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BDD and STD Transformer Differential Relays

BDD AND STD TRANSFORMER DIFFERENTIAL RELAYS

INTRODUCTION

Within the past year or so a number of papers have been written regarding the general subject of power transformer protection by means of harmonic restraint differential relays. These papers have raised questions in the minds of many Protection Engineers regarding the adequacy of the harmonic restraint characteristics of existing relays for the protection of modern power transformers. It is the purpose of this paper to first provide a brief history of the development of this type of protection within General Electric; second to define the basic problems of transformer magnetizing inrush and overexcitation, and last to outline the harmonic restraint characteristics of the BDD and STD relays so that users will be better informed with respect to the expected performance of these relays.

SUMMARY

Because the harmonic content of transformer exciting currents (during conditions of overvoltage) and inrush currents cannot generally be predicted accurately, and because every high speed harmonic restraint transformer differential relay responds not only to the harmonic content of the applied current but also to its wave shape, it is not possible to predict by calculation the performance of such relays during these abnormal conditions. Thus, field experience offers the best means for selecting a proper relay. The over 35,000 BDD and STD relays shipped by General Electric during the past 10 years have provided excellent field service. This is very likely the result of a design that provides for harmonic restraint from all harmonics, and produces a transient behavior that adds to the security against false tripping on inrush. In general, reducing the percentage of second harmonic required to restrain a relay or adding harmonics from all three phases to restrain each phase will make a relay more secure against false tripping on inrush. However, this will also tend to delay tripping significantly in the event of a transformer fault at the time it is being energized. Thus, these approaches should be used only where all else fails.

HISTORY

In 1938 the General Electric Co. announced, in the October issue of Relaying the News, a harmonic restraint relay for transformer differential protection. This was the type HDD relay which was indicated to be suitable for protection of two and three winding power transformers. These HDD relays were single-phase devices that operated on fundamental frequency and restrained on all harmonics. They were provided with a slope selection of 15, 25 and 40 percent and a direct trip instantaneous unit. The relays were intended to restrain on 35 percent second harmonic. Because at that time second harmonics were difficult to obtain in test, and third harmonics fairly easy via iron core reactors, the relays were actually adjusted in the factory to restrain on 25 percent third harmonic. The harmonic restraint characteristics of these relays were such that with this third harmonic adjustment they would restrain on 35 percent second harmonic. In 1953 the HDD relays were replaced by the type BDD15A and 16A relays. This was done to reduce the relay size and the burden by substituting a small sensitive Sigma sensing relay for the cumbersome double coil, double throw hinged armature sensing unit of the HDD. No characteristic changes were intended or made.

In 1956 the BDD15A and 16A relays were replaced by the BDD15B and 16B relays. These new devices operated on exactly the same principles as the relays they superceded except that the harmonic restraint was now adjusted with second harmonic (rather than third) to restrain at 20 percent (rather than 35 percent). These changes were motivated by two events that occurred at that time. First, reliable high current germanium diodes became available which made it easy to obtain controlled amounts of second harmonic currents for testing the BDD relay. Second, cold-rolled grain-oriented electrical steels were then beginning to be universally employed in power transformers and it was believed that inrush currents would contain lower harmonic content so that the 20 percent second harmonic restraint figure would be more suitable.

Since 1956 until the present, the BDD15B and 16B have been included in the General Electric Co. offering of electromechanical relays for differential protection of power transformers. During this period, BDD relays with additional restraint circuits have been made available until today relays with as many as 7 restraint circuits are in service.

In 1968 the STD15B and 16B relays were added to the product line. These are static devices that operate on the same principle as the BDD but employ solid static circuitry to replace the Sigma relay. That is, they restrain on all harmonics and operate on fundamental frequency. As is the case of the BDD, the STD relays are factory adjusted to restrain on 20 percent second harmonic content. STD relays with as many as 10 restraint circuits have been developed. While the BDD relays are still available, it is expected that the STD will eventually make them obsolete. This would eliminate the need for the Sigma relay (The sensing unit in the BDD) which is somewhat difficult to adjust.

In late 1975 the original STD15B and 16B relays were superceded by a new line of STD15C and 16C relays. This was done to reduce the dropout delay, and to improve the overall reliability by printed circuit card component part rearrangement and increased surge filtering. Also, the immunity to radio frequency interference (RFI) was increased. No changes were made to the basic operating principles such as percent harmonic restraint, slope, pickup, etc.

Within the last 10 years, General Electric has shipped over 35,000 BDD and STD relays for differential protection of power transformers of all ratings and connections.

GENERAL OPERATING PRINCIPLES

The BDD and STD transformer differential relays are single-phase devices so that three relays are required to protect three-phase transformer banks. Like most other multiple restraint differential relays, the STD & BDD devices utilize a number (depending on the application) of separate restraint circuits plus one operating circuit. The circuits of these relays are arranged in such a way (see figure 1) that during load and external fault conditions, the phasor sum of all the currents entering the restraint circuits is equal to the phasor sum of all the currents leaving so that no (or essentially no) current flows in the operating circuit of the relays. In the case of the STD & BDD relays, the currents flowing in these restraint circuits add together to restrain the relay from operating.

When a fault occurs in the transformer bank being protected, this balance of restraint currents is upset and some current (depending on the severity of the fault) will flow in the operating circuit of at least one of the three phase relays. The relay will operate to trip if the ratio of operating current to restraint currents exceeds the slope setting (15, 25 or 40 percent) and if the magnitude of the operating current is greater than the basic sensitivity of the relay (approximately 30 percent of

The description so far generally applies to all, or most all, multi-restraint percentage differential relays. The harmonic restraint feature of the STD and BDD relays, as in the case of most other harmonic restraint relays, is obtained in the operating circuit by filters that separate the fundamental and harmonic components of the differential operating current. In all harmonic restraint transformer differential relays marketed in the United States today, the fundamental component of current is always used to produce operation and the second harmonic is always used to produce (harmonic) restraint. However, the remaining harmonics are used in different ways in different relays. In the case of the STD and BDD relays <u>all</u> the remaining harmonics are used to restrain the relay from operating. Thus, in these General Electric relays, operation is produced by the fundamental quantity of the differential (operating) current while restraint is produced by <u>all</u> the <u>harmonics</u> in the differential current. This harmonic restraint is added to the restraint developed in the through restraint circuits. The sum total of these restraints is then balanced against the operating quantity developed by the fundamental component of current flowing in the operating circuit.

(It should be noted that General Electric has produced a very small number of STD and BDD relays that operate on fundamental frequency only and restrain only on second harmonic. These relays are applied on a limited basis to protect transformers that supply silicon controlled rectifier loads where high odd harmonic content may exist. These relays are not intended to be a part of this discussion).

In addition to the percentage differential and harmonic restraint characteristics of the STD and BDD relays, a simple instantaneous overcurrent unit is included in the operating circuit of each relay. This unit is set with a rather high pickup (about 8 times tap value) and operates on the RMS magnitude of the <u>total</u> current (harmonics and all) flowing in the differential operating circuit. It provides for extra high speed protection in the event of severe faults in the protected zone.

OVEREXCITATION AND MAGNETIZING INRUSH

In general, except for the distorting effects of current transformer saturation, which over the years apparently have not introduced any problems with harmonic restraint relays, internal fault currents, external fault currents and load currents supplied to relays are comprised of essentially fundamental frequency components. Thus, the harmonic restraint circuits have had little affect on the fault protection afforded by these devices. The user concern that has developed recently relates to the ability of harmonic restraint transformer differential relays to restrain successfully under two different circumstances. First, when the protected transformer is suddenly energized by a switch or circuit breaker in the process of restoring it to service, magnetizing inrush currents to the transformer bank result. These inrush currents appear to the protective relays as differential currents of high magnitude and distorted wave shape. Also, when a transformer bank already in service (loaded or unloaded) is subjected to overvoltage, the magnitude of the exciting current taken by the bank can increase several fold. Here again, these currents contain harmonics and appear to the relays as differential or operating currents. The questions being raised relate to the ability of the existing harmonic restraint relays to successfully cope with these situations in modern power transformers.

