DESIGN CONSIDERATIONS FOR A NEW SOLID-STATE TRANSFORMER DIFFERENTIAL RELAY WITH HARMONIC RESTRAINT

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PRESENTED BEFORE THE FIFTH ANNUAL
WESTERN PROTECTIVE RELAY CONFERENCE
OCTOBER 15-18, 1978
SACRAMENTO, CALIFORNIA

GOULD

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SUMMARY

Some of the history of transformer differential relaying is reviewed for the purpose of establishing criteria for the design of a new relay. Among the basic requirements of a sound design are ratio-matching taps, a percentage-differential characteristic, and restraint based on the harmonic content of the relay currents.

Magnetizing inrush current is, of course, the principal cause of malfunctions of relays of this type. The characteristics of this type of current are analyzed in detail, and the conclusion drawn that restraint by fifteen percent second harmonic content is appropriate. As the text explains, the reasons for this decision include the undependable nature of the other harmonics due to inevitable delta connections, as well as the presence of those harmonics in legitimate fault currents.

The electrical design of the new solid-state relay is discussed in detail, with mathematical analysis of the circuitry. Oscilloscope traces of points of interest within the circuit confirm these analyses.

Finally, data on tests conducted at full power in a typical installation confirm the results of the analysis, with data presented to verify proper operation of the new relay design.

INTRODUCTION

In order to overcome the problem of nuisance tripping experienced on energizing power-transformers, modern transformer differential relays have for years been designed utilizing the principle of "harmonic restraint". To our knowledge, the first relay to use the powerful concept of restraint proportioned to the harmonic frequency component of current was reported by Kennedy and Hayward in 1938 (1).

Although a transformer-differential relay using harmonic restraint was apparently being developed at that time, it was not reported until 1941 (2). Curiously, the 1938 report disclosed a relay not for transformer protection, but for bus protection. Harmonic restraint was used in the 1938 bus relay to provide security against tripping on external faults causing severe saturation of the current-transformer on the faulted feeder.

We consider the work reported in that paper among the most valuable in the differential relay literature. However, the extension of the principles of that paper to the design of percentage-differential relays for transformer protection can be questioned.

Table 1 emulates Table 1 of Kennedy and Hayward's paper. It gives the author's Fourier analysis of three waveforms which are difficult for differential relays to handle:

Internal Fault, No CT Saturation
External Fault, with CT Saturation
Transformer Magnetizing Inrush

These are illustrated in Figures 1, 2 and 3 respectively.

TABLE 1

HARMONIC WAVE ANALYSES OF TYPICAL CURRENTS APPEARING IN DIFFERENTIAL RELAY CIRCUITS DUE TO VARIOUS CAUSES

	DIFFERENTIAL CURRENT DUE TO:		
COMPONENT	INTERNAL FAULT FIGURE 1	SATURATED C.T.'s FIGURE 2	MAGNETIZING INRUSH FIGURE 3
Peak	145%	126%	244%
DC	38%	0%	58%
Fundamental	100%	100%	100%
Second Harmonic	9%	4%	63%
Third Harmonic	4%	32%	22%
Fourth Harmonic	7%	9%	5%
Fifth Harmonic	4%	2%	32%
Sixth Harmonic	6%	1%	4%
Seventh Harmonic	2%	3%	3%

The high content of third-harmonic in the present of saturated CT's (Figure 2) is the principal reason in the author's decision to use all harmonics to restrain the relay. After long analysis, we have decided that this decision is not appropriate for transformer relays, for two reasons:

1) Modern transformer relays are designed to take advantage of both percentage-restraint as well as harmonic restraint; this bus differential relay was not provided with percentage restraint.

2) The assumption that the CT on the faulted feeder is the most likely to saturate on an external fault is only true for a bus situation, since all the other sources connected to the bus are feeding the one circuit. However, in protecting transformers, an internal fault is just as apt to produce large currents (particularly for bushing faults). Therefore, these CT's will saturate just as badly, and probably worse, for an internal, as for an external fault.

MAGNETIZING INRUSH CURRENTS

The Currents Taken By Each Winding of the Transformer

The nature of the inrush current is shown in Figure 3. References 2, 3 and 4 each contain Fourier analyses of the frequency components of such waveforms.

Table 2 lists the results of these analyses. Although some 35 years had elapsed in the interval spanning this work, and different methods used to obtain the results, one observes close correlation among the data presented - startling when the number of variables involved is considered.

