13.8 KV SELECTIVE HIGH-RESISTANCE GROUNDING SYSTEM FOR A GEOTHERMAL GENERATING PLANT-A CASE STUDY

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Abstract: **13.8 kV selective high resistance grounding systems for bus connected generators are non-existent due to two reasons: One, the stray capacitance current of the system can be high, (>10-12A); second the sensitivity and selectivity of the ground fault devices to detect low-levels of ground fault currents is required. The paper describes the relay types, sensors, settings on protective relays, flow of currents for various fault locations in a 13.8 kV system and demonstrates how a selective HRG has been implemented. To the author's knowledge, there is no HRG selective system at 13.8 kV.**

***Index-Terms*:** **Selective high resistance grounding system, neutral displacement relays, zig-zag grounding transformer, sensitive ground fault settings and coordination.**

1. INTRODUCTION

In an HRG system it is documented that:

$$\frac{R_{KW}}{C_{KVA}} = 1 \qquad (1)$$

Where R_{KW} is the grounding resistor kW and C_{KVA} is the charging kVA of the system; then the transient overvoltages will be a minimum for ratio 1. A ratio somewhat >1 is acceptable and commonly employed, but it should not be < 1, [1-7] A factor called Coefficient of Grounding (COG) is defined as:

$$COG = \frac{E_{lg}}{E_{ll}} \qquad (2)$$

Where E_{lg} is the highest RMS voltage on the unfaulted phase, at a selected location during a fault effecting one or more phases to ground and E_{ll} is the rms phase-to-phase power frequency voltage obtained at that location with the fault removed. COG can be calculated using symmetrical components and these expressions are not included in this paper [7-9]. Note that IEC earthing fault factor is:

$$EFF = \sqrt{3}COG \qquad (3)$$

Unlike ungrounded systems, there is little likelihood of intermittent arcing faults in a properly designed high resistance grounding system (HRG). This was one major consideration that led to the development of HRG systems.

An effectively grounded system is the one in which the ratio X_0/X_1 is positive and <3 and ratio R_0/X_0 is less than one. Solidly grounded systems are, generally, effectively grounded systems. Theoretically, again, there is a very little likelihood of intermittent arcing ground faults, though none seems to have been documented in the literature.

Thus, the first step in designing the HRG system is to accurately calculate the system stray capacitance current. Generators, motors, transformers, surge arresters, cables, and overhead lines-- all have distributed stray capacitance to ground. These are lumped together. The stray capacitance currents can be accurately calculated using the published data [2, 10].

Figure 1 shows a zig-zag grounding transformer, with a grounding resistor of say 5A sized based upon (1). A zig-zag grounding transformer can be used for deriving the neutral on an ungrounded delta connected system. Figure 1 shows the basic construction of a zig-zag transformer, the windings a_1 and a_2 are on the same limb and have the same number of turns but are wound in opposite direction.

Thus, the zero-sequence currents in these two windings will have canceling ampere turns (or MMFs). All winding currents must be equal:

$$i_{a1} = i_{a2} = i_{b1} = i_{b2} = i_{c1} = i_{c2} \qquad (4)$$

The impedance to zero sequence currents is that due to leakage flux of the windings. For positive and negative sequence currents, neglecting magnetizing current, the connection has infinite impedance

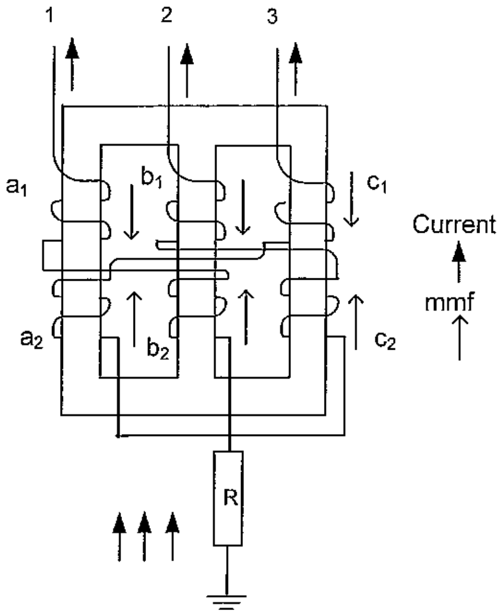


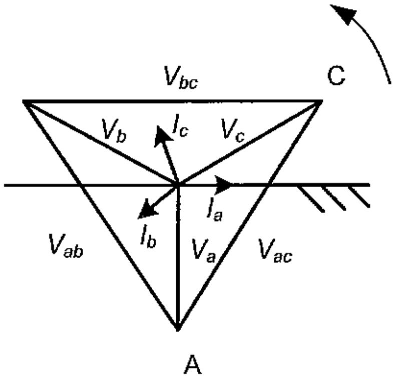
Figure 1: Currents and MMF's in a zig-zag transformer

Once the stray capacitance per phase is determined, the charging current per phase is:

$$I_c = \frac{V_{\ln}}{X_{co}} = -j\omega C_0 V_{\ln} \qquad (5)$$

Where C_0 is the stray capacitance per phase considered lumped together and $V_{\ln}$ is the system line to neutral voltage.

Under no ground fault conditions, no capacitance current flows through the ground or grounding resistor or zig-zag transformer.