Magnetizing Inrush

Figure 2 illustrates a two winding grounded wye-delta transformer, the current transformers associated with the differential protection, and the circuit breakers on both sides of the bank. It will be noted that the current transformers on the delta side of the bank are connected in wye while those on the wye side are connected in delta. In any case, regardless of which side of the bank is energized first, current will flow only in the leads to the windings (primary or secondary) that are energized.

For example, in Figure 2, if circuit breaker 1 is suddenly closed (while circuit breaker 2 is left open) there will be current flow in the leads supplying the wye winding but no current in the leads to the delta winding. If on the other hand, circuit breaker 2 were to be closed (with circuit breaker 1 left open) the converse would be true. In this latter case, current would flow only in the wye connected current transformers through restraint circuit 2 and the operating circuit of the relay. In the former case, current would flow only in the delta connected current transformers, through restraint circuit 1 and the operating circuit of the relay. In both cases, the magnetizing inrush currents to the power transformer, and hence the currents flowing in the operating circuits of the relays, will be relatively high in magnitude and will contain harmonics as well as fundamental frequencies. The magnitudes of these inrush currents will generally be sufficient to operate sensitive differential relays if the harmonic content does not produce sufficient restraint to overcome this operating tendency. It is obvious that whether or not a harmonically restrained transformer differential relay will trip undesirably as a result of inrush currents when the associated power transformer is suddenly energized, depends on the wave shapes of these currents, the current transformers connections and the characteristics of the relay.

From the above discussion it appears that in order to successfully predict the performance of a harmonic restraint transformer differential protection scheme under these conditions, one must first establish the harmonic content of the inrush current in all three phases of the transformer. Next these power transformer currents must be converted to relay currents taking the associated current transformer connections, and any possible saturation effects into consideration. Finally, the steady state and transient characteristics of the transformer differential relay must be taken into consideration and the overall performance determined analytically.

It is obvious that to do this is impractical at best and probably impossible. A General Electric paper "A Dissertation on Power Transformer Excitation and Inrush Characteristics" by Berdy, Kaufman and Winick was presented to the Georgia Institute of Technology Protective Relay Conference in May 1976. Among other things, that paper provides the necessary background discussion to conclude that it is not possible to accurately predict by calculation the harmonic content in the inrush current to three-phase power banks.

It is apparent that the lower the percent harmonics required to restrain a relay, the more secure it will be against false operations during inrush conditions. Unfortunately, reducing the percent harmonics required to restrain a relay makes it less likely to operate, particularly if a fault were to be present during energization of the transformer. Well then, how does one select a relay that has the optimum characteristics for transformer protection? In the opinion of the authors, one must use a combination of engineering judgement plus experience to assure a good selection. Subsequent sections of this paper provide steady state and transient test data relating to the harmonic restraint characteristics of the General Electric STD and BDD relays which it is hoped will provide some assistance to the Relay Application Engineer in this regard.

Overexcitation

In addition to preventing misoperation of a transformer differential relay on transformer inrush currents, harmonic restraint can help to prevent undesired tripping during short time overvoltage conditions that produce large exciting currents in a transformer bank. Such overvoltages (at rated frequency) can occur when an unloaded transformer is "hanging" on the end of a long radial line, or in the case of unit type generator installations, the associated main and auxiliary power banks may be subjected to significant overvoltages for short periods of time in the event of load rejection. When such conditions exist, exciting currents with magnitudes greater than relay pick-up values can sometime result. These exciting currents will flow in the differential (or operating) circuits of the differential relays. If the harmonic content of these currents is not sufficient to restrain the relays, a false trip will result. The Berdy, Kaufman, Winick paper mentioned earlier also discusses transformer overexcitation and concludes that the percent harmonics in the exciting current, in addition to the magnitude of the applied voltage, depends on

a) The design of the transformer
b) The type of steel used in the core
c) The phase of the transformer under consideration
   (The exciting currents in all three phases of a three-phase transformer bank are not the same.)

It is not possible to predict with any accuracy the harmonic content of this current as a function of the magnitude of the applied voltage.

In any case, exciting current harmonics are overwhelmingly odd (as against even) and the magnitudes decrease as the order of harmonic increases. Because of the power transformer connections and/or the associated current transformer connections, zero sequence harmonics (3rd, 9th, etc.) are for the most part excluded from the differential relays. Thus, with standard transformer differential connections, if a relay is to accommodate significant overexcitation it must do so by restraining on the 5th, 7th, 11th, etc. harmonic components of the exciting current. Because there is no way to generalize regarding the harmonic content in exciting current, this author knows of no way to establish the percent harmonic restraint required to prevent false tripping when a given transformer is significantly overexcited except by full scale testing at the applied voltages under consideration. However, it is obvious that the differential relay should restrain on at least one of these odd non zero-sequence harmonics if it is to have any security during significant transformer overexcitation.

BDD AND STD HARMONIC RESTRAINT CHARACTERISTICS

The following information relates to the performance of General Electric BDD and STD relays during inrush and overexcitation conditions. This information, along with past experience, should aid the user to determine whether or not these relays will meet his needs. The key to the performance of these relays is in the harmonic restraint characteristics of the operating or differential circuits. Figures 3 and 4 illustrate these portions of the STD and BDD relays respectively. A perusal of these two figures will indicate that they are the same except for the circuits where the operating and restraining quantities are compared to each other. In the case of the STD relay, a three input solid state summing amplifier with level detector is used. In the summing amplifier the weighted instantaneous magnitudes of the through and harmonic restraint inputs are summed against the instantaneous magnitude of the operating circuit input. During the instants in each cycle that the operate quantity is greater than the sum of the two restraint quantities by an amount that exceeds the level detector setting, an output from the solid state circuitry is directed to the coil of the trip output relay. This relay integrates these pulses and closes its contacts to produce a trip output if the pulses are of sufficient duration.

In the BDD relay the arrangement is similar except that in this relay the instantaneous magnitudes of the through and harmonic restraint quantities are added and fed to the restraining coil of the Sigma relay. The operate quantity is fed to the operating coil. The Sigma relay has a very quick response and it will operate to close its contact when the operate quantity exceeds the restraint quantity even momentarily. The outputs from the Sigma relay are integrated by the trip relay which provides a trip output when the input pulses to it are of sufficient duration.

While the diagrams of Figures 3 and 4 illustrate only one through restraint circuit, there are at least two and as many as ten such circuits in the STD and BDD relays.

The pick-up calibration of these relays is attained by passing the desired pick-up level of fundamental component of current through one restraint circuit and the differential (or operating) circuit as illustrated in Figures 3 and 4. Resistor R1 is then adjusted to that point where the relay just operates to produce a trip output.

The slope characteristic is adjusted by a passing fundamental frequency currents into one restraint circuit and out one other (not shown in Figures 3 and 4) with sufficient difference in the magnitudes such that the differential current represents the desired percentage (slope) of the lower of the two through restraint circuit currents. Resistor R3 is adjusted to cause the relay to just restrain for this condition. Note that this adjustment of R3 will have some slight affect on the pick-up setting so that R1 may have to be readjusted to obtain the desired pick-up level.

Finally the percent second harmonic current that will restrain the relay is adjusted by means of resistor R2. Both the BDD and STD type relays are adjusted in the factory to restrain when the second harmonic current into the relay is 20 percent of the fundamental component. This is accomplished by feeding into the 5 ampere tap of the relay an ac component of current with a magnitude of 5 amperes RMS plus a half wave DC component with a magnitude of 4 amperes average. The test wave shapes are illustrated in Figure 5. Note that the harmonic content of the combined currents is 20 percent second harmonic, 4 percent fourth harmonic plus additional even harmonics none of which exceeds two percent. No odd harmonics are present. This total test current is applied to the STD and BDD relays so that it flows into the terminal indicated in Figures 3 and 4 as I_{in}. It leaves the relay via the terminal designated as I_{diff}. The total current flows in one through-restraint circuit and in the differential circuit of the relay.