TABLE 2

MAGNETIZING INRUSH CURRENTS

COMPONENT	REFERENCE 2	REFERENCE 3		REFERENCE 4*		
		CYCLE #2	CYCLE #13	240°	210°	180°
Peak	244	203	133	-	-	-
DC	58	70	6	75	-	64
Fundamental	100	100	100	100	100	100
Second Harmonic	63	23	33	17	29	42
Third Harmonic	27	9	3	9	7	0
Fourth Harmonic	5	-	-	2	3	8
Fifth Harmonic	4	-	-	2	4	0

*For Reference 4, a progression from 240° thru 180° represents elapsed time, during which the inrush is subsiding.

The variance of the second-harmonic components reported is most probably attributed to the particular cycle analyzed. A characteristic of inrush current is that the base-width of the sinusoidal pulses decreases, as well as its peak, as the inrush subsides. See Figure 4 for a representation of this effect. The second-harmonic component of the phase-winding suffering the worst inrush will gradually increase, and then decrease to zero. Therefore, References 3 and 4 are in basic agreement as to the nature of the second-harmonics' performance. The fact that Reference 4 is purely theoretical, and References 2 and 3 report measured data, justifies both approaches and makes each more valuable.

In line with the theory of Fourier analysis, the higher harmonics appear in ever-decreasing amplitude, and for this reason, those above the fifth are not analyzed since their contribution is negligible.

The Line Currents of Delta-Connected Banks or CT's

In delta-wye connected power-transformers or banks, the current-transformers are connected wye-delta, in order that they:

1) Obtain the proper phase-shift from high-to-low side load or through-fault currents, and to

2) Supply the required zero-sequence elimination to provide proper relay performance on external-ground faults.

In wye-wye connected banks, the CT's are connected delta-delta for the second reason above. In all cases, a delta winding is encountered in either the power-, or the current-transformer connections.

Because of these connections, the currents supplied to the relay are not those listed in Table 2, but modified due to manner in which the delta-winding currents combine to form the line currents. As shown in Figure 5, the fundamental components add at 60° while the second-harmonics add at 120° the third-harmonics at 180°, and so forth.

In the worst case, that is when the inrush current is the same in two adjacent windings, the dc component delivered to the relay decreases to zero, the second harmonic to 57.7%, the third to zero, the fourth to 57.7%, and the fifth is unchanged. The results of these operations are indicated in Table 3, and represents the actual currents delivered to the relay for the inrush currents listed in Table 2.

We stress here that Table 3 does not represent any actual test result with which we are familiar, but rather is a worst-case situation, illustrating the quantities on which a relay designer may depend. In considering quantities for restraint, any of the harmonics may be greater than indicated.

TABLE 3

WORST-CASE MAGNETIZING INRUSH CURRENTS

Delivered to the relay, as a result of Delta Connection.

COMPONENT	REFERENCE 2	REFERENCE 3		REFERENCE 4		
		CYCLE #2	CYCLE #13	240°	210°	180°
DC	0	0	0	0	0	0
Fundamental	100	100	100	100	100	100
Second Harmonic	36	13	19	10	17	24
Third Harmonic	0	0	0	0	0	0
Fourth Harmonic	3	-	-	1	2	5
Fifth Harmonic	4	-	-	2	4	0

SOME CONSIDERATIONS IN THE RELAY DESIGN

The Odd Harmonics and CT Saturation

While it is certainly true that the current-transformers should be selected so that they do not saturate for the largest anticipated fault current, this is often impossible to realize, and so problems of CT saturation should be addressed in the design of protective relays.

Saturation of current-transformers produces harmonic components for reasons similar to those causing the harmonics in inrush currents. In the steady-state, however, the harmonic analysis will show that there are only odd harmonics (plus fundamental) since there is no dc component. Thus the odds are characteristic of CT saturation and the evens are not. This indicates that the odd harmonics not be used for restraint, lest undesirable restraint be provided in the event of a severe fault, internal to the power transformer, which causes the current-transformers to saturate.

Arcing Faults and Waveform Distortion

A common occurrence is a fault occurring within the transformer winding, not adjacent to the terminals, so that the fault current is limited by the relatively high reactance between different portions of the winding, and also that of the laminations. Such a fault, both through the action of the iron involved, and on account of the low current and high voltage in the resulting arc, will tend to produce harmonics of appreciable magnitude.

