# Ground Differential Protection: Revisited

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***Abstract*** **– This paper reviews the principles of ground differential protection within industrial power systems and discusses the use of directional overcurrent relays in this application. Electro-mechanical product type relays have been the device used primarily for this application. The use of current polarized directional ground-overcurrent relays provides a novel approach in the application of ground differential protection.**

## I. INTRODUCTION

Ground differential protection has been used for many years for ground faults within wye-connected generators and transformers, which are either solidly or low-impedance grounded. Because of the inherent design of the differential scheme, it does not require time delayed operation for coordination with other relays. Therefore, this method provides sensitive, selective, and high-speed clearing of ground faults. The merits of ground differential protection have been the topic of several papers over the years. [3,4]

Several different types of protective relays have been used for ground differential schemes. These include time-overcurrent relays, torque-controlled time-overcurrent relays, percentage differential, and product-type overcurrent relays. Some of these relay types have certain limitations and require special attention be given to their application to ensure desired operation.

Fig. 1 indicates the theory of operation of the ground differential scheme for a low-impedance grounded power transformer or rotating machine. In this application the relay is connected in a typical differential method with a current transformer (ct) on the grounded neutral providing one input to the relay and the residual connection of the phase ct's providing a second input to the relay. The polarity of the ct's must be as shown to ensure secure and reliable operation. For application on power transformers, an auxiliary ct is required to match the ct secondary currents. As shown in Fig. 1, for a ground fault within the ground differential zone, the currents in the ct's secondary combine in the parallel connection of the ground differential relay (device 87N) to cause operation. For ground faults outside the differential zone, the secondary current simply circulates within the ct's secondary circuit with no operation. Detailed explanation of operation for the various applications has been addressed sufficiently in Reference [1-4].

The product-type relay has been the foremost relay of choice for ground differential applications in the past. These relays are of electromechanical induction disk design with an upper and a lower coil, which are polarity-sensitive. Because of the design and nature of product-type relays, there are critical areas of concern with their application.

Directional ground-overcurrent relays may also be applied in a ground differential scheme. These relays provide similar benefits of security and high-speed operation inherent with ground differential protection. However, newer static analog and static digital relays offer additional benefits over the electromechanical product-type relay.

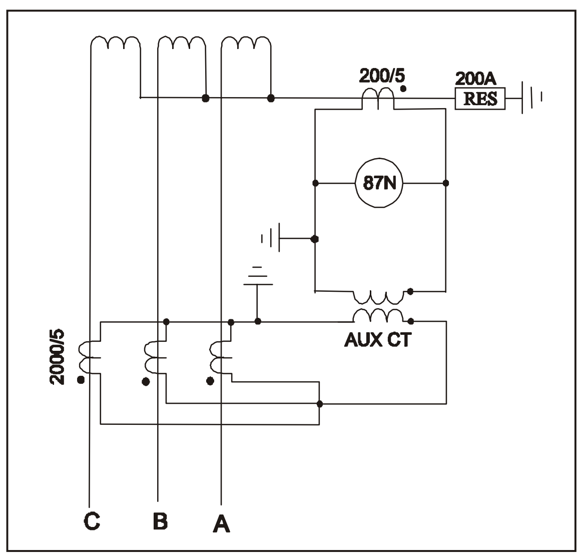


**Figure 1. Application of Ground Differential Protection on a Power Transformer**

## II. APPLICATION OF PRODUCT-TYPE RELAYS

Product-type relays, connected as shown in Fig.2, are constructed with an upper and a lower coil on the same shaft. These coils work in conjunction to provide an operating torque when the currents enter the polarity terminals (marked “+”) of both coils simultaneously.[3]

