Application of Transformer Ground Differential Protection Relays

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***Abstract*—Transformer ground differential protection relays (device 87G) have been used to protect the windings of resistance-grounded transformers. A number of strategies have been utilized with electromechanical relays in the past. With the advent of the multifunction digital protective relay, these strategies can be adapted to continue this form of protection.**

***Index Terms*—Differential relaying, ground-fault protection, protective relaying, transformer protection.**

I. Introduction

INDUSTRIAL power distribution system substation transformers often utilize resistance-grounded wye secondary windings for medium-voltage power distribution. The purpose of this is to limit damage due to ground-fault currents, while providing sufficient fault current for the operation of ground-fault relaying. The relaying utilized for the protection against ground faults in the system may not provide sufficient protection of the transformer winding against internal faults because the backup ground overcurrent relay in the transformer neutral-to-ground connection must be set to coordinate with downstream relays. In order to protect the winding itself, special relays are utilized. These include the following:

- ground differential protection with a time-overcurrent relay;
- ground differential protection with a percentage differential relay;
- ground differential protection with a percentage differential relay designed for this application;
- product-type ground directional overcurrent relay;
- restricted earth-fault relays.

Ground differential protection is now provided in multifunction digital relays. Transformer protection relays may include this feature using one of the schemes used with component relays. If a feeder protection relay is used on the secondary, in some cases, this may have a ground directional feature that can be utilized for ground differential protection.

Paper ICPSD 99–15, presented at the 1999 IEEE/IAS Industrial and Commercial Power Systems Technical Conference, Sparks, NV, May 2–7, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Power Systems Protection Committee of the IEEE Industry Applications Society. Manuscript submitted for review May 6, 1999 and released for publication July 24, 1999.

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Publisher Item Identifier S 0093-9994(00)00038-4.

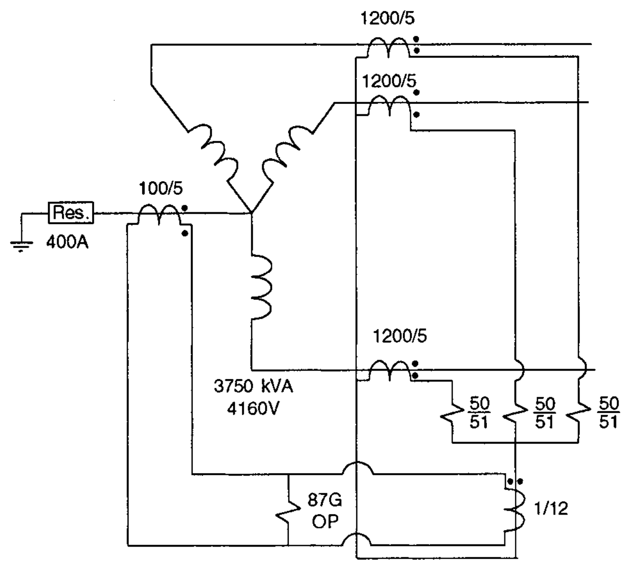


Fig. 1. Time overcurrent relay connected as a differential ground relay.

II. Ground Differential Schemes

The schemes discussed here have been implemented with component-type relays, where one relay performs each function.

A. Ground Differential Protection with a Time-Overcurrent Relay

The simplest method of ground differential relaying is to connect a time-overcurrent relay between the residual point of the phase CT's and a neutral–ground CT (Fig. 1) [2]. Because the CT ratios are usually not equal, an auxiliary matching CT is required. This application will require a neutral–ground CT with a high saturation voltage. There have been problems with the misoperation of this scheme using electromechanical relays. However, the application of low-burden electronic relays makes this scheme much more secure.

