WAYS TO ASSURE IMPROPER OPERATION OF TRANSFORMER DIFFERENTIAL RELAYS

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Abstract

This paper describes the myriad of incorrect ways that have been experienced over the years in connecting transformer differential relays. It emphasizes the fact that the ways that can be used to connect a differential scheme correctly are quite limited. It describes the influence of core-form transformers as compared to shell-form transformers, and the differences in connection required to delta-wye transformers having a high voltage delta, compared to a high voltage wye. Three winding transformer connections are also described.

Introduction

Relay designers work very hard to develop transformer differential relays that will be secure and dependable. However, a considerable amount of background and experience is required to apply them correctly. There is generally one correct way to connect and apply a transformer differential scheme and literally hundreds of ways to connect and apply them improperly. Wrong connections or applications generally manifest themselves in an undesired trip, not on first energization, but the first time any appreciable load is picked up by the transformer.

Ways To Assure Misoperation

Any list of guaranteed methods of producing unsatisfactory behavior of a transformer differential relay should certainly include:

1. Pay no attention to polarity marks
2. Consider the magnitude, but ignore the direction of the transformer phase shift
3. Pay no attention to system phase sequence
4. Fail to consider the no-load tap changer
5. Fail to consider the load-tap-changer
6. Fail to consider the nature of the core of the transformer
7. Treat the third transformer winding improperly
8. Fail to examine current mismatch
9. Fail to set the relay to accommodate the mismatch
10. Use the right taps, but the wrong inputs to the taps
11. Fail to use proper inrush restraint
12. Ground the relay circuit improperly
13. Fail to include a proper neutral return circuit
14. For a wye-winding zero sequence differential using a product-type relay, match the ct currents exactly
15. Use a generator differential relay
16. Ignore a zig-zag grounding bank inside the transformer differential zone

17. Parallel ct's to avoid using a multi-restraint relay
18. Use a [illegible]:1 auxiliary ct.
19. Ignore ct relaying accuracy class
20. Use one set of differential relays for two transformers and switch them independently

Polarity Marks

Current transformers always have subtractive polarity, which means that the primary and secondary polarity marks are physically adjacent to one another. Current flowing into the polarity marking of one winding will be essentially in phase with the current flowing out of the polarity marking of the other winding. In general, polarity marks for ct's will be physically located away from the device that they are an inherent part of, as shown in Figure 1. This convention has evidently been relaxed somewhat in recent years. It may make no difference until some other convention is applied such as "connect all the non-polarity terminals of the ct's together and the polarity terminals to the relays." One result of treating ct polarities haphazardly is shown in Figure 2b. The sum of the two currents flow in the operating circuit of the differential relay, where the difference current should be, and an undesired trip will result.

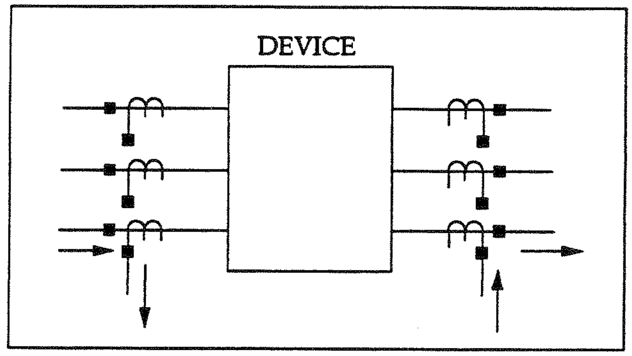


Figure 1. Conventional CT Polarity Locations.

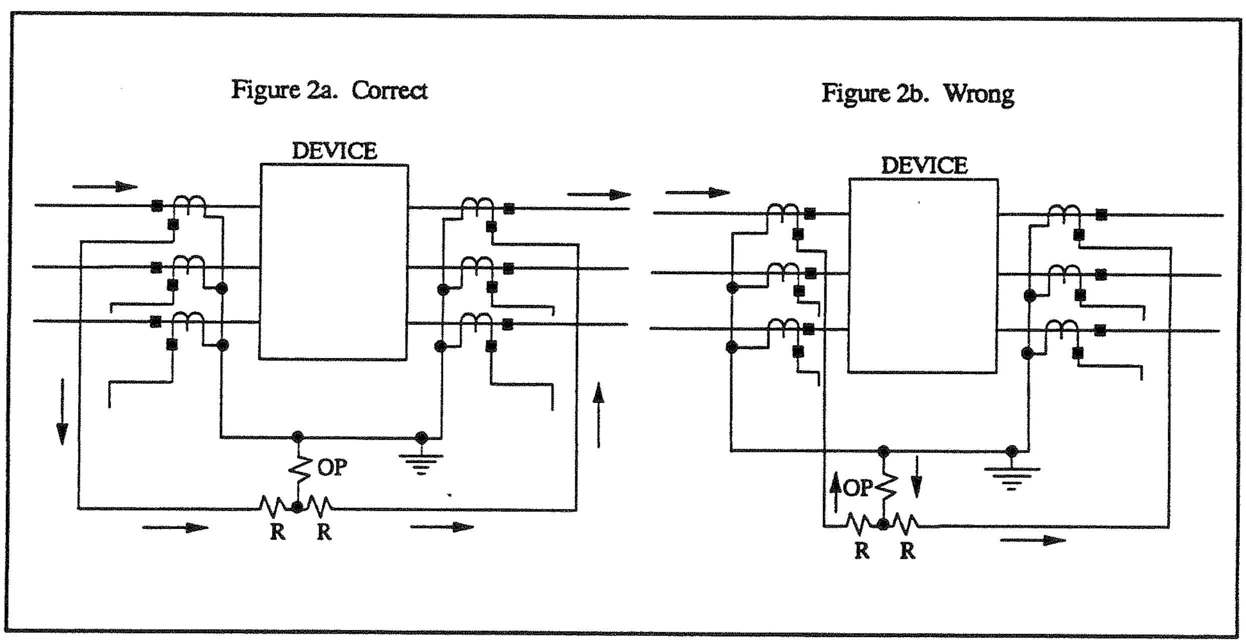


Figure 2. Conventional Polarity Markings Compared to Unconventional.