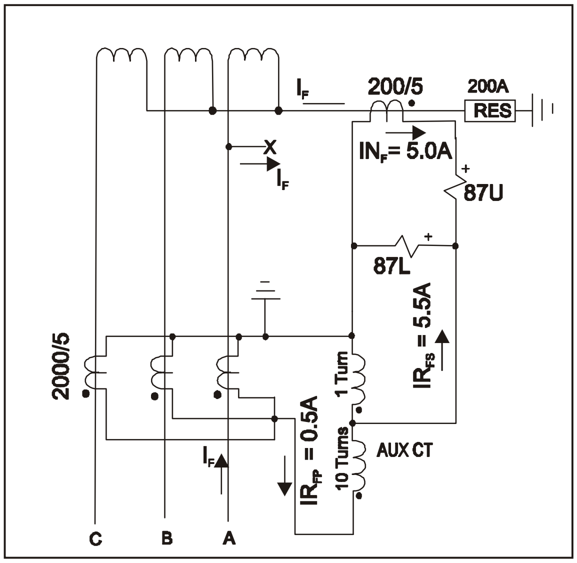


**Figure 2. Application of Ground Differential Protection Using Product-Type Relays**

The magnitude of the operating torque is a function of the current in the upper and lower coils and the phase angle between these currents, as indicated in Equation (1).

$$T \quad = \quad I_R \times I_P \cos\theta \qquad (1)$$

Where

| | | |
|---|---|---|
| $T$ | = | Operating Torque |
| $I_R$ | = | Secondary Residual Current |
| $I_P$ | = | Secondary Polarizing Current |

Maximum operating torque occurs when the currents are in phase, cos 0º = 1.

The operating characteristic of the product relay with maximum torque applied is given by an inverse time-product curve, as shown in Figure 3. These curves are a function of operating time and multiples of tap product current at maximum torque (currents are in phase). However, if the currents are out of phase, the operating time will be longer and can be determined from the curves using Equation. (1) to find the product current.

For ground faults outside the differential zone, secondary current ($IR_{FS}$) will flow into the non-polarity terminal of the lower coil, producing a negative torque to force the tripping contacts in the open direction. Ground faults within the differential zone result in secondary current from the neutral ct ($IN_F$) that flows through the upper and lower coils. Secondary current from the residual phase ct connection ($IR_{FS}$) combines to flow through the lower coil, as well. Current from both secondary circuits flow into the polarity terminal of both upper and lower coils simultaneously, causing operation of the relay.

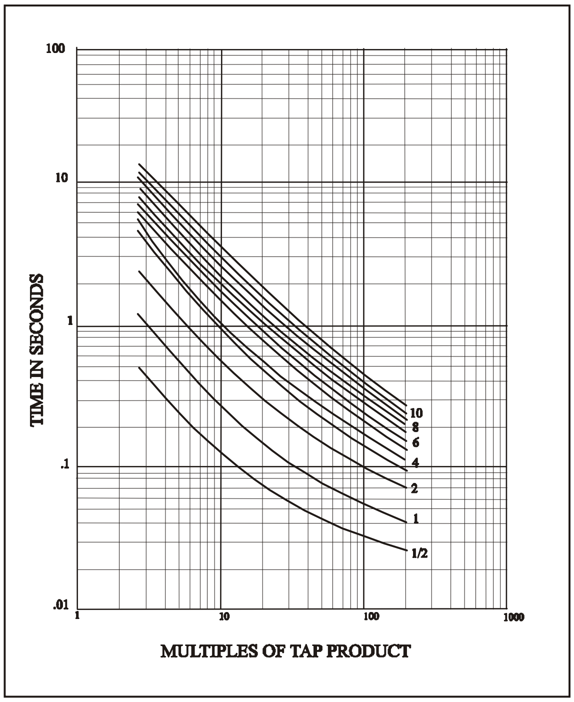


**Figure 3. Time-Product Current Operating Characteristic Curve of Product-Type Relay**

Because of the polarity sensitive nature of the electromechanical product type relay and the possibility for the occurrence of current imbalance and saturation, it has been recommended to connect the auxiliary transformer in an auto-transformer configuration.[3] For the application in this paper, the auto-transformer ct provides 10% more current contribution from the phase cts. The additional current increases the negative torque and helps maintain the contacts open. This aids in preventing misoperation when there is current imbalance or the auxiliary ct saturates. This circuit modification is a necessity for the product-type relay to operate reliably and securely.