There are two filter arrangements in the differential circuit and they are both tuned to power frequency (60 hertz in the United States). However, one of these is connected in parallel resonance so that it presents a high impedance to the fundamental components and low impedance to the harmonics. The other is connected in series resonance so that it presents a low impedance to the fundamental and high impedance to the harmonics. Thus, the fundamental component of the differential or operating current will flow in the series resonant (operate) circuit where it will be rectified and forced through resistor R1. All the harmonic components of the differential current will flow through the parallel resonant (restraint) circuit where they are rectified and forced through resistor R2.

The total current entering the relay (fundamental plus harmonics) flows in the through restraint circuit where it is rectified and forced through resistor R3. It should be noted that in an actual relay there will be at least two through restraint circuits and possibly as many as ten. All of these restraint currents supply rectified current to R3 in such a way as to add to the IR drop in that resistor. However, in the calibration of the harmonic restraint characteristics of the STD and BDD relays only one through restraint circuit is used as illustrated in Figures 3 and 4.

As noted above, the relays are calibrated to restrain on 20 percent second harmonic by means of the combination of the two inputs illustrated in Figure 5. It will be recognized by referring to Figures 3 and 4 that the harmonic restraint and the operating filter circuits of the STD & BDD relays receive currents from the secondary side of the differential current transformer. Under certain conditions this secondary current will be different from the actual input current to the relay. Thus, the relay itself can alter the input wave shape to some degree and it is the harmonic content in this altered wave shape that provides the restraint. This will be true to varying degrees in all harmonic restraint relays so that the harmonic content in the calibration wave shape is just a benchmark which in itself does not define the harmonic restraint characteristics of the relay for all input wave shapes.

Inrush currents to large power transformers have wave shapes that are generally significantly different from the wave shape used to calibrate the relay. Also, the input currents to the differential relays can be altered by saturation in the main current transformers. For these reasons attempts to relate calculated harmonic content in transformer inrush currents to relay performance will generally prove fruitless.

An example of this is illustrated in Figure 6 which shows one single pulse of a wave shape that is characteristic of transformer inrush currents. Note that a repetitive chain (one per cycle) of such pulses was fed into the STD & BDD relays in the manner illustrated in Figures 3 and 4 after the relays had been calibrated, as described previously, to restrain on 20 percent second harmonic. The second harmonic content of a repetitive wave of this wave shape increases as the base of the current duration diminishes relative to the total cycle. The wave illustrated in Figure 6 had a base just narrow enough to cause the STD relay to restrain. A harmonic analysis of this wave yielded the following results:

TABLE I – STD RELAYS

FREQUENCY	MAGNITUDE IN % OF FUNDAMENTAL
Fundamental	100
2nd	13.0
3rd	7.8
4th	3.3
5th	0.3

A wave with a slightly narrower base (not illustrated) was required to just restrain the BDD relay. The harmonic content of this wave is given in the following table:

TABLE II – BDD RELAYS

FREQUENCY	MAGNITUDE IN % OF FUNDAMENTAL
Fundamental	100
2nd	17.1
3rd	8.6
4th	1.7
5th	1.7

Thus, though calibrated with the test wave shape to restrain on 20 percent second harmonic, the STD and BDD relays will restrain on 13 and 17 percent second harmonic respectively when subjected to wave shapes similar to those obtained during inrush conditions. On the other hand, the relays do not alter the shape of the ac component of the offset sine waves that are fed into them during fault conditions. This is illustrated in Figure 7 where Figure 7(a) is a completely and continuously offset wave that was fed into the relay as in Figures 3 and 4. Figure 7(b) is a picture of the current flowing on the secondary side of the differential current transformer. It will be noted that this current is symmetrical and completely sinusoidal as near as can be established from appearances. Thus, these relays would not be expected to generate any harmonics during faults in the transformer bank that produce offset currents.

From the above described test results it is apparant that, when calibrated in the normal manner to restrain on 20 percent second harmonic, the STD relays will be somewhat more secure against false tripping on transformer inrush currents than the BDD relays. Also the BDD relays will be somewhat more secure than would be expected from the second harmonic content in the calibration wave shape.

Other tests performed on both the STD and BDD relays after they were calibrated to restrain at 20 percent second harmonic restraint with a test current as in Figure 5, was to apply a mixture (instantaneous sum) of two sine waves. The first a "pure" 60 hertz sine wave with an RMS magnitude of about tap value. The other signal was a sine wave harmonic of the fundamental but not phase locked so that the phase angle between the two could be changed. The object of this test was to establish the RMS magnitude of the sine wave harmonic, in percent of the sine wave fundamental that would be required to restrain the relays from tripping and to ascertain whether phase angle difference was a factor. Tables III and IV below illustrate the results of these tests for the STD and BDD relays respectively.

It is an interesting phenomenon (while not illustrated here) that the response of the relays was found to be somewhat dependent on the phase angle between the harmonic and the fundamental current inputs. The data shown in Tables III and IV indicate the <u>maximum</u> percentage of harmonic current required to just restrain the relays. At different phase angles, somewhat lower harmonic content would produce the same restraint. Here again is another indication that the wave shape of the input current (particularly in the case of the BDD relay) has an affect on the relay performance regardless of harmonic content.

TABLE III – STD RELAY

HARMONIC	PERCENT
2	21
3	21
4	20
5	20
6	20
7	20
8	20
9	19
10	19
11	18

TABLE IV – BDD RELAY

HARMONIC	PERCENT
2	24
3	23
4	22
5	22
6	21
7	21
8	21
9	21
10	21
11	20

Other tests were performed where sine wave fundamental plus two different sine wave harmonic currents were added together on an instantaneous basis and fed into the relays. The results of these tests indicate that the relays tend to restrain on the larger of the two harmonics rather than their sum although there was some summing effect.

As discussed earlier in this paper, exciting currents in power transformers contain significant harmonics. Because of power bank and current transformer connections, the prevalent harmonics seen by the differential relays during power transformer overexcitation (overvoltage at fundamental frequency) are the 5th, 7th and 11th. Tables III and IV indicate that the STD and BDD relays provide substantial restraint at these frequencies when tested with sine wave inputs. While it is not possible to predict the exact harmonic content in exciting current waveshapes that is required to produce restraint, it is also not possible to predict the harmonic content in the power transformer exciting current that will be supplied to the relay. Thus, the only way to be certain of the performance of any harmonic restraint relay under conditions of power transformer overvoltage is by full scale testing of the specific transformer and relay type under consideration. In any case, the STD and BDD relays which restrain on all harmonics will permit significant power transformer overexcitation without tripping.

TRANSIENT BEHAVIOR

The transient behavior of any high speed relay is of great importance and transformer differential relays are no exception. Such relays are generally required to perform properly immeadiately following a system disturbance such as a fault, or as in the case of harmonic restraint transformer differential relays, immediately following the energization of the protected transformer bank.

By virtue of their design, the STD and BDD relays tend to restrain on any initial transient regardless of the frequency. The reason for this may be observed from Figure 3 or 4. It will be noted that the differential current transformer secondary winding supplies the harmonic restraint and operate circuits in parallel. Thus, on a steady state basis, the secondary current divides such that the fundamental component will flow in the (60 hertz) series resonant operate circuit while the harmonics will flow in the (60 hertz) parallel resonant harmonic restraint circuit. However, when a current is suddenly applied to the input terminals of these relays, the initial distribution between the two circuits is significantly different from the steady state condition. The reasons for this are inherent in the transient characteristics of the two filter circuits.

The operate circuit filter, being series resonant, utilizes and inductor in series with a capacitor. When a voltage is suddenly applied across this series circuit, current tends to be slow to build up because of the electrical inertia in the series inductance. This is true regardless of the wave shape of the current and so it leads to a somewhat delayed operate signal to the Sigma relay in the BDD or to the summing amplifier in the STD. On the other hand, in the parallel resonant harmonic restraint circuit, the inductor and capacitor are connected in parallel. Any signal instantly applied across this combination will result in a rush of current through the low inertia capacitor and so produce an immediate harmonic restraint signal to the sensing units of the relays.