The sensitivity required depends upon the portion of the winding to be protected. Assuming that the voltage is induced uniformly across the windings, a relay which is set at 5% of the maximum ground-fault current will protect 95% of the winding. This would require a sensitivity of 20 A for a 400-A grounding resistor. The design issue is to select a relay–CT combination that will be sufficiently sensitive to cover the winding yet be insensitive to external faults. If there is unequal remnant flux in the phase CT's, a ground-fault current may be sensed when an

TABLE I
PERFORMANCE OF 87G WITH VARIOUS RELAY–CT COMBINATIONS

CT Ratio	Relay Tap (A)	Relay Type	Relay +CT + Lead Burden (Ω)	Relay Current @ 400A	Required Min. CT Voltage (V)
100/5	1.0	EM	1.1	20	22
100/5	1.0	SS	0.16	20	3.2
200/5	0.5	EM	4.1	10	41
200/5	0.5	SS	0.19	10	1.9
400/5	0.25	EM	16.2	5	81
400/5	0.25	SS	0.25	5	1.25

external phase–phase fault occurs. For this reason, a relay with a restraint winding is normally preferred for this application.

An external ground fault, in the worst case, will be the full 400 A, and may cause saturation of the CT on the resistor. (The line-side CT's will have a higher ratio and can be assumed not to saturate.) Table I shows the calculation of the required minimum CT voltages where the leakage current is less than the relay tap setting. CT saturation calculation methods are given in [1]. When electromechanical relays are used, many commonly used auxiliary CT's will not meet this requirement. It is necessary that a high-accuracy CT be selected. However, the use of an electronic relay effectively eliminates this problem. With standard relays, a pickup setting of 0.5 or 1.0 A would be used.

The electronic relay used in this application may have a typical burden of less than 0.1 Ω, regardless of setting. Thus, there would be no potential problems of false operation on external faults due to CT saturation. Electronic overcurrent relays have not, however, been used very frequently in this application. A single-phase unit would be necessary. A packaged three-phase relay would need an additional ground-fault function with a separate current input.

B. Ground Differential Protection with a Percentage Differential Relay

This will replace the time-overcurrent relay (87G) of Fig. 1 with a percentage differential relay (Fig. 2). With the auxiliary CT in use, both windings may be set on the same tap.

The purpose of the percentage differential relay is to permit sensitive operation for low fault currents while preventing misoperation due to CT saturation on high-current external faults. The CT leakage current at the maximum external fault current (here, 400 A) is calculated. It is then divided by the relay current and compared to the slope of the relay. If

$$\frac{I_e}{I_{\text{fault}}} \times \text{CTR} \times 100\% < \text{ Slope}(\%)$$

where I_e is the CT excitation current, then the relay will not operate for external faults.

The sensitivity of the percentage differential relay will typically be about 30%–40% of tap setting. The tap setting should be selected so that 95% coverage of the winding is achieved.

Single-phase percentage differential relays have long been available in electromechanical versions. Electronic percentage differential relays are typically available in packaged three-phase units designed for the protection of a particular piece of equipment. This scheme could be implemented by adding it to such a multifunction relay.

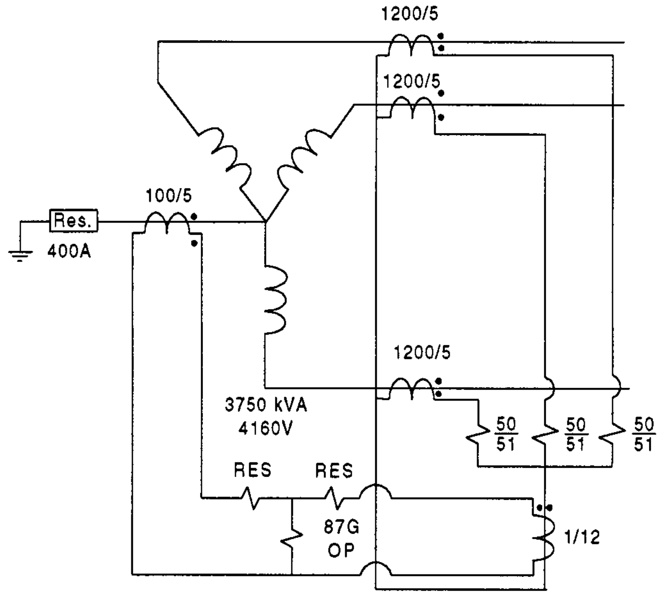


Fig. 2. Percentage differential relay connected as a differential ground relay.