(a)

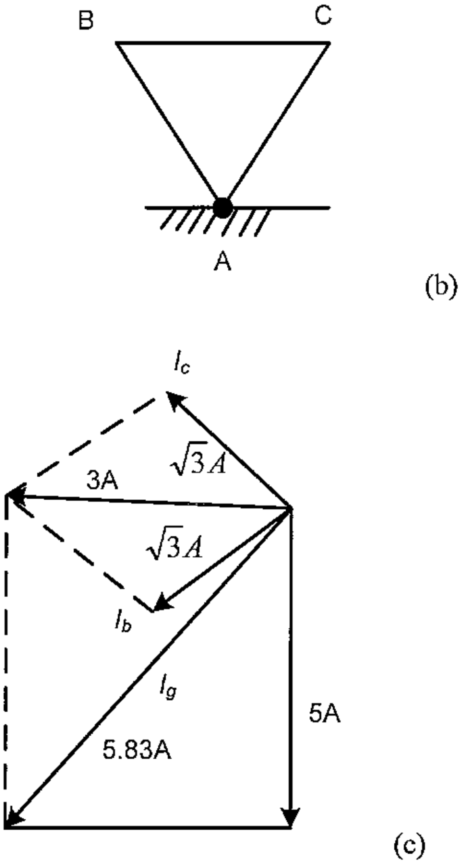


Figure 2(a): voltages and capacitance currents under no ground fault, (b) voltages with phase *a* to ground, (c) summation of capacitive and resistive components of current.

This is so because the capacitance currents in each phase will lead the voltage by 90° and thus the currents in three-phases are displaced by 120°. Their vectorial sum is zero, Figure 2(a).

$$\vec{I}_a + \vec{I}_b + \vec{I}_c = 0 \qquad (6)$$

Consider now that phase *a* goes to ground. Its capacitance to ground is short-circuited. As the line to ground voltage of the unfaulted phases *b* and *c* rises to line-to-line voltage, the capacitance current of these two phases reverses and returns to ground fault location through the transformer delta windings.

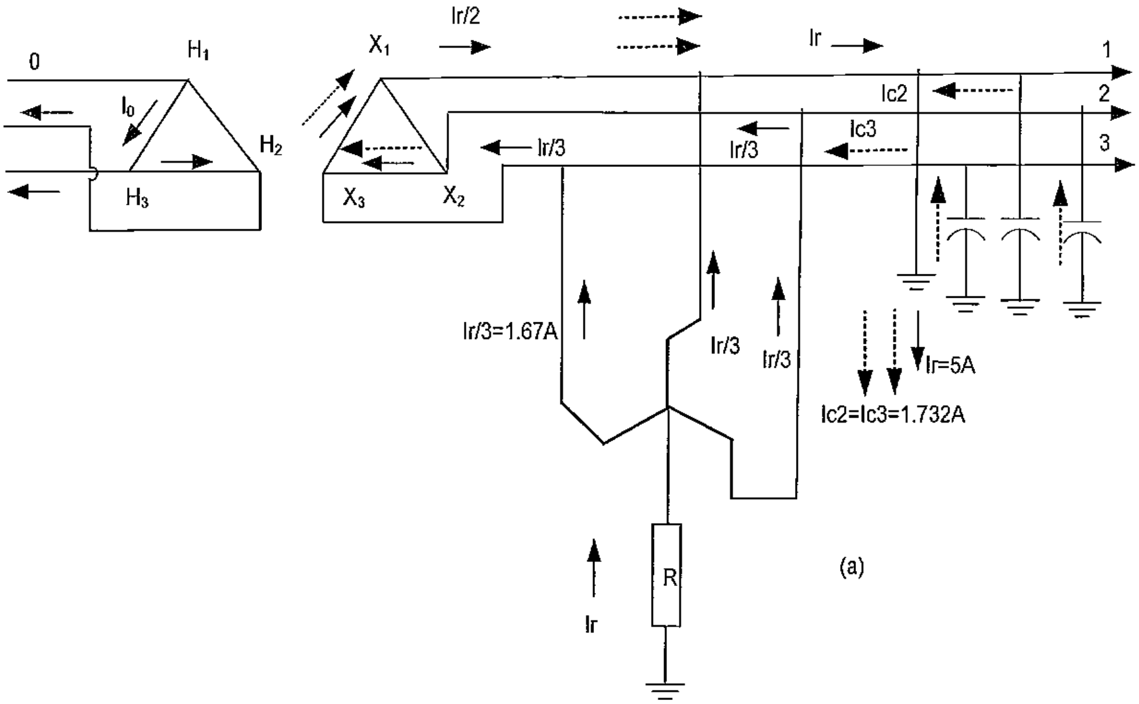


Figure 3. To illustrate flow of capacitive and resistive components of currents for a single line-to-ground fault phase *a*.

Again there is no capacitance current flow through the zig-zag transformer.

The zig-zag transformer carries the resistive component of the ground fault current mainly dependent on the ohm's value of the grounding resistor, as the sequence impedances are relatively much small and can be ignored without an appreciable error.

The flow of capacitance and resistive components of the currents to fault location is shown in Figure 2 (c), considering the following numerical values:

- Resistive component =5A
- Capacitance current in each phase =1.0A.