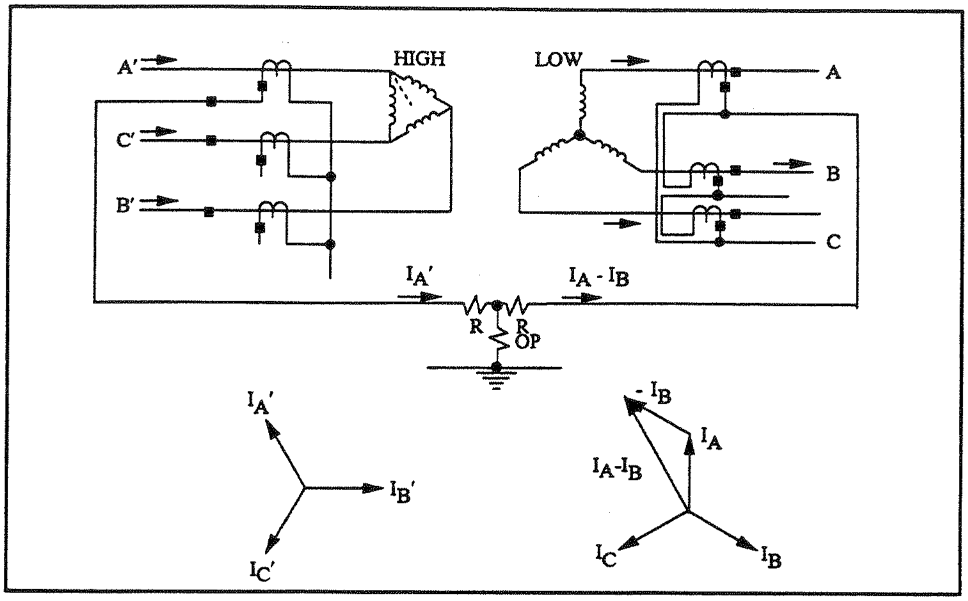


Figure 3. Differential Relay Connections for High-Voltage Delta, Low Voltage WYE.

Phase Shift

Delta-wye transformer differential relay connections differ. For ANSI Standard transformers, of which most are, the high side phase-to-ground voltage leads the corresponding low side to phase-to-ground voltage by 30°. The nominal current shift is the same amount as the voltage shift. Note this standard does not state that the delta leads the corresponding wye voltage nor vice-versa.

Figures 3 and 4 contrast the differences in connections for the two standard delta-wye transformers. Failure to observe this distinction is a guaranteed route to differential relaying disappointment.

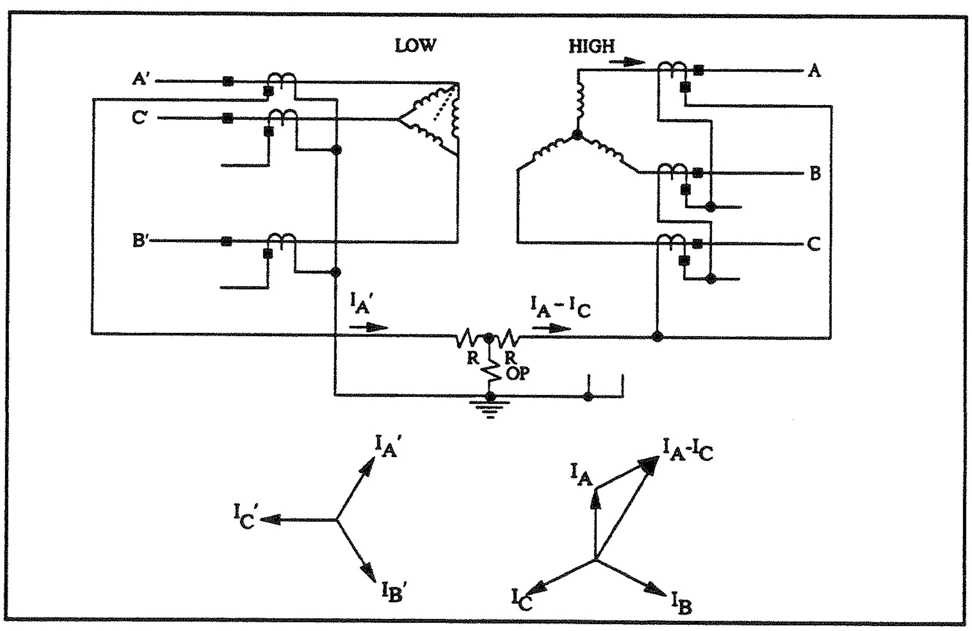


Figure 4. Differential Relay Connections for High-Voltage WYE, Low Voltage Delta.

Phase Sequence (Refer to Figure 5)

Power transformer connections are no different for conventional ABC than the widely used CBA phase sequence. With phases identified A′ B′ C′ connected, in that order, to H_1, H_2, and H_3 high-voltage terminals of an ANSI Standard transformer, if the phase sequence is A′ B′ C′, the leads connected to X_1, X_2 and X_3 voltage terminals will have ABC phase sequence. If the A′ B′ C′ leads connected, in that order to the H_1, H_2, H_3 terminals have C′ B′ A′ phase sequence, the leads connected to X_1, X_2 and X_3 will have CBA phase sequence.