To illustrate this phenomenon, the performance of an STD relay was tested under fault and fault plus inrush conditions. While the BDD was not checked in this way, similar performance is expected because similar filter circuits are employed. The first test was intended to represent a three-phase internal fault near the terminals of a transformer. Three resistors were connected in wye as indicated in Figure 8. The resistors were sized so that when the circuit breaker was suddenly closed the 60 hertz "fault" current to the STD relay was about 1.6 times tap value. Note that this current was flowing in the differential circuit and only one through restraint circuit of the relay. Figure 9 is an oscillogram of the three inputs to the summing amplifier (See Figure 3), the input to the trip relay coil circuit, and the trip contact position taken in the STD as the breaker was closed.

The bottom trace on Figure 9 is the operate signal. This is nothing more than the voltage drop across R1 produced by the rectified current through the series resonant operate circuit. It is the upper input to the summing amplifier card in Figure 3. The next trace up is the through restraint signal as developed across R3 and applied to the lower input to the summing amplifier card. The third trace up is the harmonic restraint voltage produced across R2 and applied to the center input on the same card. It should be noted that the two restraint signals enter the card with negative polarity while the operate signal does so with positive polarity. An output from the card results when the weighted instantaneous sum of the input quantities is positive and above the calibration of the level detector.

Figure 9 indicates that the relay tripped for this simulated three-phase fault condition in about 5 half cycles, or 2.5 cycles, after the fault inception. The interesting aspect of this test is not the operating time but rather the traces of the harmonic restraint and operate inputs to the summing amplifier. Despite the fact that the input current to the relay contained pure sine wave power frequency, the harmonic restraint circuit produced an initial large magnitude input to restrain while the operate circuit input to the card built up with some slight delay. It actually took about 1.5 cycles for the initial transient effects to decay to the point where the summing amplifier card produced an output to the trip output relay which in turn produced a trip output about 1 cycle later. While this transient restraining action tends to delay the operation of the relay slightly (depending on fault magnitude) during fault conditions, it adds significantly to the security of the relay during transformer inrush conditions.

It is interesting to note that had the STD and BDD relays been designed to restrain on second harmonic only and operate on all other frequency currents including the fundamental, the operate circuit would have had to be arranged for parallel resonance and the harmonic restraint circuit for series resonance. This arrangement would have produced initial transient operate outputs during fault as well as inrush conditions. Such an arrangement by itself may have resulted in a slightly faster relay but surely a less secure one.

A second test was arranged as per Figure 10. Three single-phase (5 KVA) dry type transformers were connected grounded wye-delta in the laboratory. A circuit breaker was installed in series with the wye connected windings so that the bank could be energized from that side. One single-phase STD relay was connected in the standard way to receive delta currents from current transformers on the wye side of the bank. Because the delta side on the bank was not loaded, no current transformers were employed on that side and no connections were made to the relay. To simulate an internal fault in one phase of the transformer at the instant the bank was energized, the primary winding of the phase A transformer was disconnected and a resistor R was substituted in its place. The resistor was sized to produce fault currents in the order of about 1.6 times pick-up of the relay.

This arrangement was used to measure the response of the relay when the circuit breaker was closed to suddenly energize the bank with a fault in the wye winding of one phase of the bank as simulated by resistor R connected across phase A. Note that for these conditions there would not be any current flow in the leads to the delta winding so that the connections to the relay represent actual conditions for this type of test. With these connections, wye side currents ($I_b - I_a$) would flow in the relay through the differential circuit and out via one through restraint circuit. Figure 11 is an oscillogram of the operate and restraint quantities as well as the trip output circuits.

It will be noted that tripping occurred about 9 half cycles, or 4.5 cycles, after the inception of the fault. Here again the harmonic restraint circuit output built up to a large value immediately while the operating circuit output built up in about one half cycle. The card output first appeared temporarily after about 2.5 cycles and the trip contacts closed in about 4.5 cycles (as noted earlier).

What is of great interest here, is the fact that although a significant fault was present, harmonic restraint persisted for a prolonged period of time and apparently delayed the relay from tripping. This delay is not a result of the transient behavior of the relay. It occurs because the phase B inrush current contains the normal significant second harmonic and the relay, because of current transformers connections, responds to $(I_a - I_b)$ which contains fault components as well as inrush exciting components of current. The relay tripped when the harmonic content of the inrush current in phase B decayed to a value where its harmonic content was too low compared to the total fundamental component in $(I_a - I_b)$ to further restrain the relay.

There are two important points to be made here

1. A relay adjusted to restrain on a lower harmonic content would have delayed tripping for a longer period of time. Also, restraining each phase of the relay from a summation of the harmonics present in all three phases would also have delayed tripping for a still longer period of time.
2. The transformer bank used in this test was small and the supply system was not very stiff. For these reasons the inrush to the good phases of the bank diminished rapidly. In the case of a full sized power transformer bank connected to a stiff system, the inrush current and the accompanying harmonics can persist for significantly longer times. Under these conditions, tripping could be delayed for extensive periods. Reducing the percentage of harmonics required to restrain the relay, or adding harmonics from all three phases to restrain each phase, can only further delay tripping under these conditions.