Note that 1.0 A becomes √3 x 1.0A= 1.732A in phases *b* and *c*, as the voltage rises to line-to-line voltage, Figure 2(b)

Figure 2(c) shows the phasor diagram of the capacitance and resistive components of the fault current. The capacitive currents in phases *b* and *c* vectorially sum to 3.0 A, The total ground current is:

$$I_g = \sqrt{5^2 + 3^2} = 5.83A$$

This illustrates that the total capacitance current for a phase-to-ground fault is:

$$I_{c,total} = 3I_{c,phase} \qquad (6)$$

It is three-times the capacitance current of one phase.

2. ADVANTAGES OF HRG SYSTEMS

The ground fault to stator windings of generators was examined in ref [11]. This considered 400A system ground fault current and the generator neutral grounded through 400A resistor, as per common industrial practice; with no generator neutral breaker.

Considering 6 cycle total fault clearance time, (5 cycle breaker interrupting time and 1 cycle relaying time) for the source side removal of 400A ground fault current by opening the generator breaker, greater fault energy (approximately 4 times) is released into the fault from 400A neutral current. This ground current from the neutral source decays slowly in about 0.8-1.0 seconds depending upon the generator single-line-to-ground-fault time constant. Also see Refs [12-15]. However, due to problem of selective ground fault clearance in bus connected generators hybrid grounding systems for generator neutral are recommended. These consist of a permanently connected HR system, designed according to (1) and a low-resistance grounding branch connected through a neutral circuit breaker or switching device. The low-resistance grounding circuit provides the selective coordination and is switched off after the coordinated time interval. The transients at the time of switching the neutral device are investigated in [16]. The following observations are of interest.

a. Necessity of providing generator ground fault differential protection for low-resistance grounded generators.

- In a typical bus connected industrial generator, the ground fault protection is prioritized, so that the generator is tripped last. Consider three-step coordination: (1), Ground fault on the feeder breaker (2), ground fault on a tie breaker (3) tie transformer neutral connected ground relay and finally (4), ground fault standby protection device 51G on generator neutral. This coordination, with a CTI of even 0.3 second results in a time delay of approximately 0.9 seconds, considering that feeder ground fault relays are set at instantaneous, (which may not be always practical specially when long cable lengths are involved). It is, therefore necessary to provide differential ground fault protection of the generator stator windings. It cannot be skipped even for small machines.

b. Stator 100% Ground Fault Winding Protection

- Stator 100% ground fault winding protection cannot be provided in low-resistance and hybrid grounded systems. Depending upon the sensitivity of pickup of ground differential relay, and the neutral grounding resistor a portion of the windings from the neutral terminal will remain unprotected. If the generator is grounded through a 100 ohm resistor and with the pickup settings of modern MMPR for generator application, 16% of the winding towards neutral remains unprotected, [17]. In a HRG system 100% stator winding can be protected using third harmonic distribution or other protections as discussed further in the paper. Ground fault differential protection for HRG generators is not required.

c. *Switching transients are avoided*

- The switching transients when the neutral breaker opens in a hybrid grounding systems are avoided

c *Ground fault damage is reduced*

- As the ground fault current reduces the damage associated with ground fault currents is further reduced compared to a low-resistance or hybrid grounding system. This also reduces arc flash incident energy, though this reduction is not much significant

Utility generators in unit step-up connection, with or without generator breaker are invariably HR grounded.

3. SYSTEM CONFIGURATION

The system configuration is shown in Fig. 4. It shows only the ground fault protection and basic system. Note the following features:

1. The utility tie transformer is connected in wye (230 kV) and delta secondary (13.8 kV) connection. Normally, for the bus connected generators, low-resistance grounded, the utility tie transformer is connected in delta (high-voltage) and wye (secondary voltage side) so that the wye connected neutral could be grounded through a resistor of 100A to 400A. By the reverse connection the delta winding blocks zero sequence currents. The transformer connections are identical to a GSU (Generator step-up) transformer in a unit connected generator.
2. The generator manufacturer specifies that based on the capacitance of 69 MVA generator windings, and the surge protection capacitor, the stray capacitance current is 1A per phase.
3. The stay capacitance currents in feeder circuits 1 and 2 are calculated accurately. These give:
    - Phase *a*, *b*, and *c* currents; feeder 52F1=0.5A
    - Phase *a*, *b*, and *c* currents; feeder 52F2=0.6A
    - Phase *a*, *b*, and *c* currents contributed by utility tie transformer and its connection to 13.8 kV bus= 0.01A