Tap ranges and multipliers for product type relays vary by manufacturer but the tap-product (the tap setting times the multiplier) will generally range from about $0.5A^2$ to 36 $A^2$. The lower tap settings provide greater sensitivity. However, the burden is also greater at these lower values and may cause the neutral cts to saturate under high ground fault conditions. Because of this issue, extreme care must be used to accurately calculate the burden placed on the neutral ct. Details of these calculations have been presented in detail by other authors.[3]

An additional point to consider is the application of product-type relays for generator ground differential protection. Assuming equal voltage distribution across the generator windings, the closer a ground fault occurs to the neutral, the lower the voltage and impedance will be, resulting in lower fault current. Increased sensitivity afforded by the lower tap settings is an advantage for faults of this type and may give you a false sense of greater security. As described above, adjusting the relay to operate for faults near the generator neutral by selecting lower tap values places greater burden on the neutral ct. For ground faults at the generator's terminals, the maximum fault current will flow through the neutral ct, possibly causing saturation.

## III. Application Of Directional Ground-Overcurrent Relays

Directional ground-overcurrent relays are normally used to provide sensitive tripping for currents flowing in one direction only. Directional ground-overcurrent relays consist of an overcurrent function and a directional function. The directional function determines the direction of current flow based on a polarizing input source. The polarizing source can be current, voltage or both. Output from the overcurrent function is controlled by the directional function. When the current exceeds its tap setting and is flowing in the tripping direction, the directional function enables the overcurrent function to provide an output. If the fault current is flowing in the opposite direction, the directional function will inhibit operation of the overcurrent output.

Static directional ground-overcurrent relays function similar to their earlier electromechanical counterparts using analog or digital circuit designs to perform overcurrent and directional measurement. The input quantities are generally supplied to a comparitor circuit or microprocessor that determines if the measured values are above the pickup settings and in the tripping direction. A simplified block diagram of a static directional overcurrent relay is given in Figure. 4.

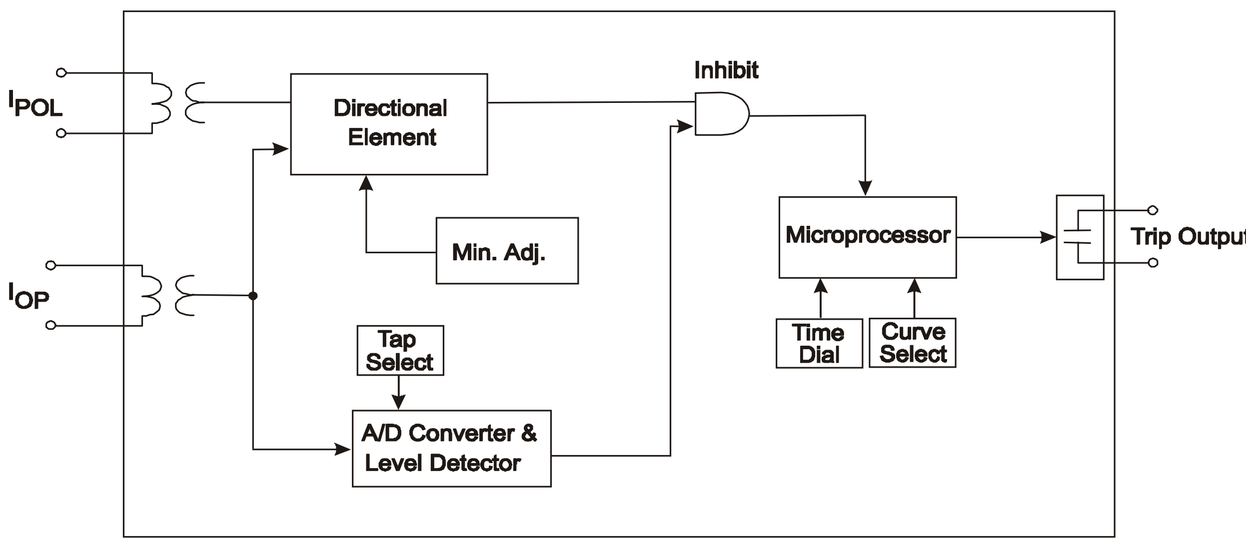


**Figure 4. Simplified Block Diagram of Static Directional Overcurrent Relay**

Since ac current flows in both directions by nature, the directionality of the current is actually determined my measuring the directional flow of "fault power" in the protected zone. By comparing the angular displacement of the measured current and polarizing quantity, the direction of power flow can be determined. As long as the polarizing quantity maintains a steady phase position as the fault location changes, it is a proper polarizing source.