C. Ground Differential Protection with a Percentage Differential Relay Designed for This Application

This type of induction disk relay has its operating coil in the neutral–ground CT circuit, and three restraint coils, one in each phase of the circuit breaker CT circuits (Fig. 3). The restraint coils produce a torque in proportion to the square of their current. This means that the relay is nondirectional, and should only be used when there are no other sources of ground-fault current than the transformer being protected. The restraint coils produce torque in a direction that opposes the closing of the relay contacts.

This type of relay was made in electromechanical form, but no electronic version has been produced.

D. Product-Type Ground Directional Overcurrent Relay [4]

The product-type relay is an induction disk unit originally intended as a directional overcurrent relay for the protection of transmission lines against ground faults [3], [4]. The electromechanical product type relay itself is of interest mainly because of its extensive use in existing installations. No electronic version of this relay has been produced.

It has two coils, which are placed in the neutral and residual circuits. The operating torque is proportional to the product of the two currents and the cosine of the phase angle between them. When the two currents are in the same direction, contact closing torque is produced. Fig. 4(a) shows the relay connected as a directional relay, while Fig. 4(b) shows the relay connected as a differential relay. It should be noted that the scheme in [3] is slightly different from that shown in the figures, but has the same general effect. When used for protection of the transformer winding, the direction of maximum torque is into the transformer. The construction of this now-obsolete relay type

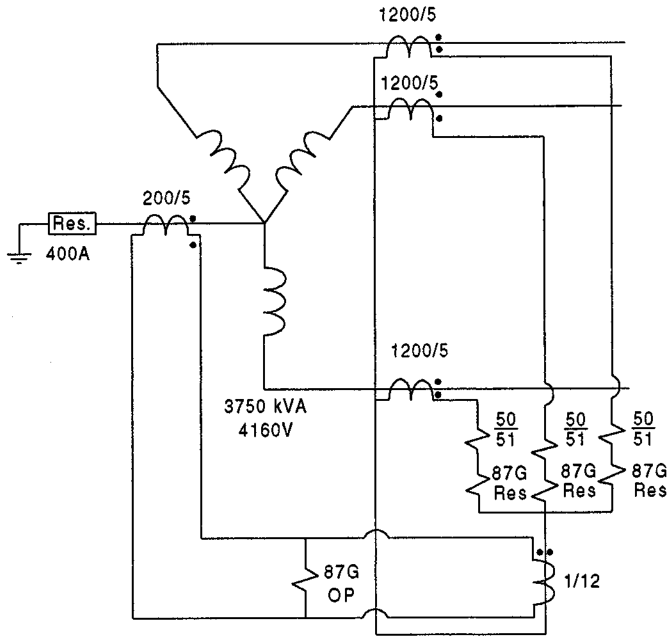


Fig. 3. Transformer ground differential relay.

resulted in constraints on the relationship of operating and restraining current which do not exist with newer technology.

The burden of the relay coils could result in saturation of the neutral CT for the maximum ground-fault current. This would reduce the current into the relay from this source. For an external fault, a current will be produced in an opposing direction by the phase CT's and auxiliary CT. If the current from the auxiliary CT is not reduced by saturation, while that from the ground CT is, then a net reverse current will flow into the operating coil. This will result in a contact opening torque. If no CT saturation were involved, then the operating coil would have a net current of zero, and no torque would be produced. Thus, CT saturation adds to the reliability of the scheme.