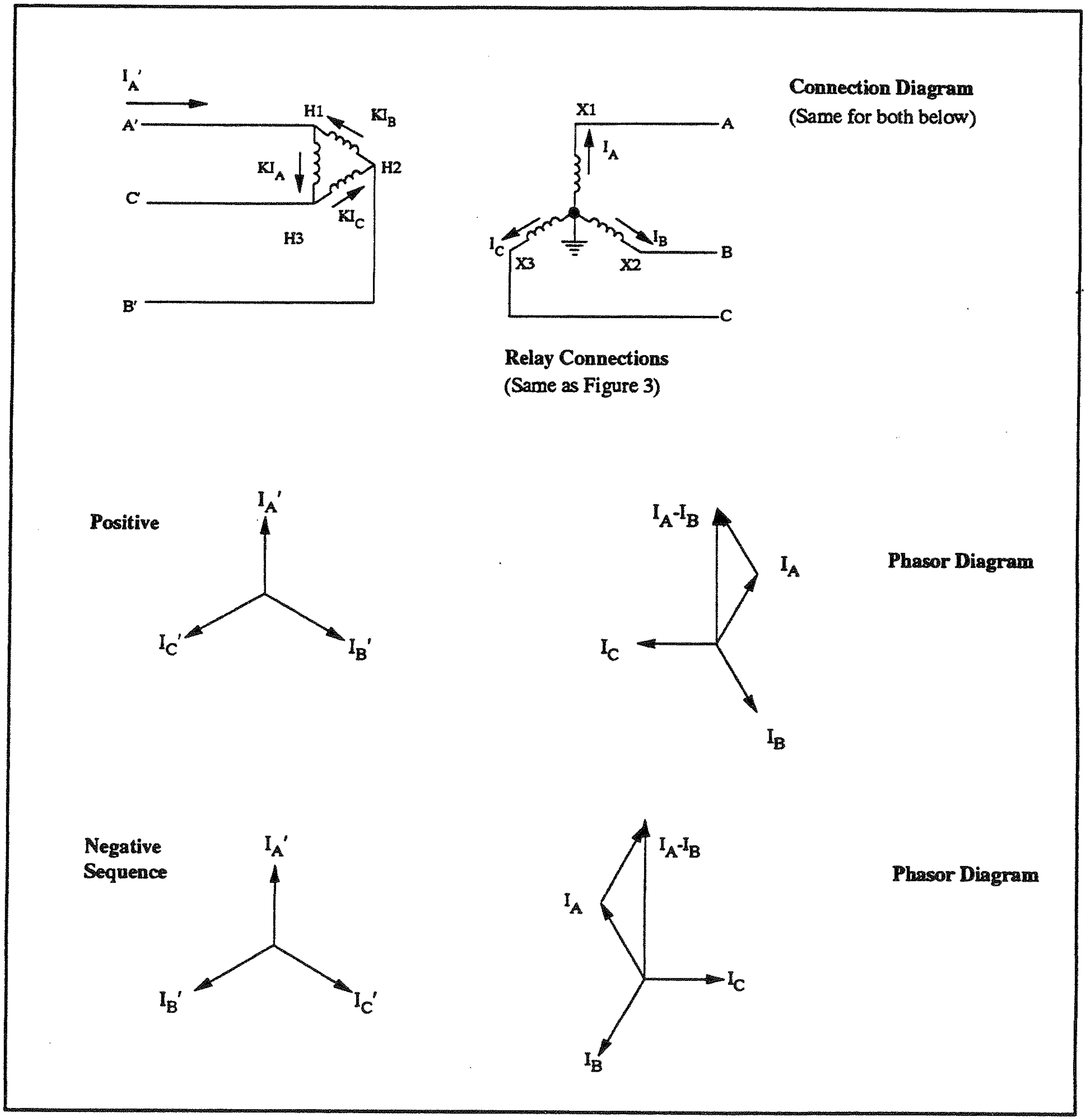


Figure 5. Consideration of Reverse Phase Sequence with Standard Connections.