As in the case of CT saturation, when symmetrical conditions are achieved, only odd harmonics will be present. Thus, restraint with any of the odd harmonics is liable to prevent tripping in this instance.

The DC and Third-Harmonic Components

As noted in Table 3, each of these is a "zero-sequence" harmonic, in that either may tend to cancel in the lines to a delta winding. For this reason, either the dc or the third harmonic component is not reliable to supply the required restraint on inrush.

Selection of Harmonics for Restraint

On consideration of the factors discussed above, it was decided to use only the second-harmonic to restrain the relay. While the fourth has desirable characteristics for this purpose, it is present in too small a quantity to justify the complexity of adding another filter circuit. If the same filter were used to obtain both second and fourth harmonic restraint, it would probably introduce some undesirable third-harmonic restraint as well.

A plausible objection to the use of the second-harmonic for restraint is that an offset fault current has a transient second-harmonic content which might delay tripping. While this is theoretically true, it is also true that the second-harmonic content is relatively small, and quickly falls below the level required for restraint, allowing trip times in the one cycle range for practical situations, provided that the proportion of restraint is properly selected.

Fifteen Percent Second Harmonic Restraint

Analysis of the data available indicates that fifteen percent is the appropriate level. By this is meant that the relay will just restrain when the second-harmonic is 15% of the fundamental component of any complex waveform. In order that this parameter be precisely defined, the relay design is such that the operating quantity is the fundamental component only.

An inspection of the data of Reference 4, Table 3, shows that the second harmonic might (in the worst-case) be only 10% during the first cycle or so of the inrush. We reiterate here that this data is purely theoretical, an analysis of sinusoidal segments resembling actual inrush currents. The analysis, however, does not take into account the damping effect provided by circuit resistance, which has the effect of modifying the actual waveshape as shown in Figure 4. The decrement, due to damping, contributes an extra measure of second-harmonic in the actual case. This fact is seen to be true when the data of Reference 3 (measured value), is considered.

Further, as will be discussed below, careful selection of the filters used to segregate the fundamental and second-harmonic allow the restraint to build up more rapidly than the operate quantity, thus providing an extra margin of coordination.

RATIO MATCHING TAPS

The main current-transformers' ratios should be chosen with regard to maintaining near equality in the currents delivered to the relay during load conditions, or for faults external to the zone protected by the relay. In order to correct for any mismatch in these currents, however, the ITE-87T is provided with ratio-matching taps.

The taps are the basic means of adjusting for these differences (which appear as false differential current to the relay). Note, however, that the percentage characteristic may also be used for this purpose, as a part of "fine-tuning" on the tap selection. In virtually all applications, these balancing devices will obviate the necessity of using auxiliary current-transformers, resulting in simpler interconnections. In addition, the added burden of the auxiliary CT's need not be imposed on the main current transformers, resulting in a higher-performance system.

PERCENTAGE-DIFFERENTIAL CHARACTERISTIC

This feature is perhaps more desirable for transformer relays than any other type of differential relay since the transformer relay will almost always suffer a mismatch in CT ratios due to the ratio of the power-transformer being protected, and the mismatch caused by action of Load-Tap-Changing equipment.

In addition, the location of an external fault can seriously affect the performance of current transformers, causing severe saturation of one CT and not the other. Some of the reasons for this unbalance are listed below:

Bus Configuration

Breaker-and-a-half, or ring bus schemes with the transformer primary winding between two breakers: the fault currents through each breaker are limited by their respective (and probably different) source impedances.

This will almost always lead to unequal distribution of fault currents, and correspondingly different CT performance.

Location of Current Transformers

When one CT is an appreciable distance from the other, the lead-drop from one CT to the relay will tend to be greater than the other. Some of this disparity may be corrected by larger-sized wire for the long run, but usually, the remote CT will have a more difficult task to remain unsaturated.

Difference in CT Ratios

Required to balance the secondary currents delivered to the relays, unfortunately the different ratios produce another problem, in that the higher ratios tend to have higher saturation voltages. This problem can be particularly acute in switchgear applications with low ratio CT's mounted in the switchgear, as C100 or C200 accuracy classifications are quite common for this type of CT, and space is only expensively available for the large volume required for the higher voltage classifications.