E. Restricted Earth-Fault Relays

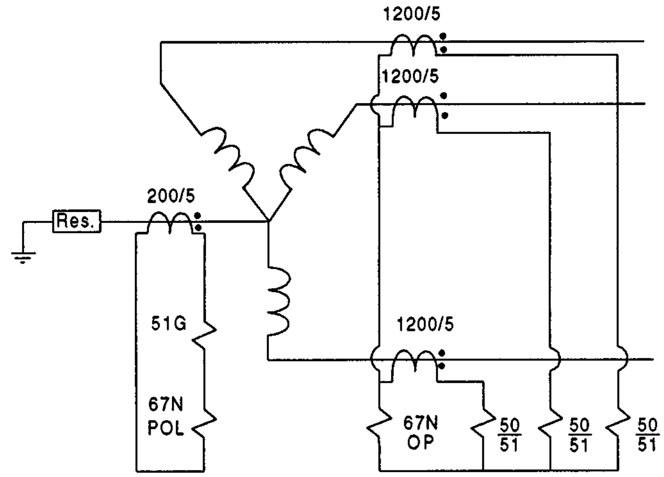
The restricted earth-fault relay [2], [5] is a high-impedance differential relay scheme (Fig. 5), which is widely used in Europe. It is essentially similar to the high-impedance bus differential relay. All CT's must have the same ratio. The voltage setting of the relay is higher than the voltage that would be seen if one of the CT's saturated for an external fault. The relay is protected by a surge arrester against damage from the high voltages that will be seen for faults within its zone of protection.

For this example, with 1200/5 CT's as above, the voltage seen on CT saturation for an external fault is

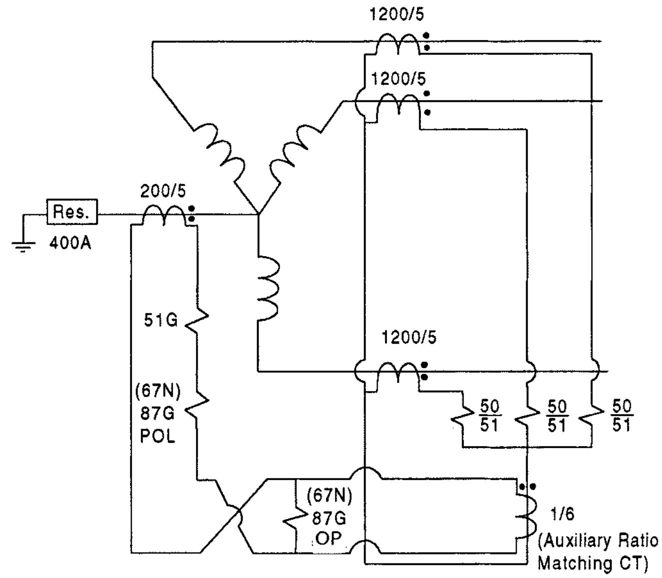
$$V = \frac{I_f}{n}(R_{ct} + 2R_w),$$

where I_f is the maximum through fault current, n is the CT ratio with resistance R_{ct}, and lead resistance R_w. If the phase-fault current is assumed to be 6500 A

$$V = \frac{6500}{240}(0.34 + 2 \times 0.029) = 10.8. \text{ V}.$$



(a)



(b)

Fig. 4. (a) Product-type relay connected as a directional ground relay. (b) Product-type relay connected as a differential ground relay.

The relay is set by means of an adjustable resistor in series with the operating element. The sensitivity of the relay is

$$I_{OP} = n(I_R + NI_e) = 240(0.038 + 4 \times 0.01) = 19 \text{ A}$$

where I_R is relay operating current at its setting (this data provided by relay manufacturer), N is the number of CT's and I_e is the CT leakage current at the setting voltage (determined from CT saturation curve). In this example, 95% of the winding is protected.

Because the restricted earth-fault relay is designed to operate with saturated CT's, no external time delay is required.

III. Multifunction Microprocessor Relays

A. Ground Differential Protection with a Percentage Differential Relay Function

New transformer protection schemes are usually built using multifunction microprocessor relays. Some relays of this type

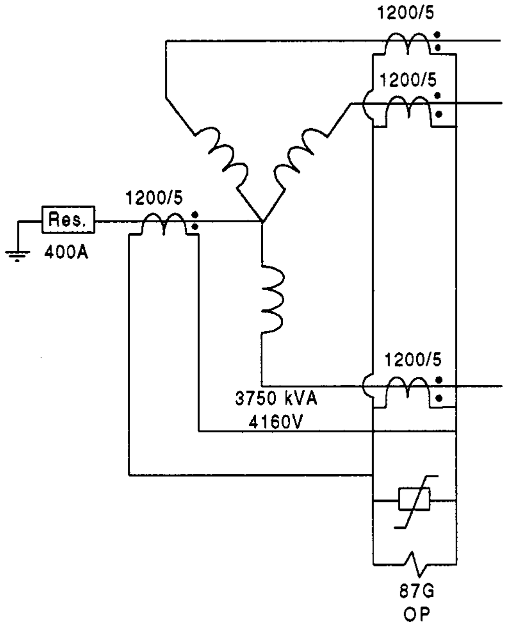


Fig. 5. Restricted earth-fault relay.