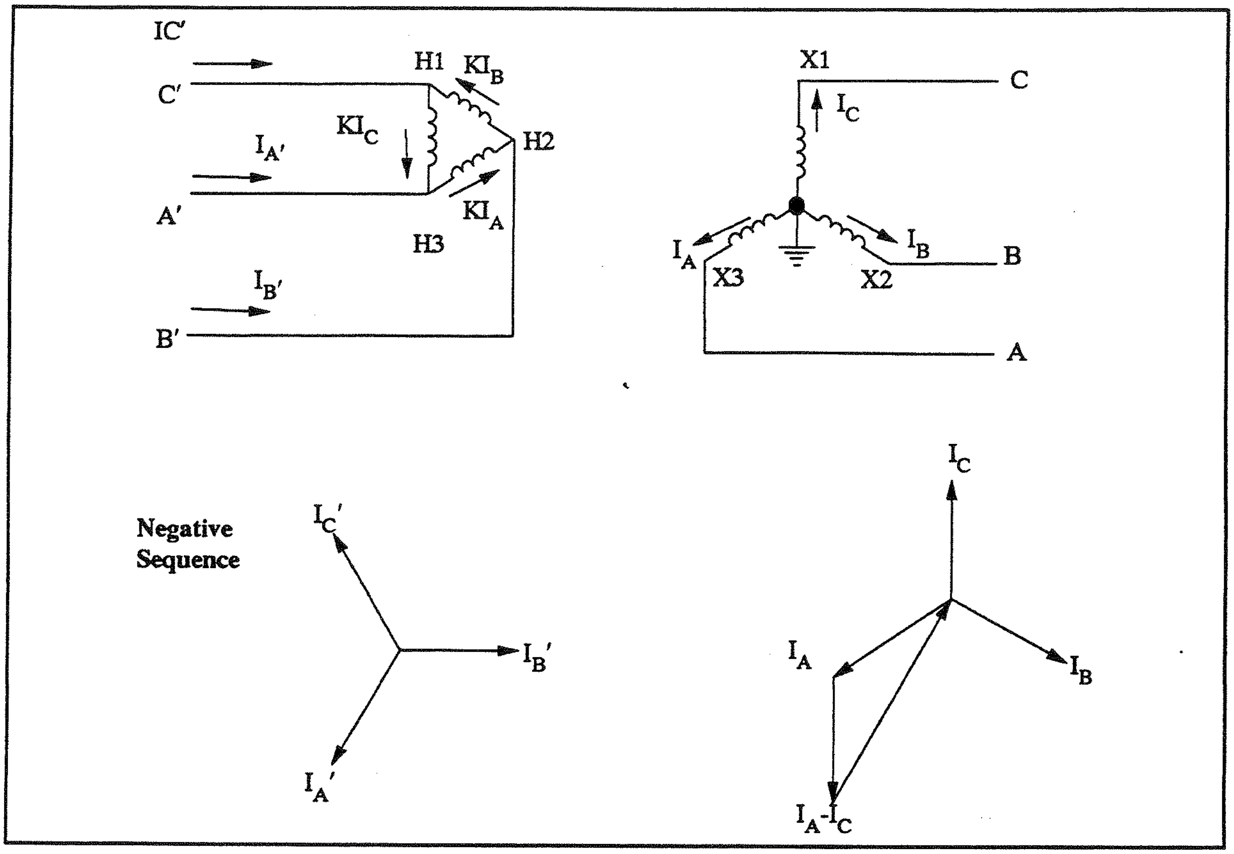


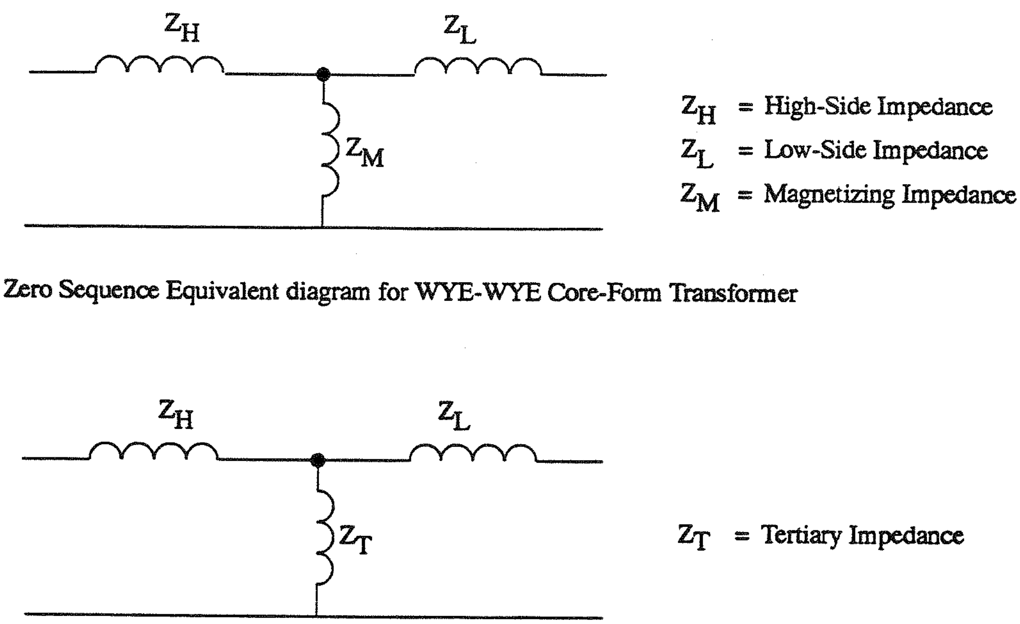
Figure 6. Reverse Phase Sequence and Different External Connections from Figure 5.

This produces the interesting effect that the high leads the low by 30° for ABC sequence, the low leads the high by 30° for CBA sequence, and the same identical connections for the phase leads, the transformer and the relay are applicable.

If now one chooses, because of a reverse phase sequence system, to connect (for an ANSI Standard transformer) C, B and A designated phases to H_1, H_2 and H_3, respectively, the circumstances of Figure 6 require that I_A be compared to I_A - I_C in the differential relay. The other phase connections for the differential relay are made symmetrically. Failure to observe this has lead to years of correct (from the viewpoint of the relay action) but undesired differential relay operations.

Tap Changers

Movement of automatic load tap changers, in response to the need for voltage correction, modifies the ratio of currents on the high side of the transformer to those on the low side. In general, the ±10% range is not particularly disruptive to the transformer differential relay, but it does introduce an error in the comparison circuit which, coupled with other errors may produce a false trip. The differential relay, in general, should be set as if the ratio of the transformer corresponded to the middle of the load tap changer range. One should not forget the no-load tap changer. It may also have a detrimental effect on the differential relay performance. While the automatic load tap-changer cannot be compensated for, with its frequent movement, the no-load tap changer position may remain fixed for years without a manual change. One should take advantage, in setting the differential relay, of a known tap position because it does affect the



a) Zero Sequence Equivalent diagram for WYE-WYE Core-Form Transformer

b) Zero Sequence Equivalent Diagram for WYE-DELTA-WYE Transformer

Figure 7. Comparison of Zero-Sequence Circuits.

relationship between currents in and out of the relay. When the no-load tap position is changed, the relay settings should be reviewed.

Effect of the Core

Most three-phase transformers have magnetic circuits that fall into the core-form or shell-form category. Because the core-form arrangement provides no complete path for the flow of three-phase fluxes that are in phase (zero-sequence), the fluxes must go into high reluctance paths, causing the zero sequence magnetizing impedance to be very much lower than that for positive sequence. Figure 7a shows the zero-sequence equivalent diagram of the wye-wye core-form transformer and compares it in 7b to that of a three winding wye-delta-wye transformer. The similarity has led to the reference of the core-form transformer as having a "residual tertiary." Because of the lowered shunt branch impedance Zm, manifested by the character of the magnetic circuit, zero sequence current flow in one of the windings will not be matched by zero-sequence current in the other (on a per unit or ampere-turn basis), when an external ground fault occurs.

While the cursory observation of the wye-wye core-form transformer would lead one to the conclusion that the ct's may be connected in either wye- or delta for the transformer differential comparison, consideration of the effect of the core in the zero sequence network proves that only the delta connection of the ct's will suffice. The ct's in the delta will still carry the zero-sequence current associated with the external ground fault, but only positive and negative sequence current will be delivered to the relays. The zero sequence current will simply circulate around the delta loop, thereby producing no effect on the relays.

Third Winding

With a multi-winding transformer having different winding rated KVA's, it is tempting to want to consider those ratings in setting the relay. The ratings are immaterial, except in establishing the ct ratios and possibly in examining the thermal capability of the relay windings. The settings of the relay must be established by considering the transformer, two windings at a time. A 3-phase through-fault at one voltage level, supplied from a source at another voltage level must not cause the relay to operate, even though all other windings be disconnected from their sources and/or loads. All combinations of windings must be considered, two at a time and balance must be achieved with all of them. Figure 8 is representative of this point. Either of the 3 breakers may be open. An external fault may occur on any of the systems