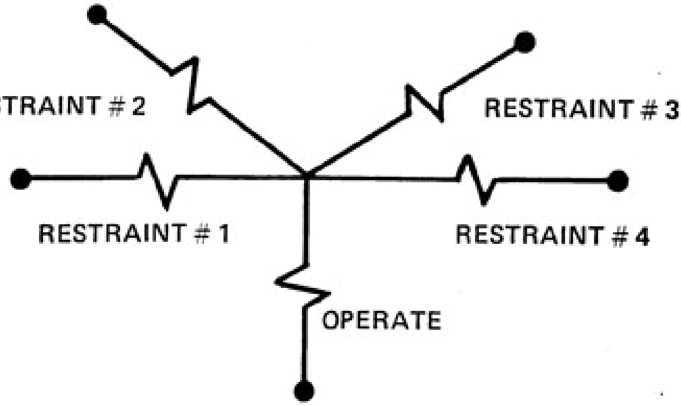


FIGURE 1

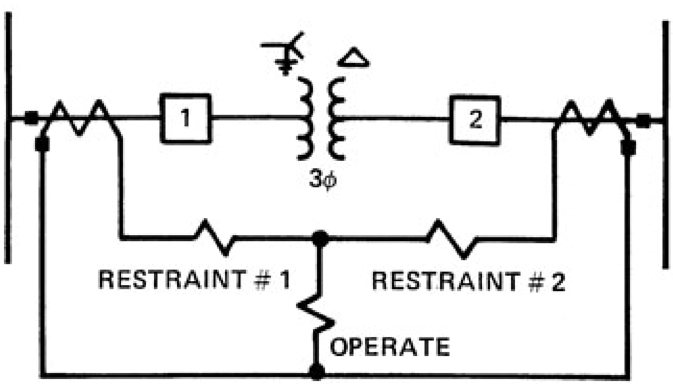


FIGURE 2

STD RELAY

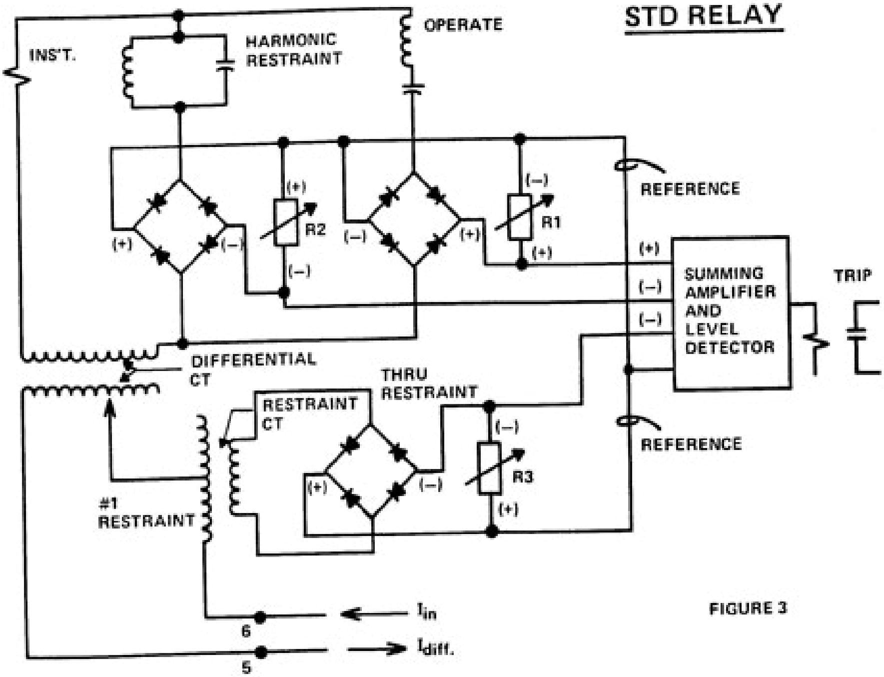
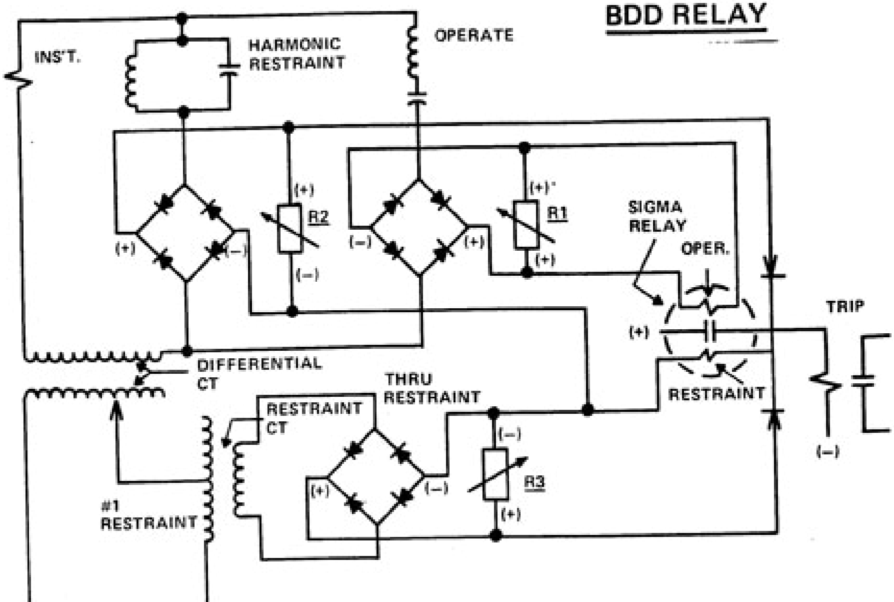
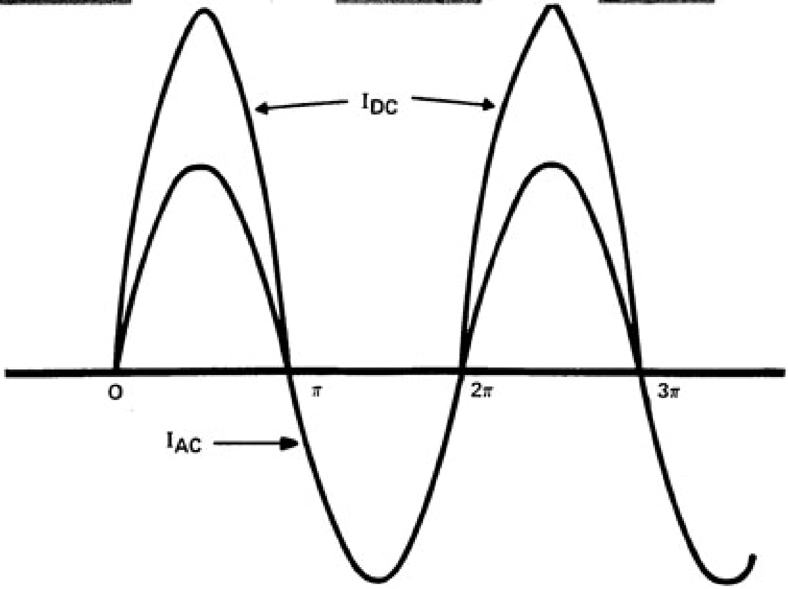


FIGURE 3

BDD RELAY



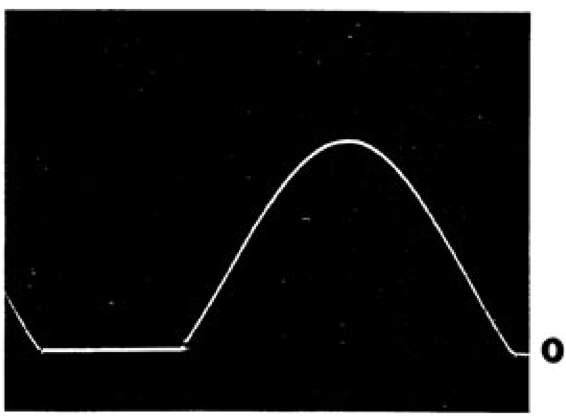


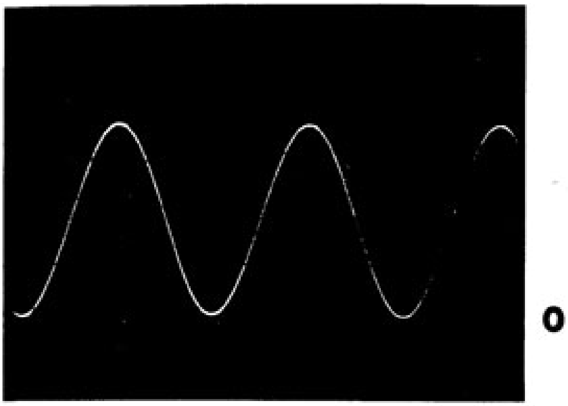
I_{AC} = 5.0 AMPS RMS = 7.07 AMPS PEAK

I_{DC} = 4.0 AMPS AVG. = 12.55 AMPS PEAK

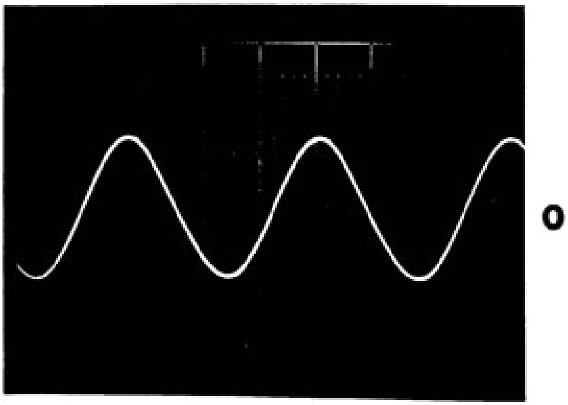
$I_{AC} + I_{DC}$ YIELDS $\begin{cases} \text{20\% SECOND HARMONIC} \\ \text{4\% FOURTH HARMONIC} \end{cases}$