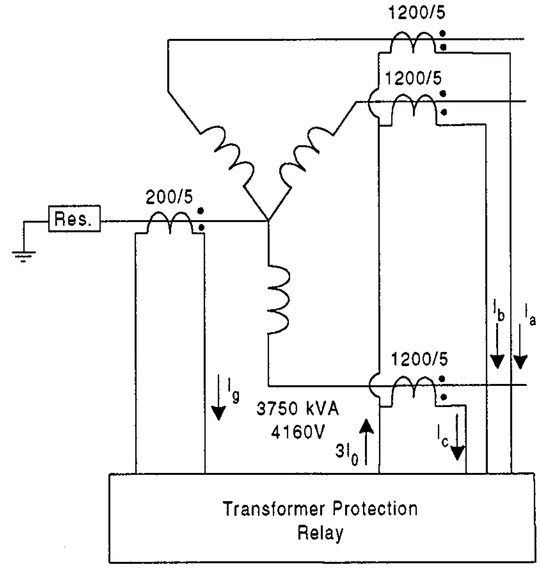


Fig. 6. Multifunction microprocessor transformer protection relay.

incorporate a ground differential function. This may be implemented as a percentage differential relay with inputs from each of the phase CT's and the ground CT. The relay connections are as shown in Fig. 6. The block diagram of the protective function is shown in Fig. 7.

For a 3750-kVA 4160-V transformer, the relay settings are as follows. The current to be detected for 95% coverage of the winding with a 400-A resistor is

$$I = \frac{100\% - \%\text{coverage}}{100\%} \times I_{\text{fault}} = 20 \text{ A}.$$

The full-load phase current is 520 A. The ground differential current I_{gd} is the difference between the ground current I_g and the residual current $3I_0$

$$I_{gd} = |3I_0 - I_g|.$$

The residual current $3I_0$ can be found by looking at the increase in per-unit primary current I_p due to the fault. If the relay is to protect 95% of the winding, this is a small effect, which can usually be ignored. For example, if there is 20 A flowing into an internal ground fault, the secondary load current in that phase is not decreased by 20 A. In fact, it is increased by 1 A. This can be seen from Fig. 8, where the secondary winding is considered as an autotransformer. Let I_1 be the current in the faulted section, I_f be the fault current, and I_2 be the current in the rest of the winding due to the fault. Then,

$$I_2 = I_1 - I_f$$

by Kirchhoff's law, and because of the turns ratio, I_f can be compared to the full-voltage resistor current I_R

$$I_f = \frac{I_2}{I_1} I_R.$$

These equations can be solved for I_1

$$I_1 = \frac{I_f I_R}{I_R - I_f}$$

with $I_R = 400$ A, $I_f = 20$ A, $I_2 = 1$ A, and I_2 is $3I_0$. Then, the differential current is

$$I_{gd} = |1 - 20| = 19 \text{ A}.$$

The relay will be set to pickup at this value.

The slope is set so that the relay will trip for the minimum differential current at the maximum line current (full-load current $+3I_0$) :

$$\text{Slope} = \frac{I_{gd}}{I_{\text{line}}} \times 100\% = \frac{19}{521} \times 100\% = 3.6\%.$$

If the 1-A correction had been neglected, the result would have been essentially the same. In order to prevent false tripping due to CT errors, the minimum slope setting should be about 4%. This will decrease the sensitivity slightly under full-load conditions. Because the slope is calculated based upon the maximum phase current rather than the current into the differential circuit, the percentage values appear to be lower than with the traditional differential relay, although the effect is similar.

