Ground Fault Protection of the Complete Generator Winding

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Presented at
The Fourth Annual Western Protective Relay Conference
October 18-20, 1977
Spokane, Washington

4th Annual

WESTERN PROTECTIVE RELAY CONFERENCE

October 18-20, 1977
Red Lion Motor Inn
Spokane, Washington

Abstract

The hazard of a ground fault in the normally unprotected neutral end of the generator winding is shown to lie in the destructive currents which can occur if a second fault occurs. A method for determining ground faults anywhere in the entire winding is described. This is based on monitoring both the third harmonic as well as the fundamental frequency voltage on the generator neutral bus. The method is also shown to identify abnormalities in the neutral grounding system external to the machine. A new relay based on this principle is described. The relay setting determination is shown to be straight forward and easily confirmed with field observations of normal conditions.

Introduction

The conventional unit type generator-stepup transformer has the neutral stabilized by a resistance loaded distribution type transformer. The resistance is sized to limit the in-phase component of line to ground fault current to a value not less than the total charging currents of the capacitances of the generator windings and associated transformers and leads. This value of neutral effective resistance has evolved over the years and results in moderate transient overvoltages of acceptable values.

The resulting ground fault current is generally less than 15 amperes. Currents this small generally do not cause serious damage to the core steel. Thus it is general practice to not use high speed detection for ground faults. For single ground faults near the neutral end of a machine winding, there will be proportionately less current, and hence less damage, Thus a ground relay sensitivity which protects 90-95 % of the winding has been considered adequate heretofore.

However, if a ground fault occurs and remains undetected because of its location, or otherwise, a second fault can lead to devastating results. Consider Figure 1, which shows a fault at the neutral and a second fault 20 % up from the neutral end of one winding. This fault will not be recognized by the standard ground relay because there is no voltage on the neutral bus. And if both faults are inside the differential CT's, it will not be seen by the differential relay either. The fault current during the subtransient and transient period may typically be 5-10 times rated generator current, depending on type of generator.

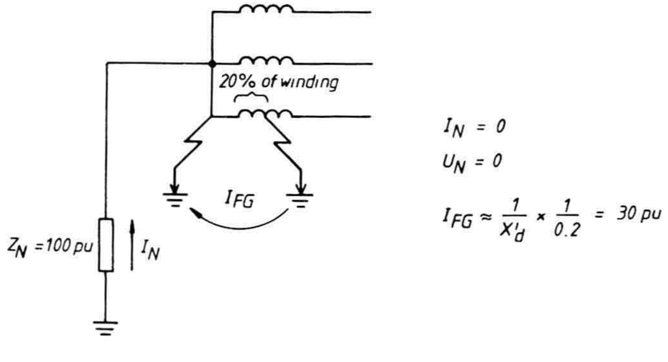


Fig. 1. Undetected ground fault can be serious if second fault occurs.

This paper will show that it is possible to recognize the first ground regardless of its location, even if it is on the neutral bus itself and to thus avoid the devastation of a second ground. It will be shown that it is feasible to monitor a reduction in third harmonic voltage on the neutral and to thus identify a ground fault beyond the reach of other ground relays.

Harmonic voltage

A pure sine wave is not produced in a conventional generator due to the limits placed on the mechanical details of the design. Efficient utilization of materials also requires working the magnetic materials into the non-linear areas. The resulting harmonics of orders of 5 and 7 are kept to a low value because they show up as distortion in the phase to phase voltage of the machine and their presence reacts adversely on the electrical efficiency of the machine.

Third order harmonics are also designed to specific maximum values. But on a three wire system, there is not the need to contain these to the same extent as the 5th and 7th orders. The thirds do not appear in the phase to phase voltage because they are in phase, in each phase. The third order harmonics behave as a zero sequence component while the 5th and 7th behave as negative and positive sequence components respectively.

The third harmonic created in a three phase generator shows up only in the line to neutral voltage. About one-half of this will appear on the neutral of the machine, as will be shown later. There will be no 5th or 7th harmonic on the neutral since these are small and they cancel out the same as does the fundamental frequency wave. Depending on machine designer's philosophy, the 3rd harmonic may be as high as 10 % or as low as 1 %. As noted above the 3rd order harmonics are the result of both physical arrangements and the non-linear magnetic paths within the generator. These two sets of harmonics will vary in relative magnitude and phase relation depending on the excitation level, loading and power factor of the load. Thus one can expect some variation in the net 3rd harmonic during different generating conditions. Typically one can expect about 50 % more 3rd harmonic at full load tha at no load. Figure 2 shows two types of variations in 3rd harmonic in addition to this general relationship. In all cases simple field observations can verify manufacturer's information and confirm the adequacy of the selected settings.