PRIOR STATE OF THE ART

A transformer differential relay with harmonic restraint measures the ratio of the difference of winding currents to the sum of the larger of the winding currents. The relay trips if the difference exceeds a predetermined percentage of the larger winding current. At the same time, the harmonic content of the difference current is separated by L-C filters and tripping is restrained if a predetermined harmonic content is present. This content is representative of magnetizing inrush current.

Formerly, relays have used separate restraint current transformers for each winding and one or two differential transformers. The transformers are connected in a T-circuit to derive both restraint and operate voltage signals.

When ratio correction taps are provided on each of these transformers, the T-connection forces a complex interconnection of windings and tap blocks. In addition, the use of conventional diodes and polarized output relays have imposed a large signal level. The large signal level has adversely affected the size and weight of the transformers of necessity and forced the use of bulky reactors and large capacitors in filter circuits.

THE NEW DESIGN

The limiting factors in previous designs have largely been overcome by the use of small-signal design and the novel input circuitry to be described below. The relay design is represented in block diagram form in Figure 6.

INPUT CIRCUIT

Figure 7 shows the input circuit of a 3-winding transformer differential relay. Burden resistors R300, R301, and R302 connected in the secondaries of input transformers T300, T301 and T302 develop signal voltages proportional to the current in each winding. Taps are provided on the primary of each transformer in the manner of a simple overcurrent relay.

Each signal is rectified by precision positive polarity full wave rectifiers U100, U101 and U102. The rectified signals are dioded coupled to obtain the signal of largest absolute value. This is the restraint signal $|V_R|$.

In addition, the AC signal voltages V_1, V_2 and V_3 are summed by means of operational amplifier U104. The resulting signal V_0 is proportional to the difference of the current in the three windings.

ZERO-DROP RECTIFIER CIRCUITRY

This signal is rectified by zero-drop (precision) full wave rectifier U103 to extract its negative absolute value. This is the operate signal $|V_0|$.

The use of simple diodes for rectification penalizes the choice of signal level since the signal must be large compared to the inherent half volt diode junction drop and its attendant change with temperature. However, operational amplifiers in conjunction with diodes produce temperature stable zero-drop rectifiers in order to utilize small signal levels.

As an example, the precision rectifier circuit U103 is shown in Figure 8. The circuit may be analyzed using the following common assumptions:

1) The gain of each amplifier is high enough to consider the voltage between its input terminals to be virtual zero.

2) The input impedance of each amplifier is high enough to consider no current enters the amplifier.

In Figure 8, the first amplifier U103A is connected as a non-inverting amplifier and feeds the output when the input V_1 is negative. With negative, input diode D2 is forwarded biased and D1 is reversed biased.

Considering conditions 1 and 2 above, resistor R_B is at the output potential E, R_A is at virtual zero, and the junction of R_A and R_B is at the input potential .

The output, therefore, can be expressed by

$$v_2 = \frac{R_a + R_b}{R_a} v_1 \qquad (v_1 < 0)$$

The second amplifier, U103B, is connected as an inverting amplifier and gets an input signal v_1 through R_A. With negative input U103B, output is poled positive, diode D4 reversed biased, and the amplifier cannot feed the output. However, when the input goes positive, the U103B output goes negative. Diode D4 is then forward biased, and U103B feeds the output. For this connection:

$$v_2 = - \frac{R_a + R_b}{R_a} \qquad (v_1 > 0)$$

Consequently, the output is again negative and equal to the value produced by the negative input. At the same time, the non-inverting amplifier output is positive for positive input and diode D2 decouples it from the output.

In summary, the input circuit of Figure 7 uses operational amplifiers to derive the restraint and operate signals. The small signal circuitry allows simple tapped input transformers to provide the required differential characteristic. However, the relay has excellent immunity against transients, as discussed in the section on testing.

HARMONIC RESTRAINT UNIT

The harmonic restraint circuit is shown in Figure 9. In this circuit, operational amplifiers are used to construct second order band pass filters for segregating the fundamental and the second harmonic from the complex waveform of the differential circuitry (V_0). The fundamental is poled to operate this unit, and the second harmonic poled to restrain.

The operate signal V_0, obtained from the input circuit of Figure 7, feeds a 60 hertz band pass filter utilizing operational amplifier U200 as an "ideal current inversion negative immittance converter".