The final setting is for time delay. This will be set to allow for instantaneous relays downstream to clear high current faults.

B. Ground Differential Protection with a Directional Overcurrent Relay Function

Another multifunction microprocessor relay that may be seen on a transformer is the feeder protection relay. Many such relays contain a ground directional function, which may be configured in a similar manner to the product-type relay discussed above. In order for this to be possible, the types of polarization available should be examined, and the CT input connections. The relay must have a separate ground CT input which provides the

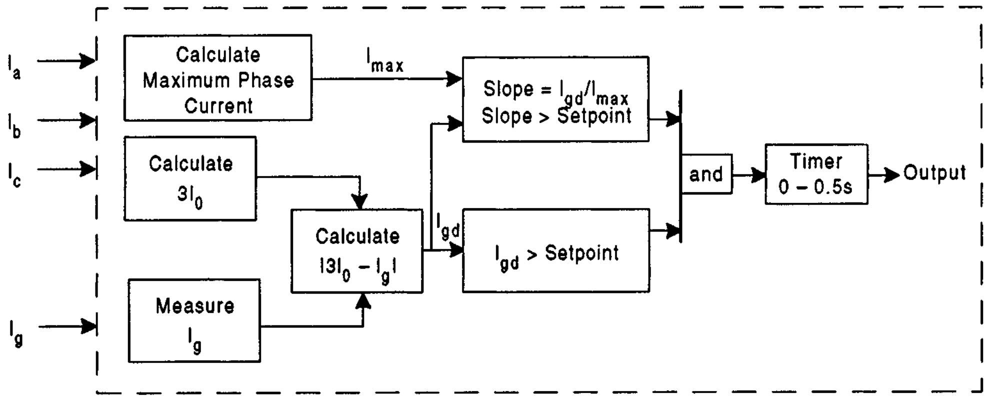


Fig. 7. Multifunction relay ground differential block diagram [6].

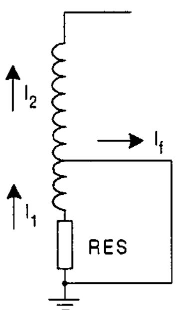


Fig. 8. Transformer secondary winding ground-fault currents.

operating current for this function. Residual current should not be used as the operating current.

For relays with current polarization, and a separate current polarizing input, there should also be a separate ground CT input. If this is the case, then the relay can be connected with the operating coil in the differential circuit and the polarizing coil in the ground circuit, as with the product-type relay [Fig. 4(b)]. The relay coils should be connected with the polarization such that the relay will trip for a ground fault within the differential zone.

Voltage polarization may also be used. The relay would then be a directional relay looking into the transformer, rather than a true differential relay.

Dual polarization uses both current and voltage polarization. Because current polarization would also be available, there is no reason to use dual polarization.

TABLE II
SUMMARY OF GROUND DIFFERENTIAL PROTECTION

Relay	Protection Type	External GF Sources	Comments
induction disk time overcurrent	differential	yes	requires good CT
electronic time overcurrent	differential	yes	
Torque controlled time overcurrent	blocking	no	requires extra relays
induction disk percentage differential	differential	yes	
transformer percentage differential	differential	yes	unnecessarily complex relay
transformer ground fault percentage differential	differential	no	restraint against phase-phase faults
product type overcurrent relay	directional connection	yes	not recommended
product type overcurrent relay	differential connection	yes	recommended
packaged ground directional overcurrent	differential or directional	yes	unnecessarily complex relay
restricted earth fault relay	high impedance differential	yes	designed to operate with CT saturation
micro-processor percentage differential	differential	yes	slope based upon maximum line current
micro-processor ground directional overcurrent	differential or directional	yes	must have current polarizing input brought out.

IV. Comparison with Other Forms of Protection

The choice of whether to apply ground differential in addition to transformer differential protection (87) and ground overcurrent protection (51G) will depend upon the size and importance of the transformer being protected. The usual guideline is to start ground differential protection with 10-MVA and larger transformers [7].

With ground overcurrent protection (51G) on a resistance-grounded system, pickup is normally set at 25% of the resistor rating, which results in 75% coverage of the winding. Ground differential protection typically protects 95% of the winding, an increase of 20%.