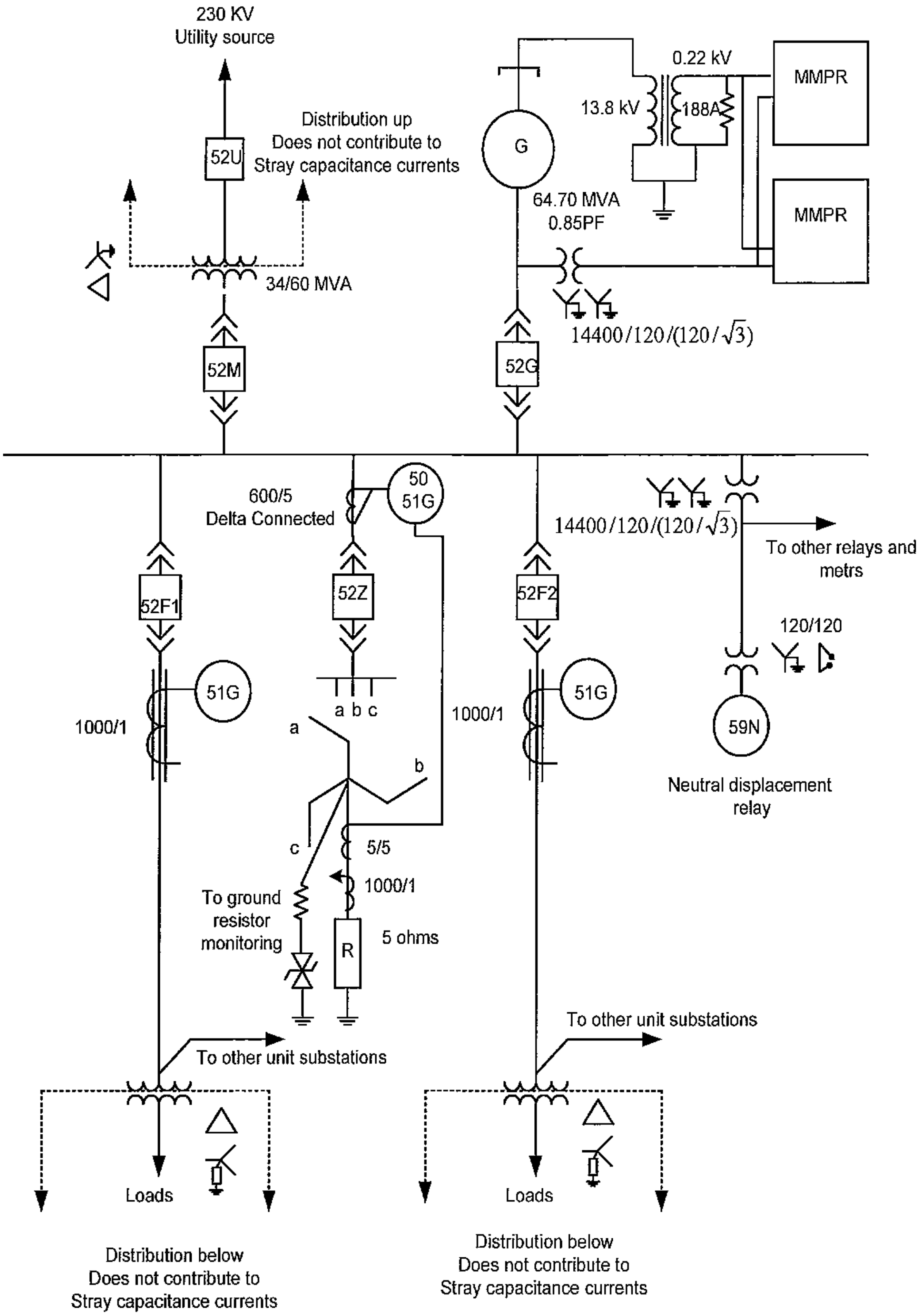


Figure 4. System configuration, showing ground fault protection and zone of stray capacitance currents.

4. Therefore the total stray capacitance current for a line-to-ground fault= 6.33A.
5. Note that when calculating the stray capacitance currents the distribution system connected on the secondary side of the substation delta-wye transformers need not be considered. To account for stray capacitance of the delta windings of the transformers use 50% of the normal capacitance value for the transformer size involved.
6. The grounding sources are divided into two parts. The generator is grounded through a distribution transformer loaded with secondary resistance as shown, primary 13.8 kV resistor current =3A.
7. A zig-zag bus connected grounding transformer with a 5A grounding resistor is the second source of ground fault current.
8. On loss of generator when the distribution system operates through utility connection only, this zig-zag transformer provides enough resistive current for selective tripping.
9. A neutral displacement relay is provided on 13.8 kV bus. In case of a ground fault on the 13.8 kV bus, operation cannot be sustained and complete shutdown is ushered.
10. The generator is provided with redundant MMPR's (Microprocessor based multifunction protective relays) and only the ground fault protection for 100% stator winding faults is shown in Fig.4.
11. Continuous monitoring of grounding resister is provided,

This forms the basic concept of selective ground fault tripping. Three separate zones have been created. The ground fault current is split into two sources of grounding—one generator and the second a bus connected zig-zag transformer.

A common concept in the industry is that the for implementation of HRG the system capacitance current should not exceed 10-12 A, or a maximum of 15A. This originates from the facts because in a HRG , the ground fault can be left un-attended for a long time. The implications are that it can create irreparable damage to the core s of rotating machines. Ref. [6] documents that even a small magnitude of 2-3A ground fault current sustained for a long time can create such a damage. Also the sensitivity of earlier ground fault relays did not permit selective tripping. In case selective tripping can be adopted, the ground faults will be cleared in couple of seconds, much akin to a low-resistance grounded system. Therefore, it is prudent to postulate that the selective HRG systems can overlap with low-resistance grounded system, and it does not matter even if the calculated stray capacitance current increases to 50 or 100A. (This will be rather unusual even for a large industrial system). Selective HRG forms a sort of bridge between HRG and LRG (low-resistance grounding).

Another point of interest will be the overvoltages, as demonstrated earlier in this paper. Though the BIL specified in ANSI/IEEE standards are equally valid for line-to-ground insulation, it is desirable to remove the higher line-to-ground voltages as soon as practical. Selective HRG systems admirably achieve this objective.