Directional ground-overcurrent relays can be use to provide sensitive ground fault protection of transformers and generators. The relay is applied similar to the product type relay as previously discussed. The ground directional ground-overcurrent relay, similar to the product type relay, provides the benefit of fast operation without the need to coordinate with ground backup devices. Because this scheme is not affected by phase faults (not involving ground) nor normal load currents, the relay can be set to very sensitive pickup values.

Applied in a ground differential scheme, the directional ground-overcurrent relay should be connected using current polarization, as shown in Figures 5 or 6. These figures show that the relay may be connected using either a typical auxiliary ct, or an auto-transformer type ct.

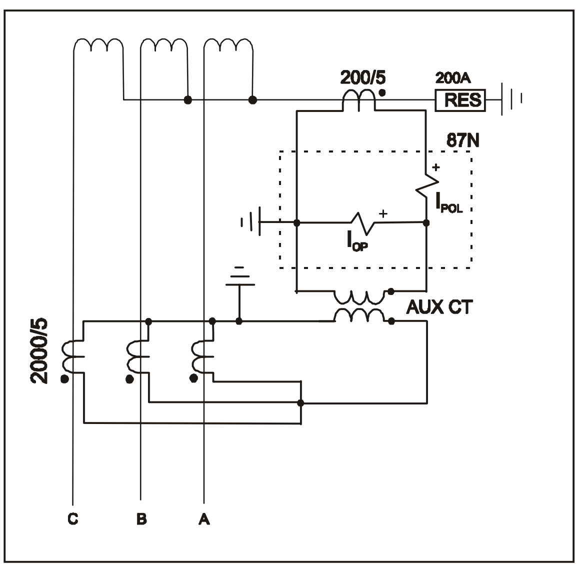


**Figure 5. Directional Ground-Overcurrent Relay Using Standard Auxiliary CT for Ground Differential Protection**

The relay is connected between the neutral ct secondary circuit and the auxiliary ct. Since the polarizing element is polarity sensitive, it connected in series with the neutral ct secondary winding. The operating element is connected in parallel with the auxiliary ct secondary winding. Similar to the product type relay, the directional ground-overcurrent relay compares the phase relationship between the polarizing quantity and the measured current in the operate circuit. The relay will operate when the currents from the polarizing element and the operate element are in-phase with current flow is into the polarity side of each element and sufficient current flows through the operate element to exceed its minimum pickup setting.

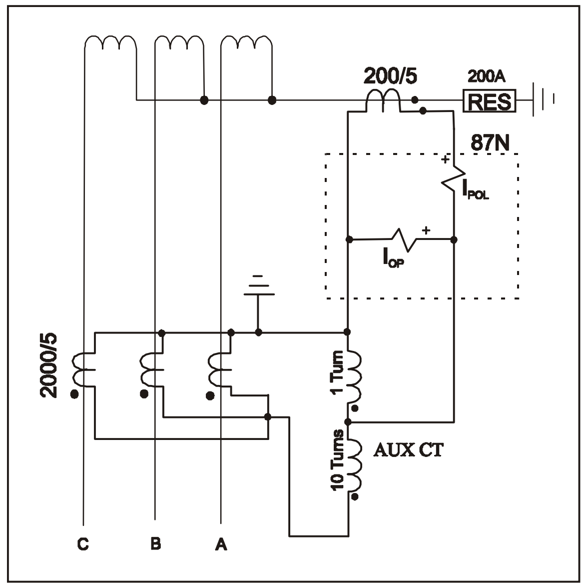


**Figure 6. Directional Ground-Overcurrent Relay Using Auto-transformer Type CT for Ground Differential Protection**

Analysis of the operation of the directional ground-overcurrent relay under fault conditions is shown in Figures 7 and 8. The arrows indicate the current flow under the given conditions. Figure 7 shows the conditions for an external A-phase-to-ground fault. In this case, the primary ground fault current will flow into the polarity side of the neutral ct and will produce a secondary current, $IN_F$, of 5.0A. Phase A primary current is also 200A, whereas, phase B and C currents are zero. Therefore, the residual current, $IR_{FP}$, of the 2000/5 phase cts is 0.5A with flow out of the non-polarity side of the winding.