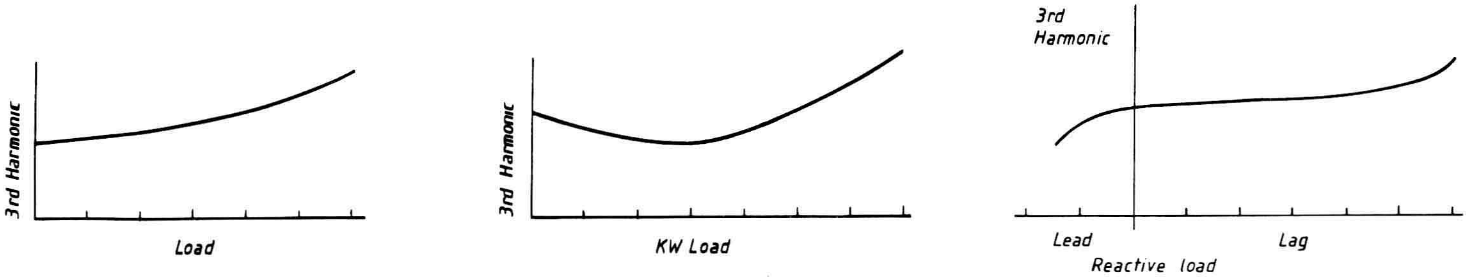


Fig. 2. Possible variations in 3rd harmonic in relation to generator loading.

Distribution of third harmonic voltage

The generated third harmonic voltage will cause a current to flow in the system phase to ground capacitance and return to the machine via the neutral grounding resistor. Figure 3, shows the capacitances to be considered. The effective neutral resistance, R_N, is usually sized to be no greater than the net capacitive reactances at 60 Hz, i.e.

$$R_N \leq \frac{1}{3\omega(C_W + C_L + C_T)}$$

Thus the capacitive reactance on each phase is equal to $3R_N$. This typical sizing of R_N assumes all of the machine winding distributed capacitance is at the terminal end. If this procedure were also used to determine the 3rd harmonic neutral voltage, a higher a value than normally observed would result. NR_N is the typical value noted above.

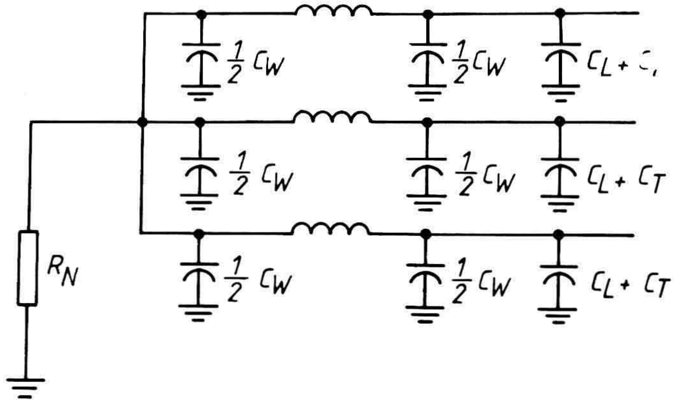
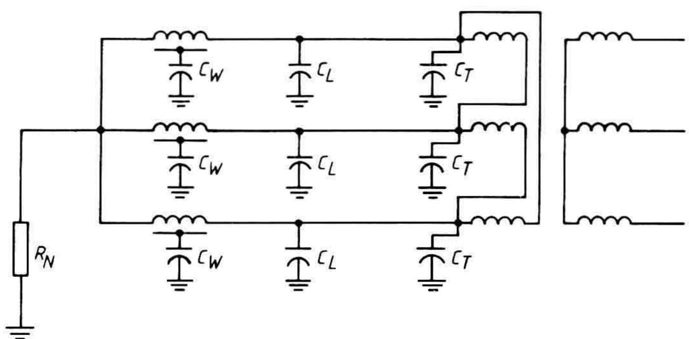


Fig. 3b. Practical distribution of machine capacitances for harmonic calculations.



C_W = Total winding capacitance to ground per phase

C_L = Total lead capacitance to ground per phase

C_T = Total transformer capacitance to ground per phase

Fig. 3a. Capacitances to be considered in determining 3rd harmonic voltage distributions.