5. FEEDER GROUND FAULT RELAYING

The feeder ground fault relaying is shown in Fig. 5. It shows a 1000/1 ratio core-balance CT, sometimes called zero sequence CT, though core-balance is the proper terminology. It operates on the principle that:

$$\phi_1 + \phi_2 + \phi_3 = 0$$

Irrespective of the current unbalance, the fluxes produces by the currents in three phases cancel, unless a ground fault and zero sequence currents are involved.

The core balance CT has a window diameter of 8.25″, a short-circuit withstand capability of 50 kA for one second and a sensitivity of pickup of 0.2A primary ground fault current. The following precautions are taken in the installations:

- Run the cables as central to the window of the CT as possible. Insulating blocks can be used to keep the cables central to the window diameter

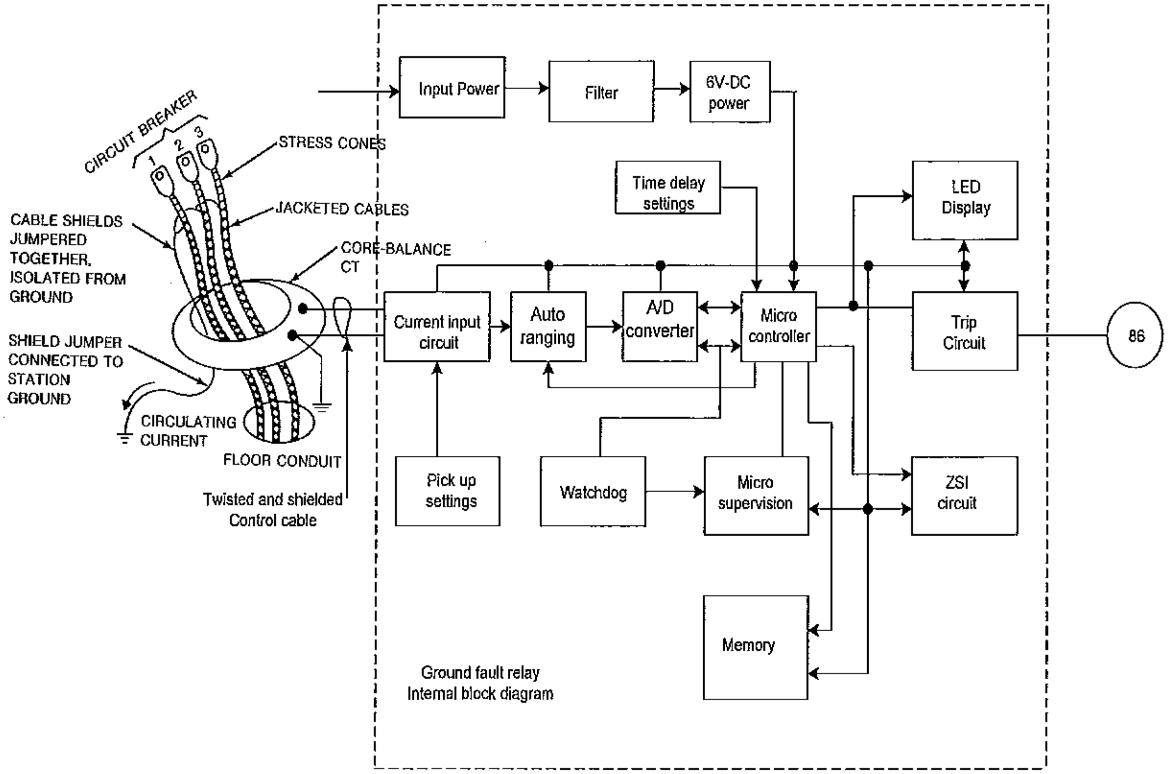


Fig.5. Sensitive feeder ground fault protection

- The left part of the figure 5 is from IEEE Standard 242 [18]. The shields are connected to a common point on the top of the CT, and then a lead brought down thorough the CT window and grounded at one point. This prevents nuisance trips due to stray induced current in the cable shields.
- The connections to the relay are made through a twisted pair shielded cable, as the secondary current will be in ma range.

The block circuit diagram of the sensitive ground fault relay is shown in Fig.5. Note that the core-balance CT does not have any C class relaying accuracy according to ANSI/IEEE standard [19]. The relay has low VA burden and the core-balance CT and relay are tested in combination. This testing shows that the pickup current error and timing error are limited to plus minus 10% for the settings and the core-balance CT and relay are tested in combination. This testing shows that the pickup current error and timing error is limited to plus minus 10% for the entire setting range.

This is the new trend in the application of core balance CTs. These are tested for operation with specific relay types and do not carry a conventional ANSI/IEEE relaying class accuracies.

The relay has a pickup setting of 1 to 20A, and definite time and definite minimum time user selectable settings. The analogue current signals are converted into proportional voltage inputs and digitized by an A/D converter in the relay, the microprocessor collects the samples at 2 ms intervals in a 60 Hz system and computes rms values. With no ground fault rms is zero. This ideal symmetry in three-phase systems is not obtained and there will be some small positive display.

Once the rms current exceeds the set value the timer action starts to activate the trip signal. The relay checks the output of core balance CT 480 times in one second. There is a watchdog and microprocessor supervision circuit which continuously monitors the status of the microprocessor. The ZSI feature in this relay has not been used in this application.