Current $IR_{FP}$ flows through the 10:1 auto-transformer such that it produces a secondary current, $IR_{FS}$, of 5.5A. This current circulates in the auto-transformer secondary circuit along with the neutral ct secondary current, $IN_F$. It can be seen that $IN_F$ current of 5.0A

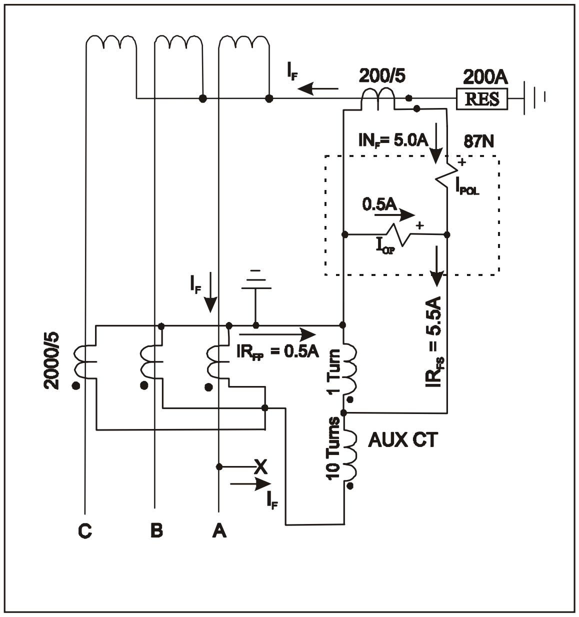


**Figure 7. Operation of Directional Ground-Overcurrent Relay for External Ground Fault**

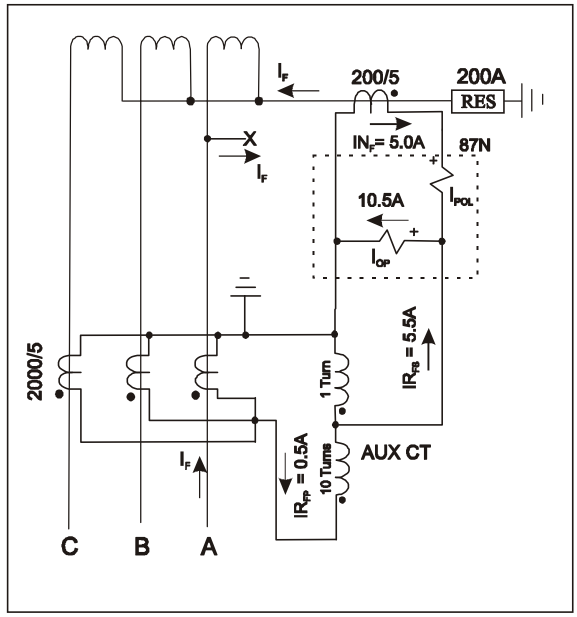


**Figure 8. Operation of Directional Overcurrent Relay for Internal Ground Fault**

flows into the polarity mark of the polarizing element a and into the connection of the operate element. Since 5.5 A flows out of this connection towards the auto-transformer, then 0.5 A must flow though the operate element from non-polarity towards polarity. However, since the current flow through the operate element is 180° out-of-phase with the polarizing quantity, the relay will not operate. As previously mentioned, these two quantities must be in-phase (indicating an internal fault) for the relay to operate.