FIGURE 5



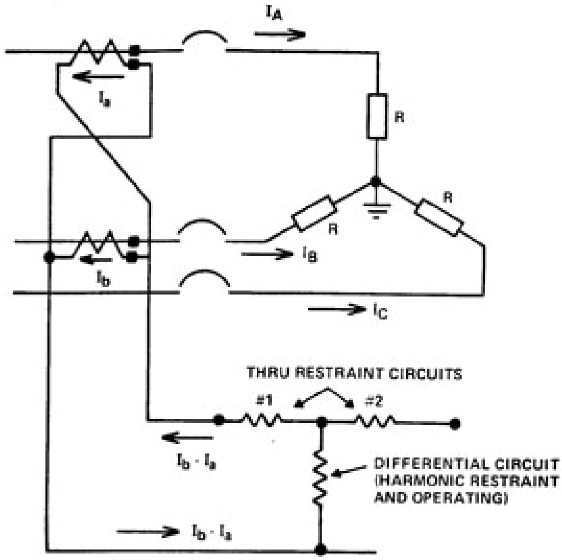


(a) RELAY INPUT CURRENT FULLY OFFSET
SINE WAVE



(b) CURRENT IN DIFFERENTIAL CIRCUIT
SYMMETRICAL SINE WAVE

FIGURE 7



STD RELAY

FIGURE 8

STD RELAY - INTERNAL FAULT

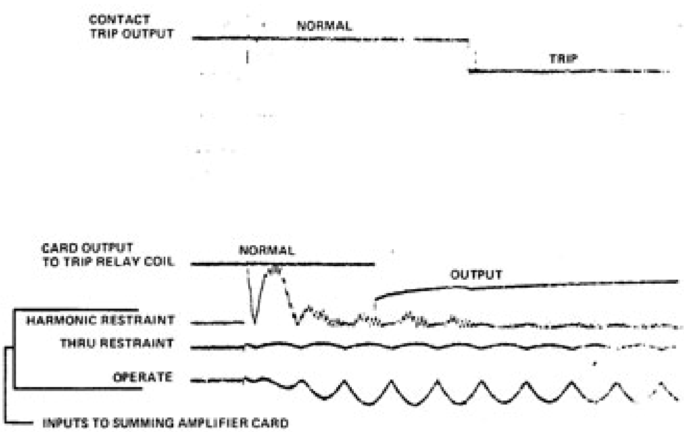
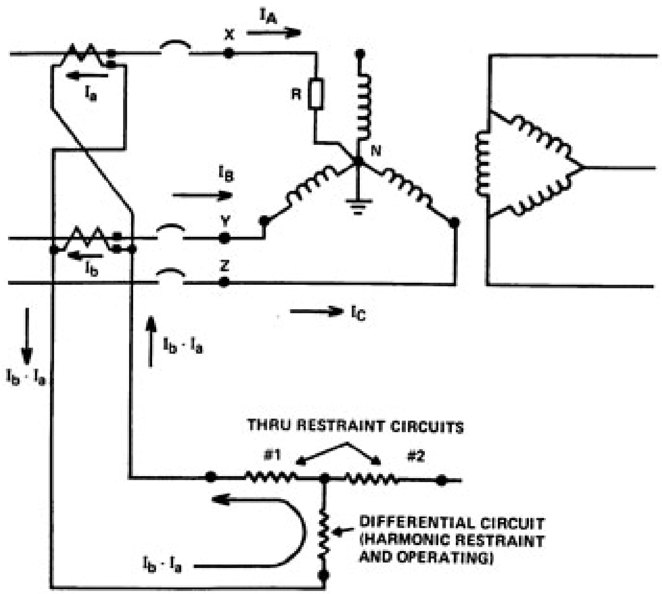


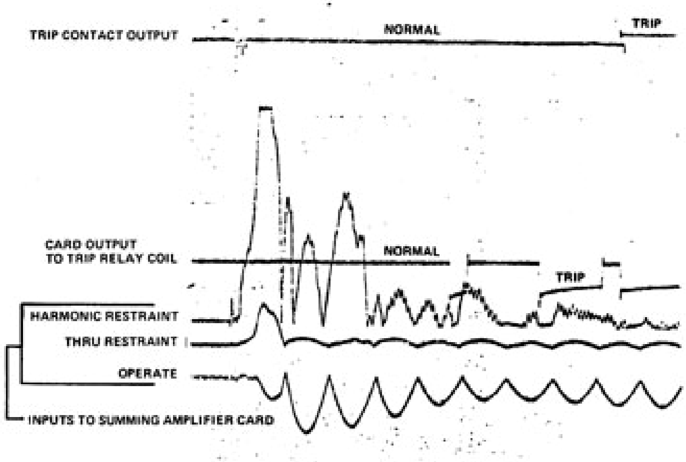
FIGURE 9



STD RELAY

FIGURE 10

STD RELAY - INTERNAL FAULT PLUS INRUSH



<u>APPENDIX I</u>

Unfortunately hysteresis loops and magnetization (β - H) curves are not always plotted to the same units. While this paper uses webers per square meter for flux density (β) and ampere turns per meter for magnetizing force (H) this is not universally used. For this reason the following conversions are provided.

<u>Flux Density (β)</u>

1.0 Webers/m^2	=	64.5 Kilolines/in^2
1.0 Webers/m^2	=	10.0 Kilogauss
1.0 Webers/in^2	=	15,500 Kilogauss
1.0 Webers/in^2	=	10^4 Kilolines/in^2
1.0 Webers/cm^2	=	64.5 x 10^4 Kilolines/in^2
1.0 Webers/cm^2	=	10^5 Kilogauss

<u>Magnetizing Force (H)</u>

1 Ampere turn/meter	=	0.0254 Ampere turn/inch
1 Ampere turn/meter	=	1.257 gilberts/meter
1 Ampere turn/meter	=	0.01257 Oersteds
1 Ampere turn/cm	=	2.54 Ampere turn/inch
1 Ampere turn/cm	=	125.7 gilberts/meter
1 Ampere turn/cm	=	1.257 Oersteds
1 Ampere turn/inch	=	39.4 Ampere turn/meter

APPENDIX II

The following calculations illustrate a method for estimating the second harmonic content in the magnetizing inrush current to a grounded wye-grounded wye bank comprised of three single-phase transformers. These calculations are based on the assumptions outlined below. Different assumptions would result in different answers.

Assumptions

1. The current transformers associated with the bank are connected in delta.
2. On energization, all three poles of the circuit breaker or switch will close and conduct simultaneously.
3. The residual flux density (β_r) in phase A is -0.50 per unit of the peak operating flux density (β_m) taken as 1.0 per unit.
4. The residual flux density in phases B and C are 0.40 and 0.10 per unit respectively of the peak operating flux density.
5. The saturation flux density (β_s) is 1.15 per unit of the peak operating flux density (β_m) taken as 1.0 per unit.
6. The phase B pole of the breaker closes at that instant in time when the phase B voltage is zero and is increasing in the direction to add to the residual flux in that phase.

Determination of Inrush Currents

Equation (14) in the main body of this paper

$$i = \frac{K}{\mu}\left[\beta_r - \beta_s + \beta_m\left(\cos\theta - \cos[\omega t + \theta]\right)\right]$$

describes the time varying flux resulting from a suddenly applied sine wave voltage to a single phase unloaded transformer having a residual flux density equal to β_r.

If a bank of three single-phase transformers is considered to be suddenly energized by a balanced three phase voltage supply, the above equation must be rewritten for each phase.

Phase B

$$i = \frac{K}{\mu}\left[\beta_r - \beta_s + \beta_m\left(\cos\theta_b - \cos[\omega t + \theta_b]\right)\right] \qquad \text{(II-1)}$$

Phase C

$$i = \frac{K}{\mu}\left[\beta_r - \beta_s + \beta_m\left(\cos\theta_c - \cos[\omega t + \theta_c]\right)\right] \qquad \text{(II-2)}$$

Phase A

$$i = \frac{K}{\mu}\left[\beta_r - \beta_s + \beta_m\left(\cos\theta_a - \cos[\omega t + \theta_a]\right)\right] \qquad \text{(II-3)}$$

For the condition of all three poles of the breaker closing simultaneously at the instant in time when phase B voltage is zero and increasing in the positive direction

$$\theta_b = 0 \text{ degrees}$$

$$\theta_c = -120 \text{ degrees}$$

$$\theta_a = -240 \text{ degrees}$$

Note that for another initiation angle other values would be used for θ_a, θ_b, and θ_c. For example, if the breaker is closed when the phase A voltage is at its positive peak then

$$\theta_a = 90 \text{ degrees}$$

$$\theta_b = -30 \text{ degrees}$$

$$\theta_c = -150 \text{ degrees}$$

The relationship between the three angles is always 120 degrees just as long as all three poles are closed simultaneously.