It can be shown that the output to input voltage transfer function of either the 60 Hz. or the 120 Hz. filter is the second order bandpass function,

$$K \frac{s/\omega_0}{\frac{s^2}{\omega_0^2} + \frac{2d}{\omega_0} s + 1}$$

In this equation, ω_0 is the center frequency, 60 and 120 Hz. respectively for the operate and restraint quantities, and d is the damping factor (1/Q).

The center frequency of each filter is determined by precision resistors and capacitors R, C and the desired Q by potentiometer R_Q. Both filters are adjusted by a Q of 10. The frequency response of the 60 Hz. filter is shown in Figure 10. The response of the 120 Hz. filter is exactly the same, but centered at 120 Hz. rather than 60.

TRANSIENT RESPONSE

A vital consideration in the selection of filter design is the response to a suddenly applied current. Figure 11 shows the response of the 60 Hz. and 120 Hz. filters to a simulated inrush current. Note that the 120 Hz. filter output rises at a rate twice that at which the 60 Hz. filter does. The reason for this may be understood by analyzing the response of the transfer function to an impulse. Such a solution would be of the form:

$$e^{-2d\omega_0 t} \sin \omega_0 t$$

This type of exponential is seen in Figure 11. Note that the time-constant of the build-up is determined by both the circuit damping and the center-frequency. With the same damping in each filter, the 120 Hz. response early in the inrush period must be twice as fast as that of the 60 Hz. filter. This allows an extra measure of coordination between the two signals and provides for transient stability.

Figures 12 and 13 show the response of each filter to offset and non-offset fault currents. Of interest here is the lack of difference - the filters virtually ignore the dc component.

PROPORTION OF HARMONIC RESTRAINT

As indicated in Figure 9, rheostat R217 adjusts the proportion of second-harmonic required to balance the fundamental (thru R208). As previously discussed, 15% has been selected as the proper amount. However, should other considerations occur, this ratio may be easily varied by the user's adjustment of R217.

This operation is preceded by the rectification of the two signals, V_{1st}, V_{2nd} by rectifiers U201 and U203. Rectifier U201 produces the absolute value of the fundamental signal with negative polarity. This signal drives current in resistor R208 and tends to pole the output of U204 positive at the same time rectifier U203 produces the absolute value of the second harmonic content of the operate signal with a positive polarity. This signal drives positive current through resistors R217 and R218 which tends to pole the output of U204 negative, which is the non-operating direction.

PERCENTAGE DIFFERENTIAL CIRCUIT

Figure 14 shows the comparator circuit utilizing the operate and restraint signal to produce the percentage differential circuit. The circuit is analyzed as follows:

With no operate signal, the positive restraint signal causes the comparator output to pole negative. As a result, resistor R120 is negative while R121 connected to positive. The resistors form a voltage divider and their values are chosen so that at their common junction is zero.

The negative operate signal tends to pole the comparator output positive, producing a positive output at V_D, the junction of R120 and R121. The balance point occurs where the negative current due to the operate signal equals the positive current due to the restraint signal, as

$$V_0/R_0 = V_R/R_R$$

$$V_0 = \frac{R_0}{R_R} V_R$$

It can be seen that the ratio of operate and restraint resistors (R_O/R_R) is the per unit slope differential characteristic. The resistance R_O includes the variable resistor R115 which provides the percentage. Consequently, the circuit produces a positive output for V_O greater than $(R_O/R_R)V_R$.

Figures 15a and 15b show the percentage characteristic thus obtained. As shown, the relay may be adjusted from 15 to 40% restraint, with sensitivity varying from 13 to 46% of tap setting.

OUTPUT CIRCUIT

Figure 16 shows the output circuit of the differential relay. To produce an output, both the differential signal V_D and the harmonic restraint signal V_H must be present at the input of the nand gate U107-2.

The RC circuit and diode, together with the two gates U107-2 and U107-3, form a retriggerable one-shot multivibrator and continues its DC output when the pulse of the unfiltered inputs occur. At the same time, the output of U107-3 feeds transistor relay and target drive circuits.

Thus, relay output occurs only when a differential signal is present and inrush containing second harmonic restrains operation by producing a zero at the V_H input.

INSTANTANEOUS UNIT

A separate unrestrained instantaneous unit, with circuitry similar to that described above, is also included in the new relay. The setting is adjustable from 8 to 20 times tap rating.