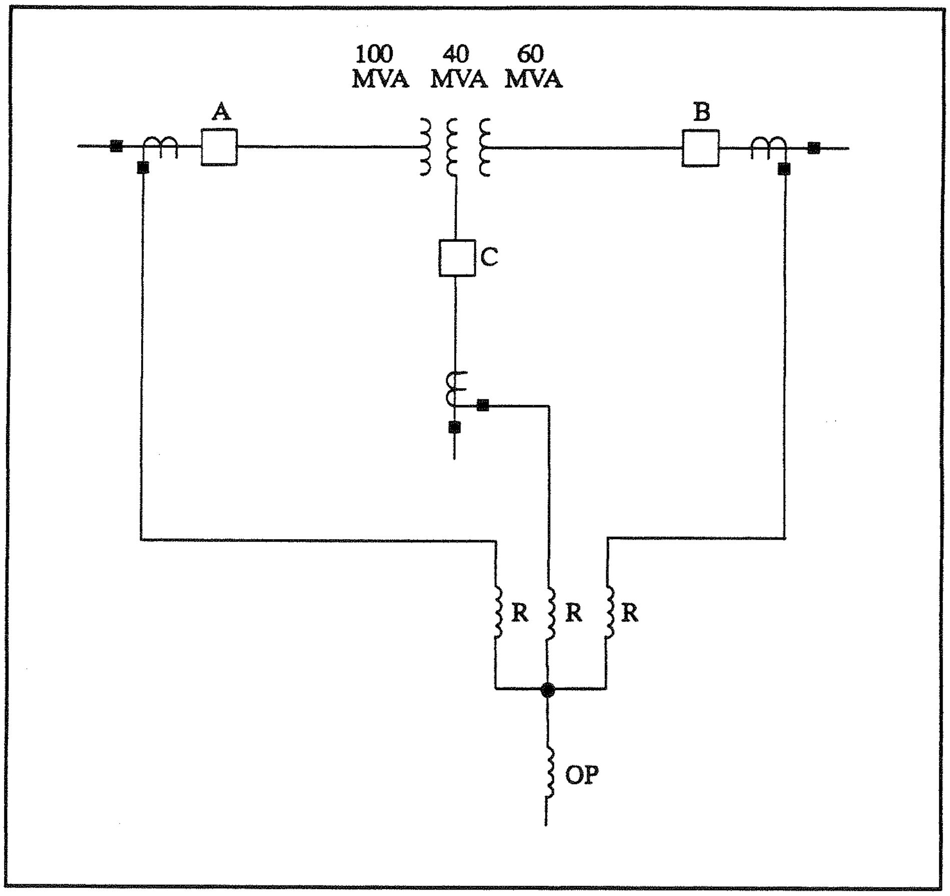


Figure 8. Example of 3-Winding Transformer.

to which the three windings are connected. If, for example B is open, and there is a fault beyond C, there will be a large through-fault MVA. Balance must be achieved in the relay even though there is zero current in B, and the windings to which A and C are connected have different ratings. All combinations (C open, fault beyond B; A open, fault beyond C) should be checked to assure proper balance.

Having done this, proper balance will be achieved in the transformer differential relay for all external fault locations and for all combinations of contributions from the sources.

Mismatch

Some transformer differential relays utilize an internal auto-transformer in the differential circuit. Figure 9 describes this. So long as the ampere-turns balance in the two windings connected to the two sets of ct's, no current will flow in the third winding. The third winding supplies the operating winding of the relay.

With normal load currents in the ratio of 3 to 1, for example, balance (no operating current) is achieved by using taps in the same ratio. In the Figure, 9 amperes is shown balancing 3 amperes. This occurs because the difference current of 6 amperes flows through 1 unit of turns, while 3 amperes flow through 2 units of turns. The effective relationship is $I_1/T_1 - I_2/T_2$ where I_1 and I_2 are currents in the T_1 and T_2 taps respectively. The T_1 and T_2 taps are inversely proportional to the number of effective turns. With discrete ct ratios (e.g. 600:5) and non-discrete power transformer

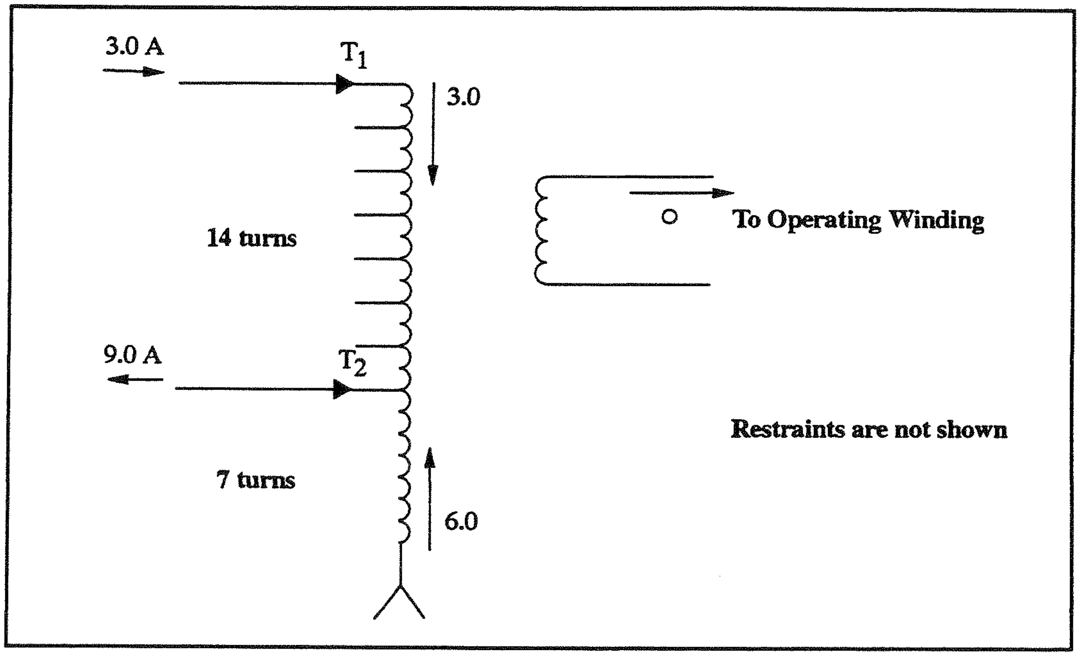


Figure 9. Typical Operating Circuit for Tapped Differential Scheme.

voltage (and current) ratios, odd currents will be associated with full load (or through-fault) conditions. An imperfect match of currents into and out of this autotransformer differential circuit is virtually guaranteed. The mismatch, M, is defined as:

$$M = \frac{\frac{I_1}{T_1} - \frac{I_2}{T_2}}{\text{least}} \times 100$$

where "least" is the smaller of I_1/T_1 or I_2/T_2. With the currents adjusted for all known errors, the mismatch should not exceed approximately 60% of the nominal slope of the relay in use.

Great care must be used to make absolutely certain that the carefully calculated tap values are connected to the proper current inputs. Carelessness in this area will most assuredly guarantee a misoperation as soon as load is applied to the transformer.

Inrush

Years of successful experience and calculations and test have proven second harmonic restraint to be a reliable method of differentiating between inrush and other phenomenon which cause offset wave forms. An outstanding reference on this subject is "Magnetizing Inrush Phenomena in Transformer Banks" by W.K. Sonnemann, C.L. Wagner and G.D. Rockefeller, AIEE Transactions Volume 77, Part 111, PA&S, October 1958, pp 884-892.

It is tempting to search for a better method of recognizing inrush current, but unless all varieties of cores, with all conceivable residual circumstances resulting from the normal non-simultaneous interruption of the magnetizing current in each phase, and all combinations of ct connections are examined, one is quite likely to devise a system with more serious shortcomings than those he is attempting to circumvent.