A more accurate calculation of the 3rd harmonic voltage distribution will result if the machine capacitance is placed one-half at each end of each winding. A value must be assigned to the other capacitances outside the machine in the bus duct and connected transformer windings. For convenience, assume these other capacitances are equal to one-half of the machine winding capacitance. Figure 4 then shows the resulting 60 Hz reactances and Figure 5 the 180 Hz, 3rd harmonic reactances, Figure 6 is the net equivalent 3rd harmonic circuit.

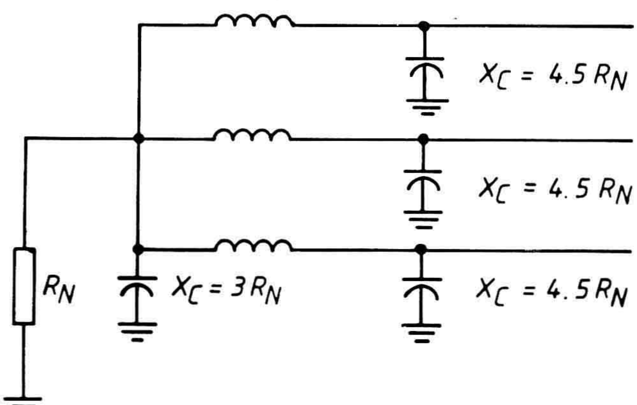


Fig. 4. Practical equivalent 60 Hz capacitive reactance distribution.

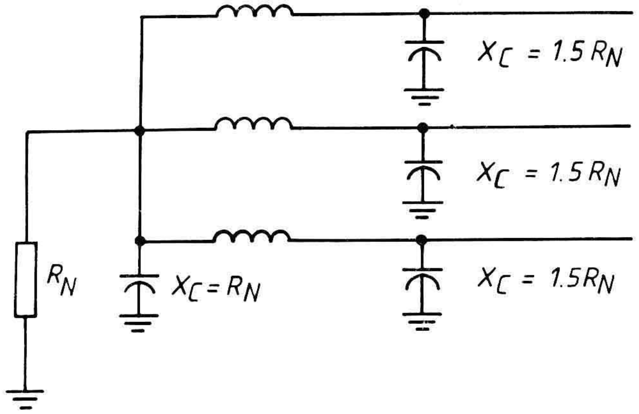
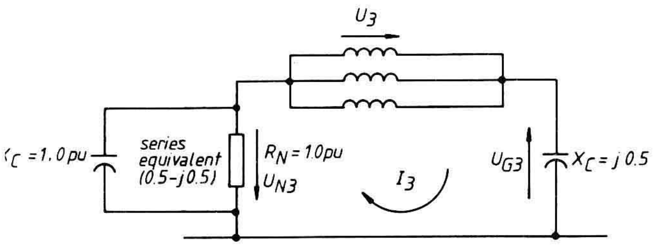


Fig. 5. Practical equivalent 180 Hz capacitive reactance distribution.



$$U_3 = I_3\left[(-j0.5) + (0.5 - j0.5)\right]$$

Fig. 6. Equivalent circuit for 3rd harmonic.

Figure 7 is the 3rd harmonic 180 Hz phasors for Figure 6. The values noted are for 1 % generated 3rd harmonic and with the assumed external capacitance equal to one-half of machine winding capacitance. One can readily explore other combinations of capacitance and neutral resistor size with these diagrams. For example, if there were only the machine winding capacitance, the noted 0.62 % 3rd harmonic on the neutral bus would become about 0.45 %.

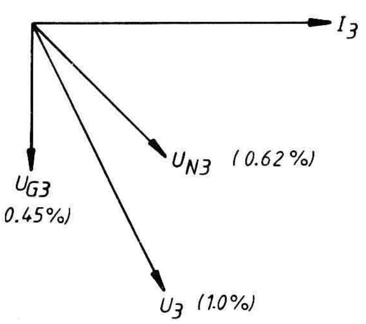


Fig. 7. Phasor diagram for Fig. 6. (Values noted are with 1 % generated 3rd harmonic voltage).

Voltage during faults

A fault on the neutral bus will cause the 3rd harmonic voltage to go to zero and the fundamental to remain at zero. A fault on a machine terminal will cause the neutral voltage to increase. The fundamental will rise to the line to neutral voltage and the 3rd harmonic will increase, from 0.62 % to the generated value of 1 % in this illustration. Thus the 3rd harmonic voltage will either increase or decrease depending on fault location. Obviously then at some fault location there will be no change in 3rd harmonic neutral voltage (although there will be a phase shift). Figure 8 shows this point is at 45 % to 62 %, up from the neutral end, depending on specific circuit constants. Using an average value of about 50 % simplifies other considerations.

