0076 pu

= 0.0076 x 656.1 = 5A

This is only 5% of rated current of 100A and is of no serious concern.

Since R dominates over X_0 for resistance grounded system and two resistances come in series in circulating current path, the third harmonic or zero sequence circulating current due to differential third harmonic voltages induced due to partial pole pitch is not significant and can be ignored.

In conclusion, for resistance grounded system, the alternators can operate in parallel with all resistors in service and no complex switching arrangement for neutral to ground connection is required as in solidly grounded system adopted for LV system.

We have not considered Neutral Grounding Reactor (Reactor instead of Resistor in Fig 4) in our discussions. Resonant grounding was tried in a few large units (>500MW) in the past. A few small units still use resonant grounding due to past legacy. But in modern system design, reactance grounding is rarely used. Only resistance grounding (high or low) is used in most cases for neutral grounding of rotating machines.

4.0 Acknowledgement

I am grateful to C A Aron for sharing valuable insights into stator winding earth faults within generator slots.

5.0 References

[1] K. Rajamani, *Application Guide for Power Engineers, Part 1 – Earthing and Grounding of Electrical Systems*, Notion Press, 2018.

[2] K. Rajamani and Bina Mitra, "*Stator Earth Fault Protection of Large Generator (95%) - Part I*" *IEEMA Journal*, May 2013, pp. 76–80

[3] K. Rajamani and Bina Mitra, "*Generator Neutral Grounding Practices*"" *IEEMA Journal*, Aug 2007,pp. 89–97

Articles cited in [2] and [3] above are available in "*KR Monograph_Jan_2022_R5", downloadable from* the following link:

https://drive.google.com/file/d/1xnLiL0zqOuPyM-0UaiCFoTmshqxcY-SP/view?usp=sharing