One misguided concept one might choose to explore is to assume half–wave rectified current. While this is, for the first few cycles, a reasonable waveshape to consider as a severe inrush to a single phase transformer, it is not at all representative of current delivered to a relay during inrush to a three phase delta-wye transformer, for example.

The winding that is energized is important. Energization of the wye-winding (not all three poles at the same time, by the way) involves energization through delta connected ct's. Each of the core legs will have a different residual flux when the transformer is deenergized. Shoulders appear on the relay current waveforms to fill in much of the area that would have zero current in the single phase energization case. Dependence on a dead period is not a reliable method of detecting inrush in the authors estimation.

To have no inrush detection on a transformer differential relay is to place dependence on time delay, the nature of the sensing unit or on chance, if undesired tripping is to be avoided. Inrush current appears as differential current and will operate a simple differential device. If it is slow enough, the relay will override the inrush. In general, the larger the transformer, the longer the inrush.

To assure misoperation, then, with a large power bank of transformers, use a high speed differential relay that is not equipped with inrush restraint or that is dependent on an unproven concept for restraint.

Grounding

The natural tendency is to provide a ground at the ct's and one or more at the relay location in a transformer differential scheme. This will lead to insecurity and possible misoperation of the relays. A difficult concept to accept is that "ground is not ground." A substation ground grid will not be at true-earth potential during a ground fault. Also, most assuredly, the voltage between points with in the ground grid will not be at the same potential. With multiple grounds in a differential relaying scheme, current will flow between those grounds as a result of potential difference. The path of this current flow will be dictated by the impedance in the various parallel paths. This indiscriminate current flow must be eliminated, if false tripping from this source is to be avoided. The solution is to permit one ground only, irrespective of the number of current transformers or relays that are interconnected in the scheme.

Neutral Return

Figure 3 shows the typical partial schematic that describes the interconnection of the ct's and relays for protecting a delta-wye transformer. It is woefully inadequate. It leaves to the intuition the need to determine how, or if, the neutral formed by the three relays should be interconnected with the wye-connected ct's and how, or if, that circuit should be interconnected to the delta-connected ct's.

One might conclude (wrongly) that, since there can be no zero sequence current flow in the leads connected to the delta winding and since the neutral current of the wye-connected ct's is zero-sequence current only, there is no need for an interconnection. However, a ground fault in the delta winding of the power transformer or on the leads connected to it will produce zero sequence current, and there must be a path in the ct secondary circuit and in the relays for this current to flow. The ct neutral and the relay neutral must be interconnected. With the ground at the relay, this also provides a connection between the ct neutral and ground.

Product Type Differential

A scheme that is widely used in protecting wye-connected generators and transformer windings is the product-type ground differential scheme shown in Figure 10. It is generally found in industrial applications and in protection of unit auxiliary transformers.

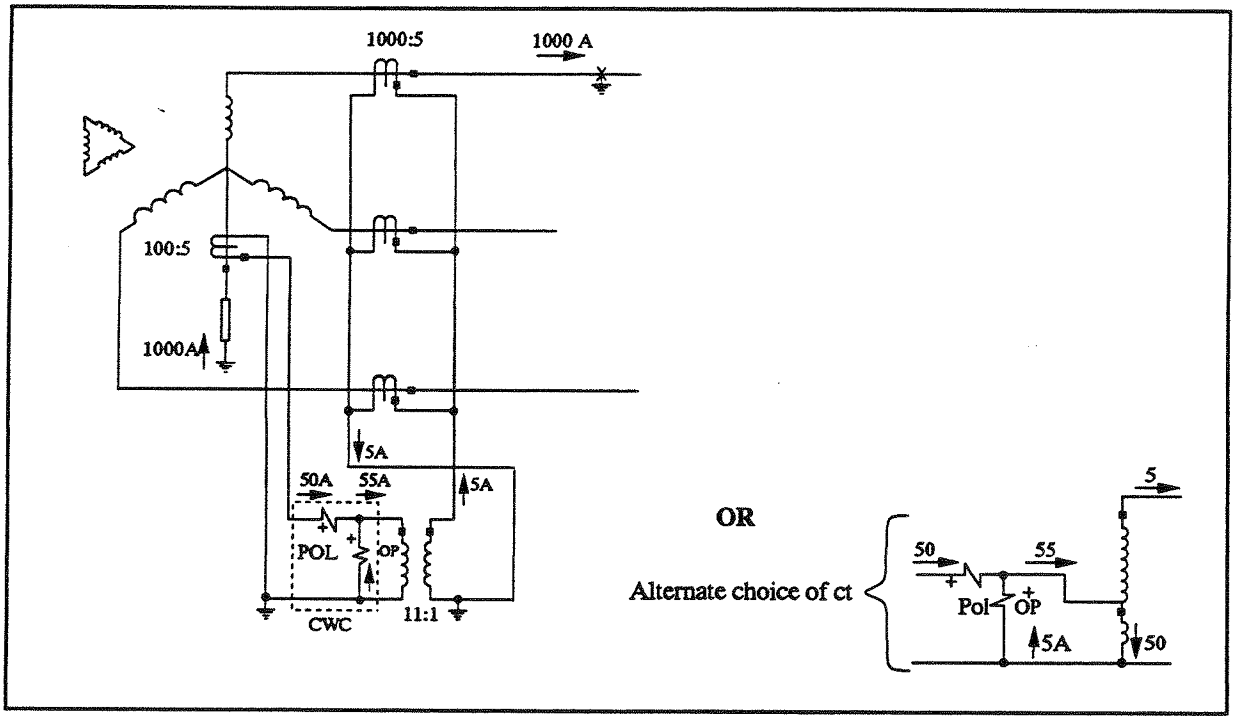


Figure 10. Product Type Relay Used as Winding Differential.

Often, two different ct ratios are used on the two sides of the winding. This requires the use of an auxiliary current transformer. Invariably, our intuitive choice of the ratio of this auxiliary ct is the wrong one. We choose a ratio equal to the ratio of the primary ratings of the two sets of ct's. In the case of Figure 10 that would be 1000/100 = 10 to 1.

A "through" ground fault would produce currents at the relay of equal magnitudes if this ratio were used, and no current would flow in the operating coil circuit. While this sounds good, the reality of the situation can be devastating. Choosing the 10:1 ratio places dependence on perfect or similarly inaccurate performance of the two sets of ct's. If this dependence is ill placed, the operating coil will have current flowing in it, for this external fault, and it can be in either direction. If, on the other hand, we choose, in this case, an 11 or 12:1 ratio of the auxiliary ct to cause an intentional unbalance, the external fault will force operating current to flow in the non-operate direction. This takes the uncertainty out of the behavior of the scheme for external faults.