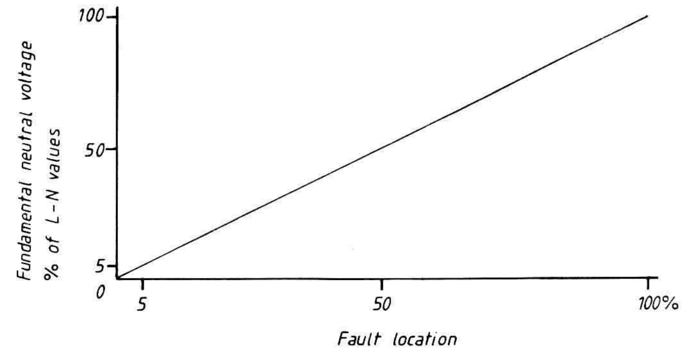


Fig. 8a.

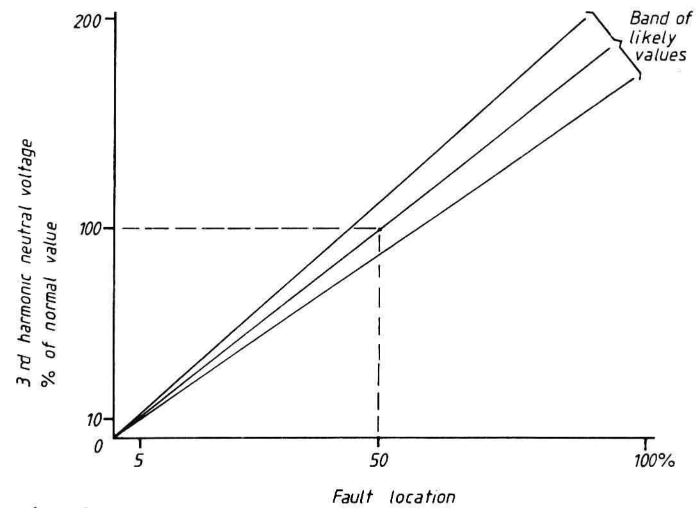


Fig. 8b.

Fig. 8. Voltages on neutral bus for various ground fault locations in machine winding.

A fault 5 % up from the neutral end will cause the fundamental voltage to increase from 0 to 5 % of the L-N value. But the 3rd harmonic will drop to a value proportional to the 5 % fault location with respect to the 50 % fault point where no voltage change takes place, i.e. to 5/50th or to 10 % of its normal value. This is shown in Figure 8. This represents a 90 % reduction in the normal 3rd harmonic voltage. This change is readily detected by the new relay thus providing a means of observing ground faults near the neutral of the machine which cannot be sensed by fundamental frequency measurements.

Relay design

A relay which responds to a reduction in 3rd harmonic as well as to an increase in fundamental frequency voltage has type designation RAGEA. Figure 9 shows how this relay is built up of standard plug-in modules in the COMBIFLEX system. The major components which are factory wired into a complete system include:

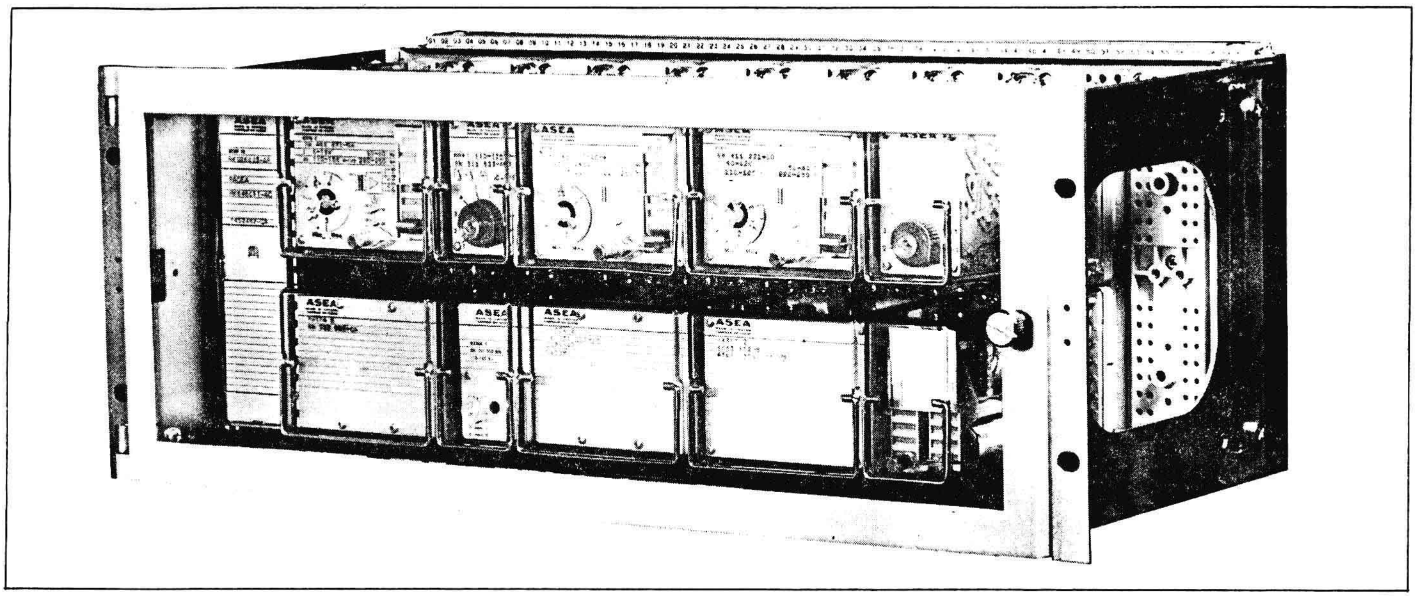


Fig. 9. 100 % generator ground protection relay type RAGEA.

1 Test switch

2 60 Hz relay with 180 Hz rejection filter (Device No. 59N1)

3 180 Hz relay with 60 Hz rejection filter (Device No. 27N3)

4 Supervising relay to block false alarms from 27N3 when machine is deenergized (Device No. 59 or 50)

5 Time delay relays and targets

The functioning of the relay is illustrated by the block diagram of Figure 10. The 59N1 relay with its associated 180 Hz rejection filter is set to operate at 5 % or more of the L-N voltage. A more sensitive setting is generally not necessary because of the protection provided by the 27N3. The 27N3 with its fundamental frequency rejection filter responds to a lack of 3rd harmonic on the neutral bus, as occurs during a fault at this end of the machine winding. For a typical machine, producing 3 % 3rd harmonic voltage, the relay will respond to winding faults within about 12 % of the neutral end when set at one-half of the normal 3rd harmonic neutral voltage. This provides adequate margins for setting the relay for variations in the generated 3rd harmonic as mentioned in connection with Figure 2.

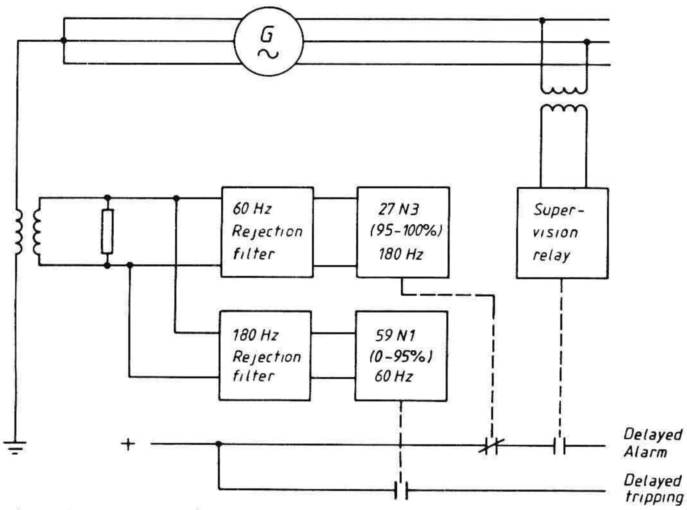


Fig. 10. Functional block diagram of 100 % generator ground relay type RAGEA.

When the amount of 3rd harmonic normally on the neutral bus is less than 1/2 %, the needed setting of 27N3 is influenced by the small amount of 60 Hz which leaks pass the associated filter. Again, the basic margins in the system are generally adequate to accommodate these minimum 3rd harmonic conditions.

Both the 59N1 and 27N3 relays are static overcurrent relays, type IG 2. They are calibrated with their respective filters in volts. The pickup setting is continuously adjustable over a 3 to 1 range and several scale ranges are available for each relay. The filter for relay 27N3 has a damping factor of 30 for the 60 Hz voltage.