Ground Fault Settings

1. Table 1 shows the single line-to-ground fault current for a feeder fault under various operating conditions.
2. For a fault on the upstream of the core-balance CT, the capacitance of the feeder circuit will feed into a single line-to- ground fault current of 1.8 A maximum
3. Thus, the settings should be > 1.8A. A pickup setting of 2.5A and definite time delay of 0.25 second is used.

Table 1.
Ground –Fault Current for a Feeder fault.

Operating Condition	Ir	Ic	It
Generator in service	8	4.83	9.34
Generator out of service	5	1.83	5.32
Generator and Feeder F2 out of service	5	0.3	5.01

6. NEUTRAL DISPLACEMENT RELAY

A neutral displacement relay will generate a zero sequence voltage when one of the phases is grounded in HRG system. To sense this displacement a bus connected wye-wye grounded PT is used, Fig. 6. This PT has a ratio of 14400/120/(120√3) and an auxiliary PT with open delta secondary winding, unity ratio is used to connect to the relay, as shown in Fig.6(a). The auxiliary PT can be eliminated, but then the main PT should have two sets of secondary windings, one in the open delta connection for device 59N and the other in grounded wye connection for the other relays and meters in the system.

The relay is tuned to the fundamental frequency. The capacitor in the coil circuit, Fig. 6(a) desensitizes the relay especially for pickup at 3rd harmonic, which is normally present on the line terminals of the generator, [20]

The resistor across the open delta windings is required to prevent ferroresonance. These phenomena could occur due to interaction of the PT inductance with the stray capacitance, though this possibility is very remote in a well-designed HRG system.

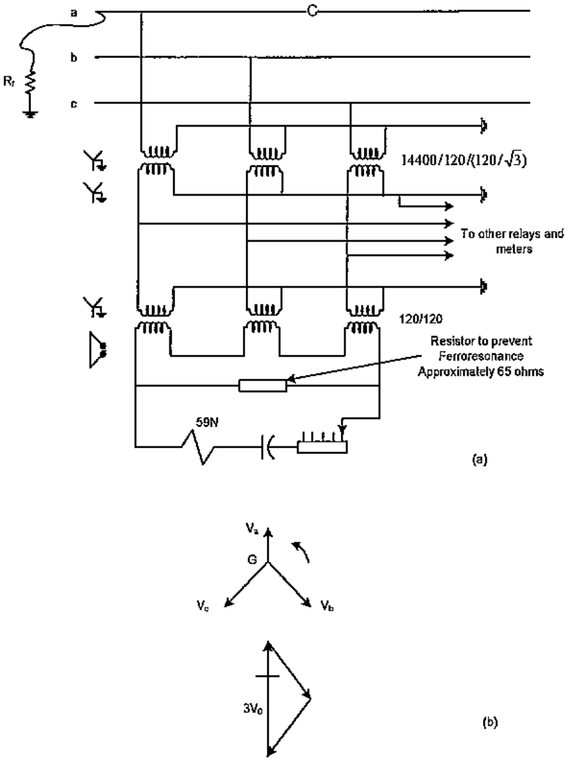


Figure 6. (a) Connections of PTs for the neutral displacement relay, (b) Phasor diagram.

When a ground fault occurs anywhere in the primary system this relay will be operative. Thus, it should be ensured that faults in the feeder circuit should be cleared fastest, followed by the fault in the generator circuit and lastly the 13.8 kV bus fault under which condition no operation can be sustained.

When the ground fault occurs, the two unfaulted phases of the PT primaries have now full phase-to-phase voltages applied and their corresponding delta secondaries are supplying √3 times the normal rated voltage. These two voltages will be added in series with a 60° phase angle. Figure 6-b shows the phasor with some ground fault resistance R_f. If the fault resistance is considered zero, that is full neutral shift, then the voltage developed across open delta secondary winding is 345 volts.

The relay is a special design of a voltage relay, electromechanical type, induction pattern and commercially available. The coil is rated to withstand 360 V for 10 seconds. The voltage pickup range is 10-40 Volts. To detect faults even with considerable fault resistance, a

setting of 10-V is chosen. The tap settings are chosen to give the following time delays:
At 2 times the tap setting=4s
At 12 times and higher tap setting=2s
The relay characteristic curves are not shown in this paper.

7. GENERATOR HUNDERED PERCENT STATOR WINDING PROTECTION

The 100% stator windings ground fault protection using third harmonic voltage distributions across the winding line terminal to neutral are discussed in IEEE Guide for Ac Generator Protection [21]. The Guide however does not picture clearly the distribution of third harmonic voltage. Third harmonic voltages act as zero sequence components and therefore, a ground fault, which generates zero sequence currents, will considerably alter the third harmonic characteristics. This philosophy is used to detect a ground fault at the neutral terminals.

Figure 7(a) shows normal distribution of third harmonic voltage with no ground fault. This shows that ratio R= third harmonic voltage at line terminal to neutral terminal =1. This varies over large limits:

$R \approx 1\ to\ 4.3$

This is so because:

- The third harmonic voltage varies with the rating of the generator
- Even for the same rating of the generator, it varies from the manufacturer to manufacturer.
- It varies with the active and reactive power load served from the generator

The third harmonic voltage settings are not made till these voltages are measured in the field after commissioning of the generator. Some manufacturers based upon their experience of commissioning many similar generators may specify the third harmonic voltage levels for their generator ratings.