For internal faults, the operating current will be reliably in the operate direction. Even with a contribution from only the transformer for a fault within the differential zone, the relay operates positively.

The alternate choice of ct's shown in Figure 10 allows the use of the 10:1 ratio transformer, but in an autotransformer mode which makes it have an 11:1 effective ratio. This then produces the desired result. The 10:1 ratio would be obtainable more easily and more economically than would be the 11:1 or 12:1 ratio, 2 winding, auxiliary current transformer.

Generator Differential Relay

A generator differential relay is generally unsuitable for transformer protection because of its lower slope (typically 10%), which describes the operating current as a percentage of minimum restraint. Also, it is not equipped with any provision to allow inrush to be ignored. It should not be used for this function.

Zig-Zag Grounding Bank

A grounding bank is frequently added to systems which contain no other "zero-sequence source," and it is often included within the protective zone of a transformer differential relay. The transformer winding connected to the system on which the zig-zag grounding transformer is located is generally delta connected. This requires that the ct's be connected in wye, and thereby the zero sequence current associated with the zig-zag contribution to external faults will be delivered, undesirably, to the relays unless special provision is included. That special provision is a zero-sequence trap. Figure 11 shows how the zero-sequence current is accommodated and excluded from the relays.

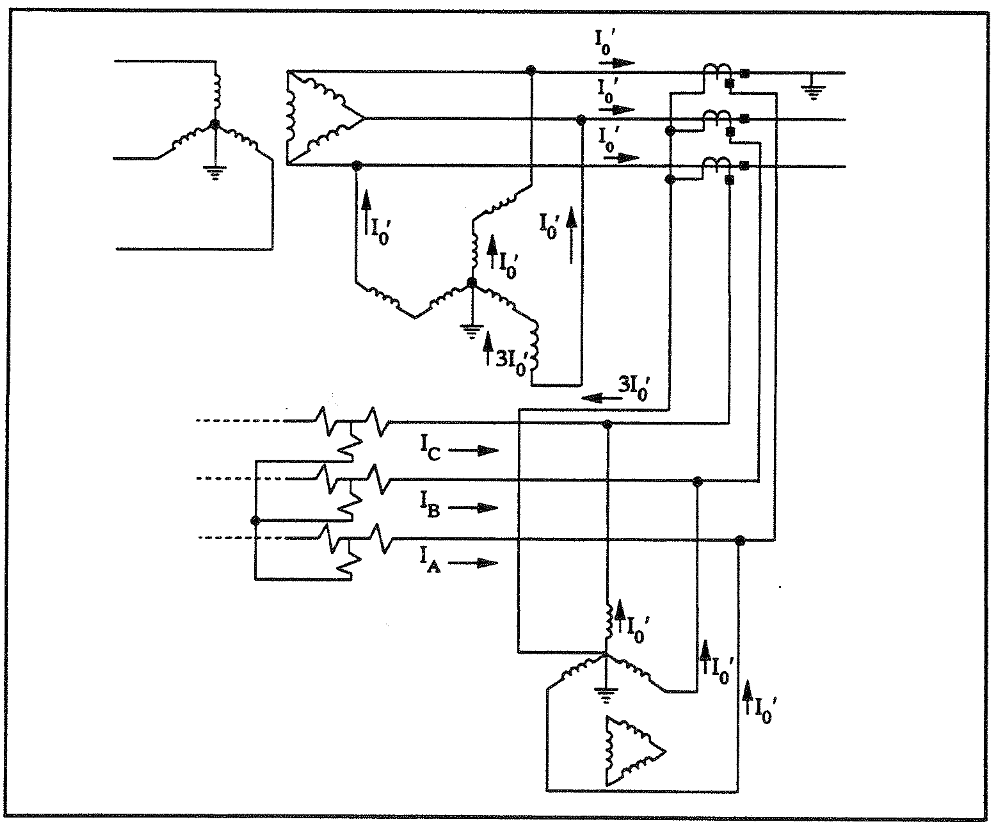


Figure 11. Grounding Bank Inside the Transformer Differential Zone.

Note that this configuration requires that the relay neutral (formed by interconnecting the operating coil circuits from the three phases) not be connected to the ct neutral. If it were, a false trip possibility would exist because all of the zero-sequence current would not be confined to the zero-sequence trap for an external ground fault.

Parallel ct's

Paralleling feeder circuit ct's, as in Figure 12a, produces no problem. Faults will occur on one circuit at a time. On the other hand, paralleling ct's, as in Figure 12b, where large through-current (not limited by transformer impedance) can occur, is indeed a hazard to security unless each circuit is individually allowed to generate its own restraint. If the two upper ct's in Figure 12b were paralleled directly and the "summation" current fed to a single restraint, the external fault would cause this restraint current to be the difference of the error currents of these two ct's. This same current would flow through the operating coil circuit, producing 100% differential and a possible false trip. Use a multi-restraint relay rather than paralleling ct's for this configuration.