The supervising relay is used to block false alarms from 27N3 when the machine is out of service. This is generally a simple overvoltage (59) relay type EG 2 which monitors machine voltage. It is set above the machine voltage level required to reset the 27N3 relay. Supervision of generator load current rather than voltage may be necessary with some generator designs which do not produce enough 3rd harmonic until loaded.

Setting and commissioning relay

Generator manufacturers can usually furnish 3rd harmonic and winding capacitance values. Other capacitances can be estimated when values are not available. Preliminary settings would be:

59N1 5 % of L-N voltage
27N3 50 % of neutral normal 3rd harmonic voltage
59 90 % of no load voltage

This provides considerable overlap in reach of each relay.

The selected settings should be confirmed by bringing the machine up to speed, applying field and raising the excitation until 27N3 opens its contacts. This should be before the supervising relay, 59 picks up and unblocks the 27N3 alarm circuit.

The amount of 3rd harmonic on the neutral bus can be observed and measured with an oscilloscope or other suitable instrument. Operate the generator over the entire expected loading range. Record 3rd harmonic voltages at various loadings and observe if any minimum values occur. Establish the final setting within a range of no more than 90 % of the minimum observed 3rd harmonic. Check that the setting of the 27N3 relay secures a 20 % tripping overlap with the 59N1 relay, due regard being taken to the influence of the 60 Hz voltage on the 27N3 relay. The damping factor for 60 Hz voltage is 30 as stated above. This system of 100 % ground protection can accept a wide variation in 3rd harmonic voltage over the operating range of the generator with the 59N1 set at 5 %.

Applications

The purpose of all type GEA relay applications is to identify the first machine ground before a second one occurs. In addition to identifying a ground within the machine as discussed above, the GEA also monitors the integrity of the entire generator neutral grounding system.

Figure 11 shows a hazard wherein the neutral connection has been opened for maintenance and not reclosed. This condition represents a hazard because without a stabilized neutral an initial fault can cause transient overvoltages which can quickly lead to a second fault. A 59N relay will not recognize this condition either before or after a ground fault occurs. But the 27N3 relay, being an undervoltage relay will respond to the lack of voltage and annunciate the abnormality before the first fault occurs.

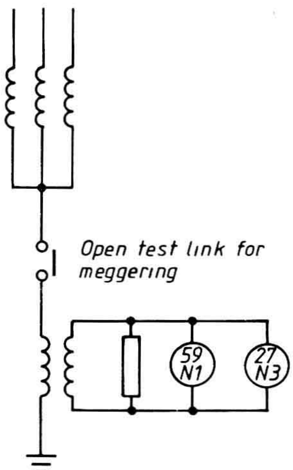


Fig. 11. Generator neutral open circuit recognized by 100 % ground relay type RAGEA.

Figure 12 shows another maintenance hazard wherein a protective maintenance ground on the generator neutral has not been removed. Again, a 59N relay will not recognize this condition. The 27N3 responding to a lack of voltage will identify the abnormality.

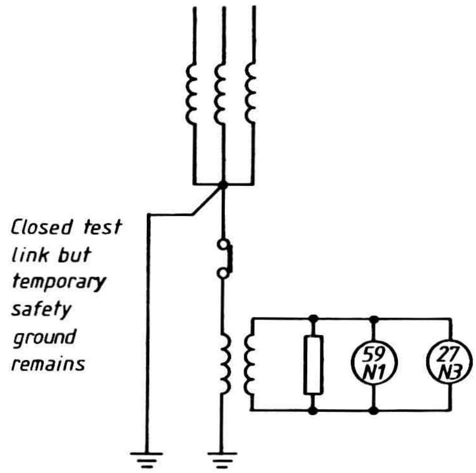


Fig. 12. Generator neutral short circuit recognized by 100 % ground relay type RAGEA.

Summary

Ground faults of only a few amperes contain the seeds of destruction of any piece of equipment. This is particularly true of generators where a second fault can result in large fault currents. These cannot be quickly removed because of the stored energy in the field and significant damage generally results.

All generators develop some harmonics. In substantially all cases there is enough third harmonic on the generator neutral bus to use in a protective system. Third harmonic voltages as low as 1/2 % of line to neutral voltage are sufficient. The reduction of 3rd harmonic is an indication of an abnormality at or near the neutral end of a generator. Such a measurement in conjunction with a fundamental frequency overvoltage measurement can provide ground fault indication for 100 % of the generator winding. The lack of 3rd harmonic can also be used to monitor the integrity of the entire generator neutral grounding system.

Relay type RAGEA is based on these principles. It provides complete ground fault protection to 100 % of the generator winding as well as the neutral bus and associated grounding components.