Figure 7(b) shows the third harmonic voltage distribution for a fault at the machine neutral or close to it. It reduces the third harmonic voltage between neutral and ground to practically zero, while the third harmonic voltage at the line terminal considerably increases.

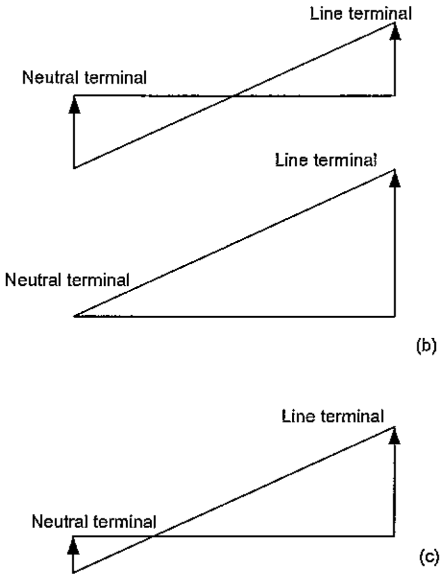


Figure 7(a) third harmonic voltage distribution across generator windings, normal operation, (b) distribution with line-to-ground fault at the neutral terminal, (c) fault at 25% of the winding from the neutral terminal.

Voltage at line terminals considerably increases. This can be theorized based upon the fault to ground at neutral end and the stray capacitance currents. In fact there is a linear shift of voltage from the line end to the neutral end.

Figure 7(c) shows third harmonic voltage distribution for a ground at 25% of the winding from the neutral terminal.

There are two redundant MMPRs for generator protection, which include identical 100% stator ground fault protection, implemented according to IEEE Guide [21], logic shown in Figure 8. The on-delay timer for the third harmonic undervoltage relay 27 is supervised by the instantaneous fundamental frequency line voltage relay 59-C to prevent operation of relay when excitation is removed from the generator. The 59-I overvoltage relay is tuned to fundamental frequency.

IEEE Guides [7, 21] may be referred for further alternatives of 100% stator winding protection for ground faults. The differential protection which actuates on the difference of third harmonic voltages at line and neutral terminal will be more effective in clearing the ground faults towards the neutral of the stator winding and will not be so much impacted by the machine load or change of excitation. Also the grounding transformer primary and secondary connections are continuously monitored in this differential scheme. However it will leave some gap in the windings protected depending on the third harmonic distribution, as shown in Figure 7(c) for a fault at 25% of the winding from the neutral terminal, when the difference in line and neutral terminal voltages reaches below the minimum pickup setting. This area, however, will be covered by the fundamental frequency overvoltage relay settings. Thus, even for differential protection with third harmonics it is necessary to retain the fundamental frequency overvoltage relay.

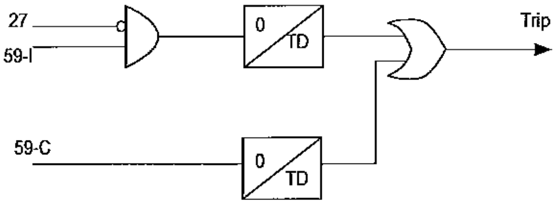


Fig.8. 100% stator winding protection using third harmonic and fundamental frequency voltage distributions.

Settings provided

The following settings are provided:

Fundamental frequency overvoltage pickup setting=6.4V. This low setting can detect faults within 2-5% of the stator neutral.

Time delay= 1s

Third harmonic undervoltage pickup setting is based upon the minimum third harmonic voltage during loading conditions. This voltage is 350V. Considering 50% setting the undervoltage setting is:

$$Setting = (0.5) \times 350 \times (13800/220) = 2.79V$$

Third harmonic undervoltage time delay= 1s.

8. ZIG-ZAG GROUNDING TRANSFORMER AND RESISTOR

Selection of Ratings

A circuit diagram of the zig-zag and grounding transformer has already been shown in Fig. 1. The resistive ground fault current is limited to 5A. This is so small that the error introduced by ignoring all the system sequence impedances, that is, positive, negative and zero sequence, and calculating the ground fault current based upon solely the grounding resistor does not introduce much errors in the calculations. This is so because relatively the zero sequence impedance of the resistor will be much higher compared to the other system sequence impedances. A resistor of 159 ohms and 5A is chosen.

The continuous ratings are:

Zig-zag transformer: 23 kVA

Resistor= 39.8 kW

Based on the ground fault settings provided, the grounding resistor and the zig-zag transformer need be rated on 10 s basis. The 10sec ratings for the zig-zag transformer need be only 3% of the continuous ratings as per IEEE standard 32 [22]. That is, 0.69 kVA.

The continuous ratings are so low, that the equipments are sized based on these ratings. The zig-zag transformer has a BIL of 110 kV.

According to IEEE 32, the time rating and permissible temperature rises on grounding resistors are:

Ten seconds or one minute short-time rating= 760°C

Ten minutes or extended time ratings= 610°C

Continuous rating= 385°C.

The tolerances on resistors with rise of temperature are another consideration. Table shows this data for two different materials:

For grounding resistors, to avoid large change in the grounding current a temperature coefficient of no more than 0.0002 ohms/°C should be specified.