Figure 8 shows the results for an internal A-phase-to-ground fault. The primary ground fault current will flow into the polarity side of the neutral ct, similar to the external ground fault, and will produce a secondary current, $IN_F$, of 5.0A. The phase A primary current of 200A flows into the polarity side of the phase ct, producing a secondary residual current, $IR_{FP}$, of 0.5A that flows into the polarity side of the 10:1 autotransformer. The auto-transformer produces a secondary current, $IR_{FS}$, of 5.5 A that circulates in the secondary circuit and into the polarity side of the relay's operate element. The neutral ct secondary current, $IN_F$, also flows into the polarity side of the relay's operate element, producing a total operate current of 10.5 A. Since the polarizing current and the operate current are in-phase and the operate current is above the pickup setting, the relay will operate for the given fault conditions.

## IV. COMPARISON ANALYSIS

Comparing the operation described previously for the product type relay and the operation of the directional ground-overcurrent relay, it appears that both relays perform satisfactorily for internal and external ground faults using the auto-transformer ct connection. Both methods will also perform satisfactorily when using a standard ct connection, as shown in Figure 5, as long as the fault current is limited to a value such that the auxiliary cts do not go into saturation and the circuit is current balanced. If the circuit is not balanced, any current imbalance that might occur during a ground fault would find a path through the operate element of the relay. If this imbalance is above the pickup setting, the relay will misoperate. Such would be the case for an internal fault where the auxiliary cts are driven into saturation.

Auxiliary ct saturation is typically not a problem with single-source impedance-grounded power systems. However, for internal ground faults with multiple ground sources, the fault current contribution from the phase cts is increased. As a result, it is possible to drive the residually connected auxiliary ct winding into saturation. The effect this would produce for an internal fault is to reduce the magnitude of current through the relay's operate element by the reduction

**Table 1. Comparison of Typical Relay Burden Data**

| Relay Type | Polarizing Element (Ω) | Operate Element (Ω) |
|---|---|---|
| Electromechanical. Product (A) | 0.42 | 3.52 |
| Electromechanical. Product (B) | 2.87 | 0.38 |
| Electromechanical. Directional Overcurrent | 0.33 | 8.10 |
| Static Analog Directional. Overcurrent | < 0.1 | < 0.1 |
| Static Digital Directional Overcurrent | < 0.2 | < 0.2 |

**Table 2. Comparison of Reflected Burden for Saturated and Non-Saturated Conditions**

| Relay Type | Burden on 200/5 CT | | Burden on 2000/5 CT | |
|---|---|---|---|---|
| | With 2000/5 CT Not Saturated (Ω) | With 2000/5 CT Saturated (Ω) | With 200/5 CT Not Saturated (Ω) | With 200/5 CT Saturated (Ω) |
| Electromechanical Product (A) | 4.44 | 0.97 | 383.37 | 100.9 |
| Electromechanical Product (B) | 3.75 | 3.41 | 69.37 | 61.85 |
| Electromechanical Directional Overcurrent | 8.93 | 0.88 | 841.37 | 107.07 |
| Static Analog Directional Overcurrent | 0.70 | 0.63 | 41.37 | 36.27 |
| Static Digital Directional Overcurrent | 0.90 | 0.73 | 51.37 | 43.25 |

of the current contribution from the phase cts. This should have little effect on the proper operation of the relay. Sufficient operate current should exist from the neutral ct contribution to cause the relay to operate.

However, for external ground faults where the fault current is sufficient to drive the cts into saturation, misoperation could occur. This condition is compounded by the fact that electromechanical product-type relays place an extremely high burden on the cts. Table 1 indicates typical burden values for the types of relays described in this paper – electromechanical product and directional overcurrent, static analog and static digital directional overcurrent.

Table 2 shows the relative burden on the phase and neutral cts considering the reflected impedance through the 1:10 A auxiliary ct for saturated and non-saturated conditions (i.e., the values given for the 200/5 ct evaluation include the 2000/5 ct for the saturated condition). These results are based on typical ct winding impedance and lead resistance values, with relay burden from Table 1. The reflected burden on the neutral ct is minimal in all cases. Although significantly higher, the burden attributed from electromechanical directional overcurrent relay is within reason. However, an examination of the burden placed on the 2000/5 ct indicates considerably higher values, especially for the electromechanical devices. There are also major variations between the saturated and non-saturated conditions. A major contributing factor is the reflection of the burden through the auxiliary ct, where the base burden must be multiplied by the square of the turns-ratio of the ct. This will produce considerably higher values for the electromechanical relays, which have an inherent higher value of base impedance than the static type relays.