APPLICATION OF NON-ELECTRICAL PROTECTIVE DEVICES ON TRANSFORMERS AND REACTORS

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SPOKANE, WASHINGTON
OCTOBER 18-20, 1977

SUMMARY

The protective schemes developed for and applied to transformers and shunt reactors can be divided into two basic categories:

a) Those devices which operate on electrical quantities, such as current and voltage. These devices will be referred to in this paper as the Electrical Protective Devices.

b) Those devices which operate on pneumatic quantities such as pressure rise, gas-accumulation, temperature and oil level. These devices will be referred to in this paper as the Non-Electrical Protective Devices.

This paper is a "Users Practice" Report. It describes the types of oil filled power transformers and shunt reactors employed by British Columbia Hydro and Power Authority (B. C. Hydro) and the various Non-Electrical Protective Devices applied on these units.

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1.0 BACKGROUND

Oil filled power transformers and shunt reactors are basically composed of the main tank, the cooling system, and the oil preservation system. In addition to this a transformer may be equipped with a tap changing system.

The main tank is filled with oil and houses the core and windings. Since the most severe faults would occur in the main tank then it must be designed to withstand the maximum internal pressure rise which may occur. B. C. Hydro stipulates that the tank must be capable of withstanding an internal pressure of 5 psig measured at top of the conservator without permanent visible distortion to the tank.

The oil in the tank serves as an insulator for all parts which operate at different potentials and as a heat transfer medium from the windings and core to the cooling system. The cooling system consists of radiators which circulate the tank oil. Cooling fans and pumps may be used to increase the cooling efficiency.

It is important that the oil is kept free from moisture, dust and any other contaminants which might tend to reduce its dielectric strength or its cooling properties. This is achieved by the oil preservation system. There are various types of oil preservation systems in use but these systems can be divided into two basic categories; those employed on "gas cushioned" equipment and those employed on "conservator" type equipment.

The gas cushioned equipment has an air space above the insulating oil in the main tank. This air space may be vented to the atmosphere directly through a silica-gel breather or it may be sealed from the atmosphere with

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1.0 BACKGROUND - cont'd

sufficient gas space provided above the oil in the main tank to allow normal changes in the oil volume without creating excessive gas pressure. Auxiliary gas tanks may also be used to restrict pressure and inert gas, rather than atmosphere air, may be employed.

The gas cushioned equipment is common in the United States but is not used by B. C. Hydro. B. C Hydro employs the conservator type of transformers and shunt reactors. The conservator is partially filled with oil and is connected to the main tank by piping. The main tank remains completely filled at all times. The oil in the conservator represent approximately 10% to 15% of the total volume of oil in the transformer.

On smaller B. C. Hydro transformers the partially filled conservator only has an air space above the oil which is vented to the atmosphere through a silica-gel breather. The breather absorbs moisture from the air thus only dry air is allowed to pass into the space above the oil.

All B. C. Hydro transformers 138 kV and above or larger than 10 MVA and above 60 kV are equipped with an air expansion cell in the conservator. With this system, contact between the oil and atmosphere is prevented by a flexible air cell which floats on top of the oil. The cell which is vented to the atmosphere through a silica-gel breather, inflates and deflates as the oil level changes in the conservator.

There are basically two types of on load tap changers employed on B. C. Hydro transformers; wall-mounted and cover suspended. The wall-mounted on load tap changer is attached to the side of the main transformer tank. The diverter switch and the tap selector switch are installed in an oil tank.

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1.0 BACKGROUND - cont'd

Since the diverter switch produces arcing which contaminates oil, the tap changer oil is separated from the oil in the transformer main tank by an oil tight barrier. An air cushion is provided on top of the oil which allows oil expansion inside the tank and is vented to the atmosphere.

The cover-suspended on load tap changer, illustrated in Fig. 1, is attached to the tank cover. The diverter switch, which is removable, is installed in an oil tight compartment. The oil compartment is immersed in the transformer oil but the diverter switch and transformer oils are isolated. The tap selector switch is mounted below the diverter switch compartment and is immersed in the transformer oil. Piping is provided from the diverter switch compartment to an expansion chamber. The expansion chamber is either a separate conservator or an isolated section of the transformer tank conservator. The expansion chamber is equipped with a silica-gel breather.