TRANSIENT IMMUNITY

As part of the standard design procedure for solid-state protective relays, the new design has successfully passed various transient immunity tests against false tripping, component damage and changes in calibration as a result of subjecting the relay to:

1) Surge Withstand Capability (SWC) Tests (ANSI 37.90a)

2) Fast-Transient Tests

3) Electromagnetic Interference Tests, utilizing 5 watt tranceivers of various frequencies in the range of 48-465 MHZ, at distances of a fraction of an inch from the relay.

TRANSFORMER INRUSH CURRENT TESTS

The ITE-87T was tested on a working installation consisting of a 1500 kVA, 4160/480V secondary unit substation supplying power to the Gould Switchgear Assembly Plant.

Figure 17 shows the transformer being energized from the 4160V side, with no load connected. As shown, the output of the 120 Hz. filter restrains the relay from tripping. The magnetizing current was measured as 23 amps secondary (300/5 CT's) or 8X full-load. Relay settings for all tests: 15% slope and instantaneous element at 29 amps.

The detail of the initial primary and secondary currents, when load is connected, is shown in Figure 18, along with the 120 Hz. filter output. The relay restrains as it did above, with no load. Of particular interest in this photo, is the apparent short-circuit of the transformer secondary during the first several cycles after energization.

The basic sensitivity of the 87T is illustrated in Figure 19. Here, the secondary CT's were disconnected from the relay so that the relay currents were zero. A legitimate trip occurs in about 0.4 seconds, when the magnetizing current has sufficiently decayed.

This seems an inordinately long time, however, since the load current was very low, the relay is operating at (.145 ÷ .13), only 111% of minimum sensitivity.

CONCLUSION

Solid-state design techniques have been exploited to implement a new relay for transformer protection utilizing the time-proven principle of percentage differential and harmonic restraint. Previously, relays designed according to these powerful principles had to suffer the disadvantages of bulky iron-core inductors, complex interconnections, and time-related calibration changes.

The use of modern electronic components such as integrated operational amplifiers, precision resistors and capacitors has eliminated these problems.

The paper has shown that solid-state designers can develop the circuitry required by the application of the device within the power-system, without suffering limitations inherent to the component parts.

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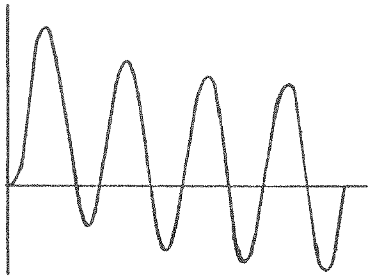


FIGURE 1
Offset Fault Current

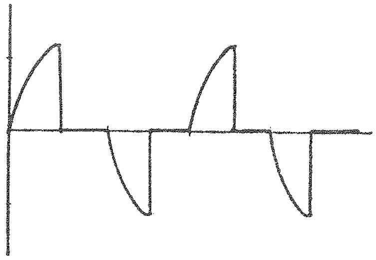


FIGURE 2
Saturated Current-Transformer
(Resistive Burden)

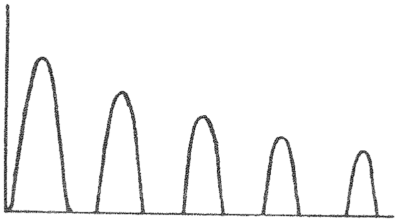


FIGURE 3
Magnetizing Inrush Current

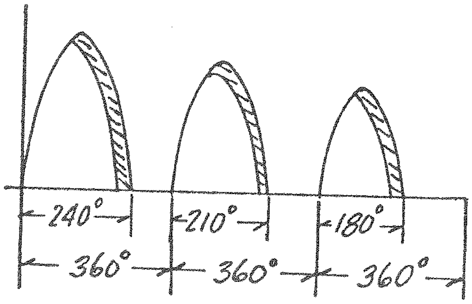


FIGURE 4
Magnetizing Inrush Current
Showing Narrowing Bases and
Effect of Damping