On the other hand, static directional ground-overcurrent relays will perform adequately for both internal and external faults using either the standard auxiliary ct connection or the auto-transformer ct connection.

## V. SUMMARY

The use of ground differential for the protection of impedance grounded transformers and generators has been increasing over the last several years. Because of its inherent selectivity and speed of operation, ground differential provides excellent protection against ground faults within the grounded winding of the equipment. However, several factors should be considered when applying ground differential protection to a power system. These factors include the type and ratings of the equipment being protected, whether it is a new installation or a retrofit project, and the type of relay being used.

The ratings of a transformer or generator will determine the normal load current and the available fault current. The load current will affect the ratio of the cts that are used and determine the requirements for the auxiliary ct. The available fault current will play a factor in determining the level of impedance grounding necessary.

The type of installation will also affect the application of ground differential protection. If the installation is new, selection of impedance grounding level, main ct ratio, and auxiliary ct ratio provides greater latitude for the protection engineer to ensure proper protection levels. If the installation is a retrofit to existing equipment, the selections are typically limited. The impedance grounding is normally in place already, as is the phase and neutral cts. It then becomes necessary for the protection engineer to select the proper auxiliary ct ratio and relay that will best fit the system for the given conditions.

As indicated in this paper, there are different relay types that may be used to provide ground differential protection. The method used in the past has primarily been the electromechanical product type relay. However, static design directional overcurrent relays are gaining acceptance in this application because of their added benefits.

The electromechanical relay provides adequate protection for most conditions. However, ct saturation is a concern because of the inherent higher burden values of these devices. The tap selection used for generator applications should also be considered carefully to ensure adequate winding ground fault protection while limiting the burden placed on the ct circuits. In addition, the auxiliary ct may be connected in an autotransformer configuration to help eliminate possible false tripping.

Static directional overcurrent relays provide selective, sensitive, high-speed protection against ground faults within the equipment. One major advantage with static analog or static digital relays is their lower burden rating. This lower burden reduces the chances of causing ct saturation, leading to misoperation.

In addition, the reduced burden of static relays may allow the selection of lower excitation class cts, resulting in reduced physical space requirements, as well as additional cost savings. Static relay design also provides greater accuracy, reduced maintenance requirements, and most likely, added capability at a reduced cost compared to the electromechanical devices.

Either relay design, static or electromechanical, may be applied for ground differential protection schemes on impedance grounded transformers and generators. Each application should be evaluated regarding ct burden and saturation to ensure proper operation. The protection engineer should carefully consider the application factors outlined in this paper to ensure that the desired level of protection is provided.

## REFERENCES


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## BIOGRAPHIES

**Norman T. Stringer** (M'82-SM'95) received his BSEE degree from the University of Texas at Arlington, in 1982 and his MBA. degree in Engineering Management from the University of Dallas, in 1985. Mr. Stringer has over twenty years experience in power system protection. He began his engineering career with TU Electric in power systems protection. He later served as a Regional Applications Engineer for ABB Power T&D and as a Senior Engineer for Brown & Root USA, Inc. In 1991, he joined Basler Electric Company in Houston, Texas. While at Basler he held positions of Regional Applications and Sales Manager, Regional Sales Manager, and Manager of Sales and Technical Support Department. In January 1999, after a short stay with OMICRON electronics, he joined Cooper Power Systems in Houston, Texas, where he is currently the Relay Sales Manager for the Industrial Market.

Mr. Stringer is a member of the IEEE Industry Applications Society (IAS) and the Power Engineering Society. He is actively involved in the Industrial and Commercial Power Systems (I&CPS) Department where he serves on several committees. These include: Chair of the I&CPS Awards & Recognition Committee, Chair of the Medium-Voltage Protection Technical Subcommittee, Chair of Chapter 14 and Co-Chair of Chapter 4 of IEEE Standard 242 (Buff Book), and is a member of the Power Systems Protection (PSP) Committee and the Technical Books Coordinating Committee. Mr. Stringer is a Registered Professional Engineer in the State of Texas.

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