Transformer differential protection with harmonic restraint (87) is recommended on units rated 5 MVA and above [7]. The primary current due to the fault will be quite small for faults near the neutral point, because the grounding resistor is seen on the primary side through the square of the turns ratio. A fault at 5% of the winding will increase the primary side current by 0.25% of what it would be for a full winding fault. With our previous example of 3750 kVA at 13 800–4160 V, with a 400-A resistor, the primary current for a phase–ground fault would be

69.6 A. With a 300/5 CT, the relay would see 1.16 A. A fault at 5% of the winding would result in a relay current of 0.0029 A. For a typical differential relay sensitivity of 0.20 A, the deepest location where a ground fault could be detected would be at

$$\%\text{winding} = 100\% \times \sqrt{I_{\rm relay} \times \text{CTR}/I_{\max}}$$

where $I_{\rm relay}$ is the relay sensitivity, CTR is the CT ratio, and $I_{\max}$ is the primary current for maximum secondary line—ground-fault current. For the example given

$$\%\text{winding} = 100\% \times \sqrt{0.20 \times 60/69.6} = 42\%$$

of the winding. Thus, the phase differential relay in this example protects 58% of the winding against ground faults. A ground differential relay that protects 95% of the winding protects 37% more of the winding than the phase differential relay.

The destructive force caused by a fault is a function of the square of the current, which is controlled by the grounding resistor, not the size of the transformer. The closer the fault is to the neutral point, the lower is the likelihood that it will do any damage. Because of the lower voltage, the likelihood of the fault occurring is also smaller. The effect of such a fault is to short a few turns through a resistor, causing a very small unbalance in the output from the transformer (see calculations above).

With smaller transformers, the damage caused by a ground fault that is not detectable by the phase differential protection may be quite small. A ground differential relay could trip a transformer for a fault that the transformer could have survived.

V. CONCLUSIONS

In the past, ground differential relaying schemes were implemented with electromechanical relays. These require careful evaluation in terms of sensitivity, effect of CT saturation, cost, and complexity. The various types of protection considered are summarized in Table II. Many of these schemes are no longer used in new designs, as electronic relays have come into general use. Those schemes which can be implemented using a single-phase overcurrent, differential, or restricted earth-fault relay can be constructed with electronic relays. The specialized types of transformer ground differential relays have not been replaced with electronic equivalents. Transformer protection is becoming the province of packaged multifunction relays, and this is where ground differential protection will be found. Either transformer- or feeder-type relays can be utilized, if they contain the necessary functions.

While harmonic-restraint phase differential relays have been applied on transformers of 5 MVA or greater, transformer ground differential relays have been applied for transformers of over 10 MVA [7]. In cases where a greater degree of protection is desired, these relays have been applied on smaller transformers. With the introduction of multifunction electronic relays, the issue of the cost of adding this protection decreases significantly, becoming only a small adder for the extra relay function. An evaluation must then be made of the degree of protection required for the size transformer being considered. The added protection provided by ground differential protection should be balanced against the severity of the faults being detected. Therefore, the existing guidelines for applying ground differential protection are still applicable.

REFERENCES

[1] D. J. West, "Current transformer application guidelines," in *Proc. IEEE I&CPS Tech. Conf.*, Pittsburgh, PA, May 9–12, 1977, pp. 110–126.

[2] *Ground Fault Protection*, C37.91-1985, 1985.

[3] J. L. Blackburn, *Protective Relaying*. New York: Marcel Dekker, 1987, pp. 304–312.

[4] "Directional ground relays, Type ICC," General Electric Co., Schenectady, NY, Pub. GEH-1779.

[5] "High impedance differential relay, type MFAC," GEC Alsthom, Stafford, U.K., Pub. R6007H.

[6] "Transformer management relay, SR745," GE Multlin, Inc., Markham, Ont., Canada, Pub. 1601-0070-AS.

[7] "IEEE recommended practice for protection and coordination of industrial and commercial power systems," in *IEEE Buff Book*, 1986, pp. 430–431.

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