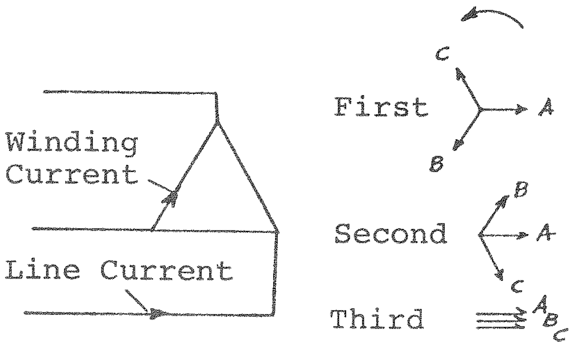


FIGURE 5
Winding and Line Currents
First, Second, Third Harmonics

FIGURE 6
Block Diagram - Type ITE-87T
Transformer Differential Relays

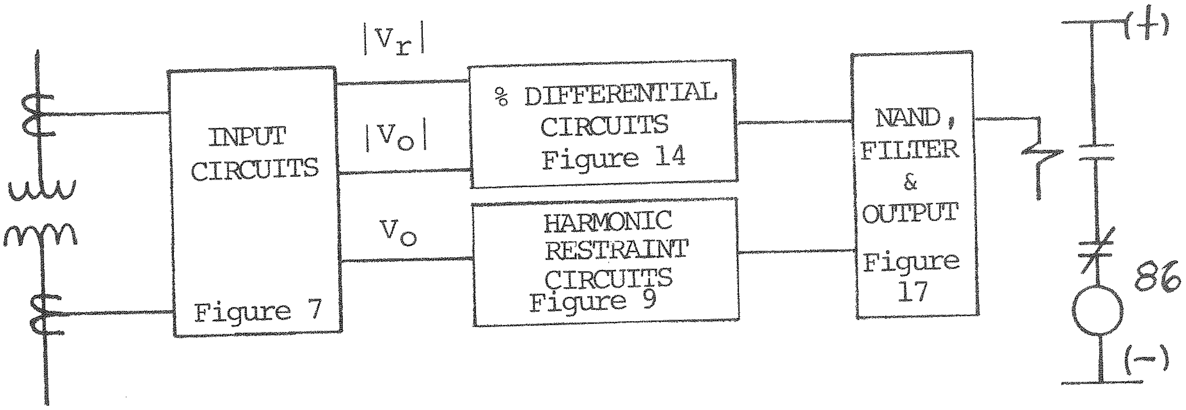
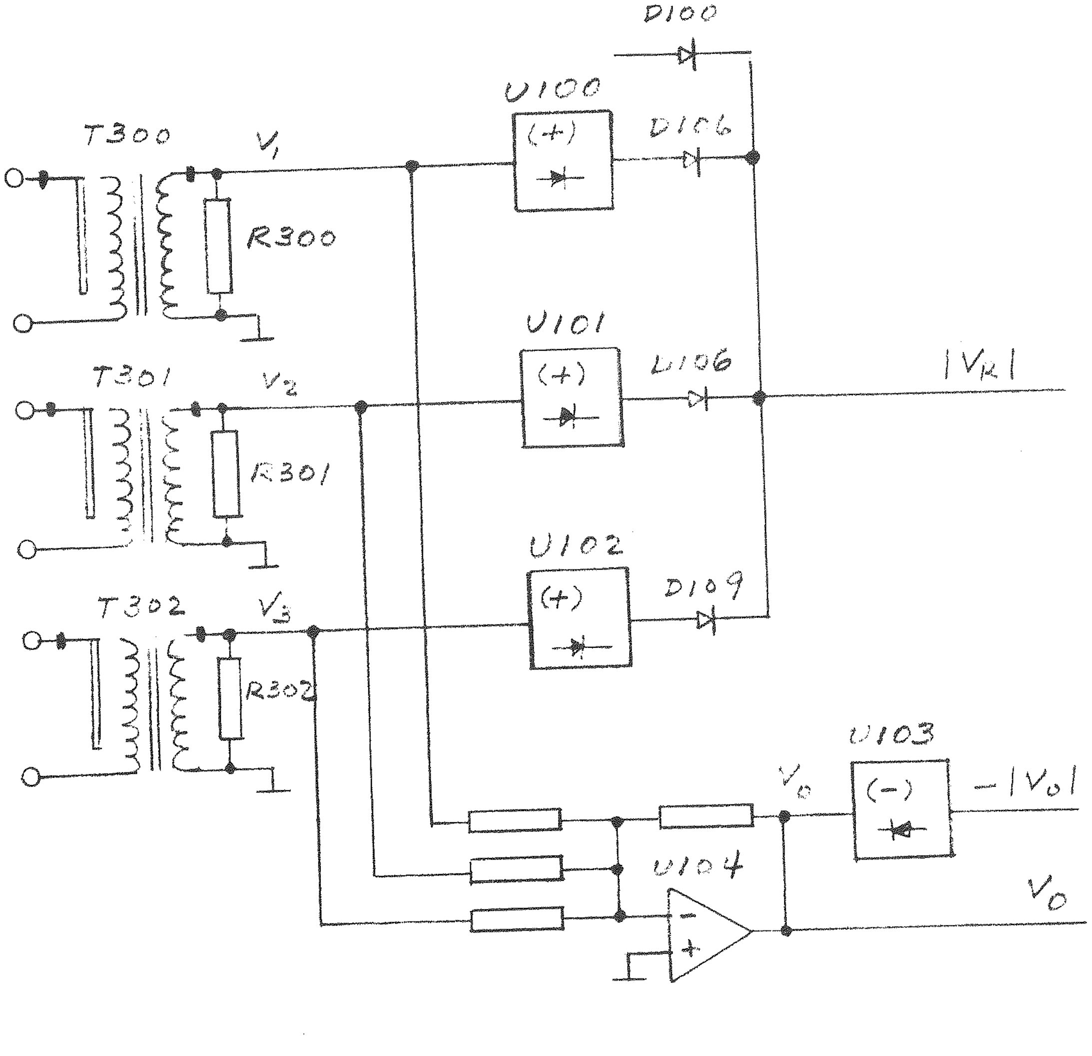