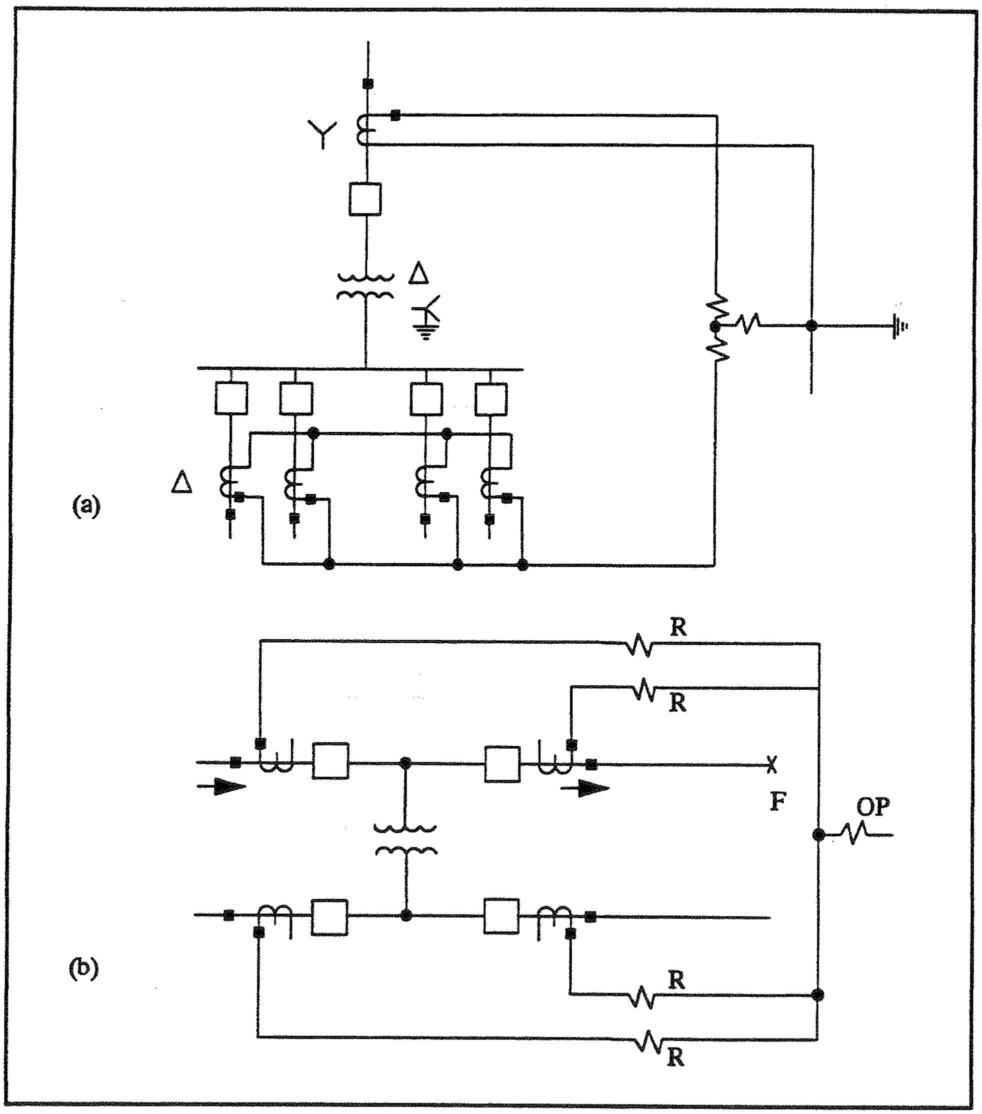


Figure 12. Paralleling Ct's.

Large Ratio Auxiliary ct's

Occasionally, very large auxiliary ct ratios will be required to get into the tolerable range for currents to be matched in a transformer differential relay. From a sensitivity viewpoint, it is desirable to step up one of the currents to the relay rather than stepping down another. If this is done, it should be remembered that the apparent impedance of the relay as viewed from the main current transformers is increased by the turns ratio squared. For example, a 20:1 auxiliary ct will increase the relay burden in ohms to 400 times its value without an auxiliary ct. One should be sure that the ct's can handle it, or better, insert a set of ct's in the right place with the right ratio and get rid of the need for auxiliary ct's. Sometimes, of course, this is not possible.

Current Transformers

No relay can perform accurately using inaccurate information from the ct. In the case of differential relaying, good or identically imperfect behavior of the two sets of current transformers must be the goal. To assure similar behavior on external faults, identical relaying accuracy class voltages, on the ct tap in use, should be chosen. Reasonably matched burdens are required. If different classes or unmatched burdens are present, a detailed study is in order.

The maximum 3-phase through fault current is limited by the transformer impedance. For this fault, the secondary current of each ct should not exceed 100 amperes, and the relaying accuracy class voltage (on the ct tap in use) should not be exceeded. Any deviation from this is a compromise.

For internal faults, large currents will produce instantaneous trip operation (for relays equipped with such). The ct should be chosen so that the maximum dc component of fault current will not cause saturation until the instantaneous unit has had time to operate. For lower currents, the differential elements will recognize the internal fault sensitively, and ct performance is not critical.

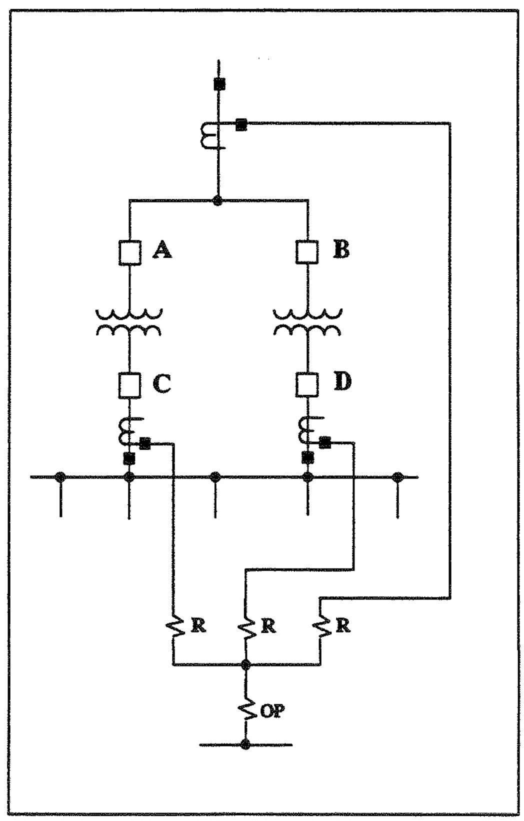


Figure 13. Improper Use of Differential Relays with Independent Switching.

One Set of Differential Relays for Two Transformers

Even though one chooses a differential relay having the finest of inrush trip suppression principles, it will be of little value if it is applied in a scheme such as shown in Figure 13. The difficulty (first described by C.D. Hayward in his paper published in the 1941 AIEE Transactions, page 1096) arises when one bank of transformers is pre-energized and a second is being energized. Both transformers may experience the characteristic inrush waveform, but the peak current in one will occur approximately 180 electrical degrees after that in the other. The combination current which is then delivered to the relay though the current transformers has a comparatively undistorted waveform. Even though large inrush is experienced in one transformer with the "sympathetic" inrush in the other, the differential relay inrush detecting scheme is thwarted because of its observation of the combination current rather than the individual transformer inrush current. False tripping results.

To avoid this, each transformer should be equipped with its own individual differential relay.

Conclusions

Many subtleties exist in the application of transformer differential relays. Failure to be attuned to the needs of the relays and the use of haphazard connections will certainly lead to misoperations. The time spent in making certain the connections and settings are right will be more than rewarded in reliable service.