Substituting the values assumed for flux densities into equations II-1, 2 and 3 and assuming that the peak operating flux density β_m is 1.0 per unit.

Phase B

$$i_b = \frac{K}{\mu} [\, 0.40 - 1.15 + 1.0 \,(\text{Cos } 0 - \text{Cos } \omega t) \,] \qquad \text{(II - 4)}$$

$$i_b = \frac{K}{\mu} [\, 0.25 - \text{Cos } \omega t \,]$$

Positive Peak of $i_b = (1.25)\ \frac{K}{\mu}$

At the instant $i_b = 0$

$\text{Cos}\omega t = 0.25$
$\omega t = 75.5$ and 284.5 degrees, etc.

The base angle, or conduction angle during which the phase B magnetizing inrush current is positive is
(284.5 - 75.5) = 209 degrees

Phase C

$$i_c = \frac{K}{\mu}\left\{ -0.10 - (-1.15) + 1.0\,[\,\mathrm{Cos}(-120) - \mathrm{Cos}\,(\omega t - 120)\,]\right\} \qquad \text{(II - 5)}$$

Note that the per unit residual flux plus 1.0 Cos (-120) is equal to -0.40. The per unit saturation flux density (-1.15) is assigned a negative value because we are now dealing with the negative half of the hysteresis loop. There will be no positive current flow in phase C because in the positive half cycle the flux density never exceeds a value of 1.15 per unit.

$$i_c = \frac{K}{\mu}\,[\,0.75 - \mathrm{Cos}\,(\omega t - 120)\,]$$

Negative Peak of $i_c = -(0.25)\ \frac{K}{\mu}$

At the instant $i_c = 0$

$\mathrm{Cos}(\omega t - 120) = 0.75$
$(\omega t - 120) = -41.5$ and 41.5 degrees, etc.
$\omega t = 78.5$ and 161.5 degrees, etc.

The base or conduction angle during which the phase C magnetizing inrush current is negative is (161.5 - 78.5) = 83.0 degrees

Phase C

$$i_a = \frac{K}{\mu}\left\{ -0.50 - (-1.15) + 1.0\,[\,\mathrm{Cos}\,(-240) - \mathrm{Cos}\,(\omega t - 240)\,]\right\} \qquad \text{(II - 6)}$$

The comments regarding β_r and β_s in the equation for phase C also apply for this equation relating to phase A.

$$i_a = \frac{K}{\mu}\,[\,0.15 - \mathrm{Cos}(\omega t - 240)\,]$$

Negative Peak of $i_a = -(0.85)\ \frac{K}{\mu}$

At the instant $i_a = 0$
$\mathrm{Cos}\,(\omega t - 240) = 0.15$
$(\omega t - 240) = -81.4$ and 81.4 degrees, etc.
$\omega t = 158.6$ and 321.4 degrees, etc.

The base or conduction angle during which the phase A magnetizing inrush current is negative is (321.4 - 158.6) = 162.8 degrees

Equation (II - 4), (II - 5) and (II - 6) are plotted for one cycle in Figure II-A for i_b, i_c and i_a respectively. Also plotted in Figure II-A are $i_a - i_b$, $i_b - i_c$ and $i_c - i_a$ for one complete cycle. It is now possible to perform a harmonic analysis on the wave shapes of the three difference-currents. This can be done by analytic methods that involve measuring the ordinate values every few degrees. There are standard procedures to do this either manually or by computer. Another method involves using Table II in the main body of this paper to establish the magnitudes and relative phase angles of the fundamental and harmonic components. While both approaches yield the same results, only the latter method will be discussed here. The former approach is well documented in the literature.

Harmonic Analysis

Table II in the main body of the paper provides the relative phase angles and the magnitudes of the harmonics as a function of the base angle of the wave. Figure II-A illustrates the three inrush phase currents i_a, i_b, i_c. It will be noted that the currents i_a and i_c are negative and their peaks are displaced 120 degrees from each other. These negative peaks are symmetrically displaced by 60 degrees each about the positive peak of i_b.

The basic approach is to use Table II to provide the relative magnitudes and relative phase angles of the fundamental and harmonic components for each phase individually as if the other two phase currents did not exist. Then to establish the relative magnitudes and relative phase angles between similar components in the three phases so that $(i_a - i_b)$, $(i_b - i_c)$ and $(i_c - i_a)$ may be calculated for each frequency separately.

Table II provides the peak value of each harmonic as a function of the peak of the current wave and the base or conduction angle. Thus,

Phase A

$$\text{Peak of wave} = 0.85 \frac{K}{\mu}$$

$$\text{Conduction Angle} = 162.8 \text{ degrees}$$

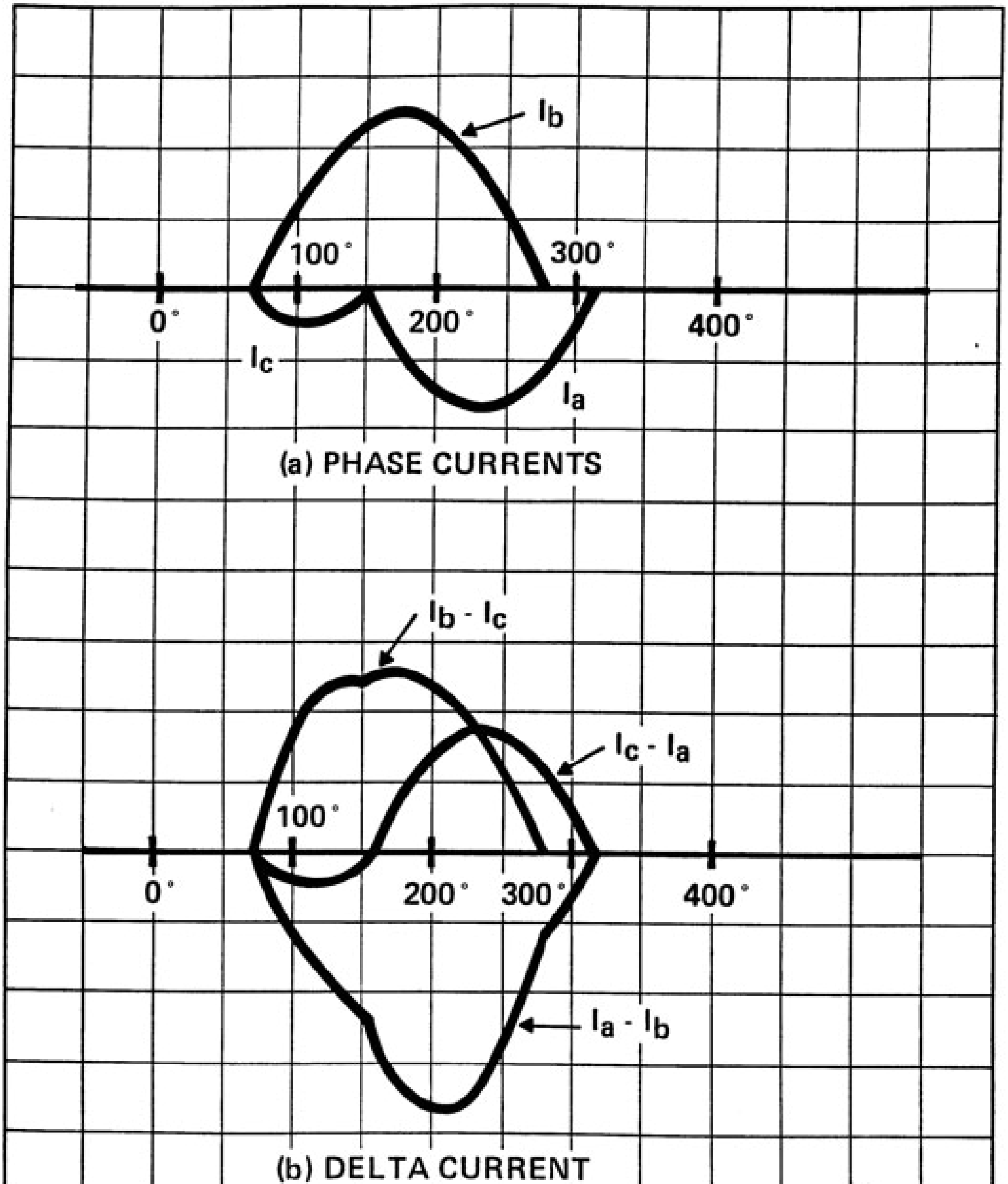
From Table II by interpolation between 150 and 165 degrees