Figure 9 shows the assembly of the zig-zag transformer and grounding resistor in stainless steel enclosure, NEMA 3R (though meant for indoor applications)

Protection of Zig-Zag Transformer

The zig-zag transformer should be protected for internal faults and also from damage due to un-cleared ground faults. The CTs for overcurrent protection must be connected in delta to block the zero sequence current, figure 4.

Table 2
Variation in Resistance with Temperature

	AISI 304 Nickel Chrome	Aluminum Chrome Steel
Temperature coefficient	0.001 ohms/°C	0.00012 ohms/°C
Ohms at Ambient	8 ohms	8 Ohms
After 10 sec	14.08 ohms	8.7 ohms
Change	43.2%	8.1%

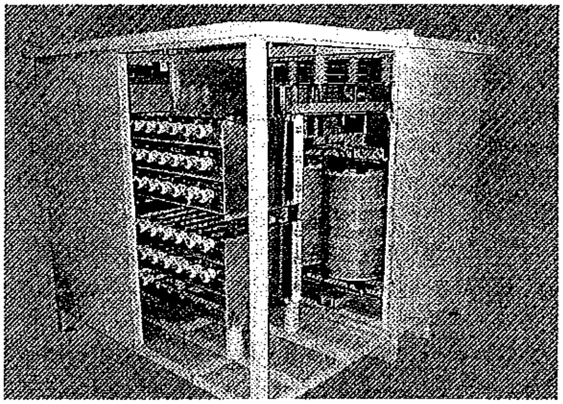


Fig.9. Zig-zag transformer, grounding resistor and CTs in SS enclosure.

Protection for a prolonged ground fault is provided by a CT in the neutral circuit, set for 5A instantaneous, with time delay of 5 seconds. As the zig-zag transformer is connected to a source of high short-circuit power a winding or terminal phase fault can result in high magnitude of current. To limit the damage a setting of 100A instantaneous with a time delay of 1 second is provided. The phase CTs must be connected in delta. The zig-zag transformer can also be provided with differential protection.

9. MONITORING OF GROUNDING RESISTOR

A grounding resistor may become faulty due to corrosion, overloads, extreme temperature changes, vibration and manufacturing defects. It is essential that the grounding resistor is continuously monitored. Consider some implications of the faults on the grounding resistor.

Open circuit:

This is the most common mode of failure. If the resistor has opened, it can remain undetected for a long time; there is a possibility that it is detected under normal periodic maintenance. The grounding system will revert from high resistance grounded to an ungrounded system, with the consequent possibility of arcing grounds, high resonant overvoltages through inductive capacitive couplings and the resulting insulation stresses. Voltages equal to 4-5 times the system voltage have been measured due to intermittent ground faults in ungrounded systems [9].

Short-circuit

Short-circuits have a low possibility of happening, but cannot be entirely ruled out. A short-circuited grounding resistor connects the neutral solidly to ground, and the system transitions from high resistance grounding to solidly or effectively grounded system.

Thermal damage

Thermal damage can occur due to prolonged ground fault current flow, inadequate ratings during selection and application, or simply because of a loose connection or a weld getting open. This will result in an open circuit, though it is possible that some percentage of the resistor windings is short-circuited and are overheated.

Thus, the implications of a damaged grounding resistor for the system grounding point of view are serious.

Some monitoring devices are:

1. *A voltage relay across the grounding resistor*

This does not have the capability to monitor the grounding resistor continuously. It monitors the neutral voltage and will not operate until a ground fault occurs.

2. Overcurrent relay

An overcurrent relay has similar limitation; it cannot monitor the resistor unless a ground fault occurs.

With the combination of the voltage and current measurements, if the voltage measurements show presence of a voltage and the current flow is zero, this is an indication during ground fault that the resistor is open.

3. Resistance measurements

The resistance measurements can indicate whether the grounding resistor is healthy even if it is not carrying any current. There can be some interference by external dc sources [23].

A system which monitors all the three parameters, the resistance, the current and the voltage can be considered a continuous monitoring system, Fig. 4.

10. APPLCATIONS TO OTHER 13.8 KV SYSTEMS

Each electrical syste4m is unique in some respects and cartful considerations are required to implement selective HRG. Note the following.

- Three-step coordination in a radial syste4m is demonstrated. However, the industrial systems are complex—a large system may have multiple utility interconnections, plant generators, synchronizing reactors and buses. It may not be only difficult but impractical to protect all these with three-step coordination
- The flow of capacitance currents in *either direction* in each section of the system is important. If these currents are approximately equal, a simple non-directional ground fault device cannot be applied.
- The directional ground relays require an appropriate polarizing source, voltage, current or both; properly derived. However these devices are not so sensitive to set as the settings illustrated in this paper. It may be necessary to raise the ground fault current in case directional elements are employed.

11. COMMISSIONING AND OPERATING EXPERIENCE

The system was commissioned in June 2011 and since then no ground faults or trips have been reported.

12. CONCLUSIONS

The paper describes the selective ground fault system, split into three distinct zones. Providing two sources of ground fault currents, and calculating the stray capacitance currents accurately, with connecting the utility tie transformer secondary winding in delta are the key elements of design. This coupled with sensitive protective devices and sensitive core balance ground fault CTs, achieves the desired objectives. The system as described can be replicated in any *similar* 13.8 kV radial distribution. Where applicable, the conventional limitations of capacitance currents not to exceed 10-12 A are not applicable—selective HRG provides a seamless application from HRG to LRG.

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