2.0 NON-ELECTRICAL PROTECTIVE DEVICES

2.1 General

B. C. Hydro employs various sizes and types of oil filled power transformers and shunt reactors. The non-electrical protective devices for this equipment was selected on the basis of technical evaluation of the worth of the various forms of protection, recommendations of the equipment suppliers and past experience. The devices employed and their tripping functions are listed in Table 1. Location of the devices is illustrated schematically in Figure 2.

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TABLE 1

NON-ELECTRICAL PROTECTIVE DEVICES
ON TRANSFORMERS & SHUNT REACTORS

DEVICE	LOCATION	TYPE	ALARM	TRIP
1. Gas Relay with	Transformer & Reactor Tank	CGE Model 11		
a) Gas Accumulation Chamber			X	
b) Sudden Pressure Chamber				X
2. Sudden Pressure Relay				
a) Wall-Mounted LTC	Not provided			
b) Cover-Suspended LTC	LTC piping to Conservator	Buchholtz Relay (type selected by supplier)		X
3. Pressure Relief Devices				
a) For a Transformer and Reactor	Transformer & Reactor Tank	Qualitrol Model 208-60		X
b) Wall-Mounted LTC	LTC Tank	Qualitrol Model 208-60		X
c) Cover-Suspended LTC	Not provided			
4. Transformer and Reactor Top Oil Thermometer	Transformer & Reactor Tank	Selected by Supplier	X	
5. Transformer Winding Hot Spot Simulator	Transformer Tank	Selected by Supplier	X	
6. Reactor Winding Hot Spot Simulator	Reactor Tank	Selected by Supplier	X	X
7. Low Oil Level Gauge (visual indication only)	Transformer & Reactor Tank	Selected by Supplier		
8. Low Oil Level Device	Transformer & Reactor Conserv-ator	Selected by Supplier	X	
9. Low Oil Level Device (on transformers 41.6 MVA & larger)	Conservator Low Oil Level Gauge Plus Gas Relay Gas Accumulation Contacts	See Above		X

2.2 Gas Detector Relay

B. C. Hydro employs the Canadian General Electrical Model 11 Gas Detector Relay on their oil filled transformers and shunt reactors. This relay consists of a gas accumulation chamber and a pressure chamber. A cross section of the relay is shown in Fig. 3.

The gas accumulation chamber consists of an oil chamber with a float which operates a magnetic oil gauge. The gas chamber is normally full of oil but on accumulation of gas in this chamber the oil is replaced with the gas which causes the float to lower.

The pressure chamber consists of a front and rear section. The rear section is an oil chamber which is connected to the transformer. Flexible brass bellows separate the front and rear sections and a bellows stop is provided to prevent damage to the bellows due to over travel. A diaphram is mounted across the air side of the bellows. A pressure wave through the oil will compress the flexible bellows. When the air is compressed by the displacement of the bellows it causes the flexible diaphram to operate a microswitch. The sensitivity of the pressure chamber is controlled by a small leaf spring valve which controls the rate of air escaping past the diaphram from the bellows side to the front of the diaphram, thus controlling the air pressure on the diaphram.

Sensitivity is controlled by turning the pointer of the by-pass valve. Sensitivity is increased if pointer is turned clockwise and decreased if it is turned counter clockwise. One full counter clockwise revolution (360°) represents 32 divisions. The normal setting is zero which represents approximately

2.2 Gas Detector Relay - cont'd

1/3 psi/sec rate of pressure rise that is required to actuate the microswitch. Approximate characteristic and desensitizing curves of the Model 11 Gas Relay are illustrated by Figs. 4 and 5 respectively.

In a transformer or a reactor the evolution of gas may result from defective insulation, defective supporting and insulating structures, improperly brazed joints, phase to phase and ground faults, short circuited turns, flash-over between parts, tap changer problems, foreign bodies inside the transformer or reactor which are heated by the electrical and magnetic fields, to name only a few. Faults of a minor nature result in a slow evolution of gas, whereas, on a major fault, gas will be given off at a rate sufficient to cause a definite rise in pressure.

The gas accumulation portion is used to detect a minor fault and give an alarm. The gases produced are usually combustible and after collecting in the accumulation chamber they may be removed via the bleeder valve and analyzed. Analysis could possibly indicate the type of insulation being broken down; i.e. laminations, core-bolt or major insulation. To assure that the gas produced collects inside the gas relay the top of the transformer and reactor tank is domed or sloped so that the produced gas collects at the highest point and the gas relay be located at that point. In order to prevent the accumulated gas from being carried off to the conservator the elevation of the conservator tank is such that the gas detector relay is below the minimum oil level in the conservator tank. Piping to the conservator is not used for the gas relay.

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