$$\text{Fundamental} = 0.476 \ (0.85) \frac{K}{\mu} = (0.405) \frac{K}{\mu}$$

$$\text{2nd Harmonic} = -0.241 \ (0.85) \frac{K}{\mu} = -(0.205) \frac{K}{\mu}$$

$$\text{3rd Harmonic} = 0.036 \ (0.85) \frac{K}{\mu} = (0.031) \frac{K}{\mu}$$

The negative sign associated with the second harmonic indicates that this component is 180 degrees out-of-phase with the fundamental. This means that this harmonic has a magnitude of zero when the fundamental has a zero magnitude, and that it increases in a negative direction as the fundamental increases in the positive direction with time. It should be recognized at this time that the second



I_b
100°
300°
0°
200°
400°
I_c
I_a
(a) PHASE CURRENTS
$I_b - I_c$
$I_c - I_a$
100°
0°
200°
300°
400°
$I_a - I_b$
(b) DELTA CURRENT

FIGURE II - A

harmonic (and all other even harmonics) when "out-of-phase" with the positive half cycle of the fundamental will be "in phase" with the negative half cycle of the fundamental and visa-versa. On the other hand, the third harmonic (and all other odd harmonics) will have the same phase relationship to both the positive and negative half cycles of the fundamental. Thus, a third harmonic that is in phase with the fundamental is in phase with both half cycles. This is true in phases B & C as well as in phase A.

Phase B

$$\text{Peak of wave} = (1.25)\ \frac{K}{\mu}$$

Conduction Angle = 209 degrees

From Table II by interpolation between 195 and 210 degrees

$$\text{Fundamental} = (0.521)\ (1.25)\ \frac{K}{\mu} = (0.65)\ \frac{K}{\mu}$$

$$\text{2nd Harmonic} = -(0.154)\ (1.25)\ \frac{K}{\mu} = -(0.19)\ \frac{K}{\mu}$$

$$\text{3rd Harmonic} = -(0.038)\ (1.25)\ \frac{K}{\mu} = -(0.048)\ \frac{K}{\mu}$$

In this case both the second and third harmonics are out-of-phase with the fundamental component.

Phase C

$$\text{Peak of wave} = 0.25\ \frac{K}{\mu}$$

Conduction Angle = 83 degrees

From Table II by interpolation between 75 and 90 degrees

$$\text{Fundamental} = 0.287\ (0.25)\ \frac{K}{\mu} = 0.072\ \frac{K}{\mu}$$

$$\text{2nd Harmonic} = -0.244\ (0.25)\ \frac{K}{\mu} = -0.061\ \frac{K}{\mu}$$

$$\text{3rd Harmonic} = 0.183\ (0.25)\ \frac{K}{\mu} = 0.046\ \frac{K}{\mu}$$

In this case the second harmonic is out-of-phase with the fundamental component while the third harmonic is in-phase with the fundamental component.

Difference of Phase Currents

Because on the wye side of a transformer a differential relay will see the difference of two phase currents, it is these difference currents for which the harmonic content is of prime interest. These may be determined by obtaining separately the fundamental component of the difference currents, and each harmonic component of the difference currents.

Fundamental Components

Because of the assumptions made in the derivation of the equations for the inrush currents, these currents are (all three phases) portions of pure sine waves. Thus, they are symmetrical in shape about their peak values. For this reason, the peak of the fundamental component in phase A will be exactly in phase with the peak of the inrush current in phase A. Similarly, the peaks of the fundamental components in phases B and C will line up with the peaks of those inrush currents. It may therefore be stated that the positive half cycle of the fundamental component in phase B will lag the negative half cycle of the fundamental component in phase C by 60 degrees and lead the negative half cycle of the fundamental in phase A by the same amount. This then can be extended to say that the three fundamental components of phase currents are 120 degrees apart with B lagging A, and C lagging B. Therefore, the magnitudes of the fundamental components of the three difference-currents are

$$i_a - i_b = \left[(0.41 \angle 0 - 0.65 \angle -120) \right] \frac{K}{\mu} = 0.93 \frac{K}{\mu}$$

$$i_b - i_c = \left[(0.65 \angle -120 - 0.07 \angle -240) \right] \frac{K}{\mu} = 0.68 \frac{K}{\mu}$$

$$i_c - i_a = \left[(0.07 \angle -240 - 0.41 \angle 0) \right] \frac{K}{\mu} = 0.45 \frac{K}{\mu}$$

Second Harmonic Components

It was stated above that Table II indicates the second harmonic components in each of the three phase-currents to be 180 degrees out-of-phase with the corresponding fundamental components. However, because Table II takes no cognizance of the polarity of the wave it analyzes, these phase relationships must be interpreted. In the case of phase B, because the wave is positive, the second harmonic is 180 degrees out-of-phase with the positive half cycle of the associated fundamental component. In the case of phases C and A, because the waves are of negative polarity, the second harmonic components are 180 degrees out-of-phase with the negative half cycles of the respective fundamental components. Or, in phases C and A the second harmonics are in-phase with their respective fundamental components positive half cycles. A simple plot of the second harmonic components in all three phases (left up to the reader) will indicate that the second harmonic in phase A will lag that in phase C by 240 degrees (note that the fundamentals differ in phase by 120 degrees and one fundamental-frequency degree is equal to two second-harmonic degrees). The second harmonic in phase B will lead that in phase C by 2 (120) - 180 = 60 degrees. Thus,

$$i_a - i_b = \left[(0.21 \angle 0 \;-\; 0.19 \angle -60\,) \right] \frac{K}{\mu} = 0.20\ \frac{K}{\mu}$$

$$i_b - i_c = \left[(0.19 \angle -60 \;-\; 0.06 \angle -120\,) \right] \frac{K}{\mu} = 0.17\ \frac{K}{\mu}$$

$$i_c - i_a = \left[(0.06 \angle -120 \;-\; 0.21 \angle 0\,) \right] \frac{K}{\mu} = 0.24\ \frac{K}{\mu}$$

Third Harmonic Components

In a similar manner, it may be shown that the third harmonic components in phases C and A are in phase with each other and 180 degrees out-of-phase with that in phase B. Thus,

$$i_a - i_b = \left[0.031 \;-\; (-0.048) \right] \frac{K}{\mu} = (0.08)\ \frac{K}{\mu}$$

$$i_b - i_c = \left[-0.048 \;-\; 0.046) \right] \frac{K}{\mu} = (0.09)\ \frac{K}{\mu}$$

$$i_c - i_a = \left[-0.046 \;-\; 0.031 \right] \frac{K}{\mu} = (0.02)\ \frac{K}{\mu}$$

Percentage Harmonics

The percentage harmonics for each of the phase currents are given in the following table

CURRENT	% 2nd HARMONIC	% 3rd HARMONIC
$i_a - i_b$	0.20(100)/0.93 = 21.5	0.08(100)/0.93 = 8.6
$i_b - i_c$	0.17(100)/0.68 = 25.0	0.09(100)/0.68 = 13.2
$i_c - i_a$	0.24(100)/0.45 = 53.0	0.02(100)/0.45 = 4.4