FIGURE 7
3-Winding Input Circuit to Develop
Restraint and Operate Signal



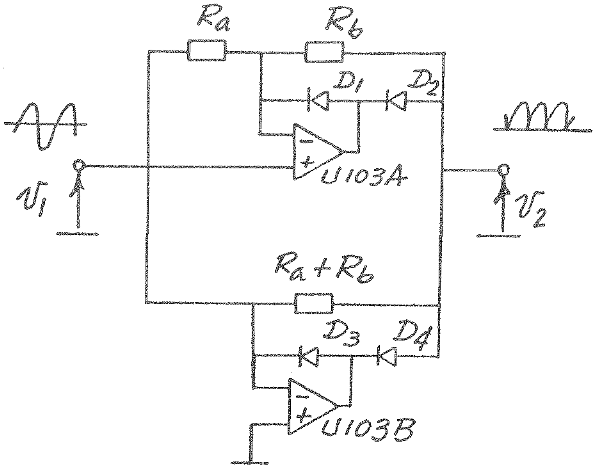
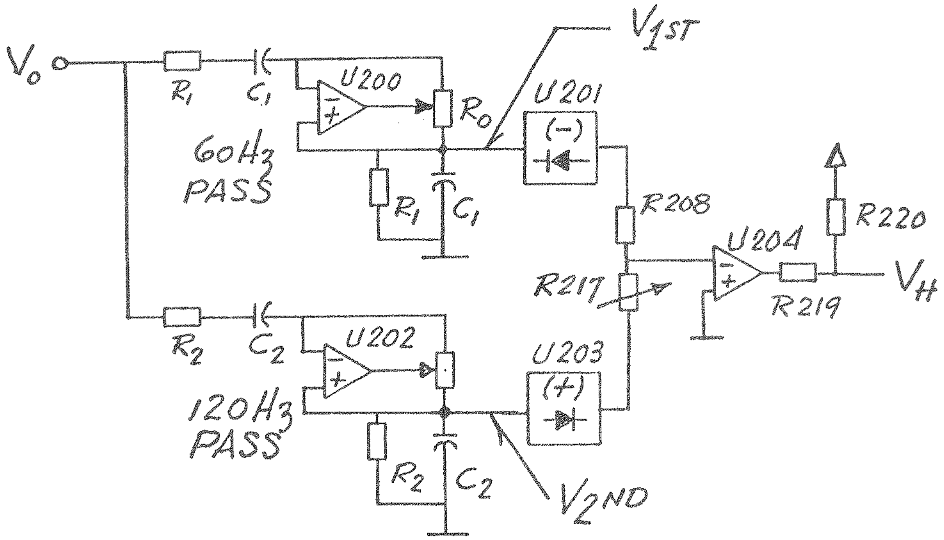


FIGURE 8
Zero-Drop
Rectifier Circuitry

FIGURE 9
Harmonic Restraint
Circuitry



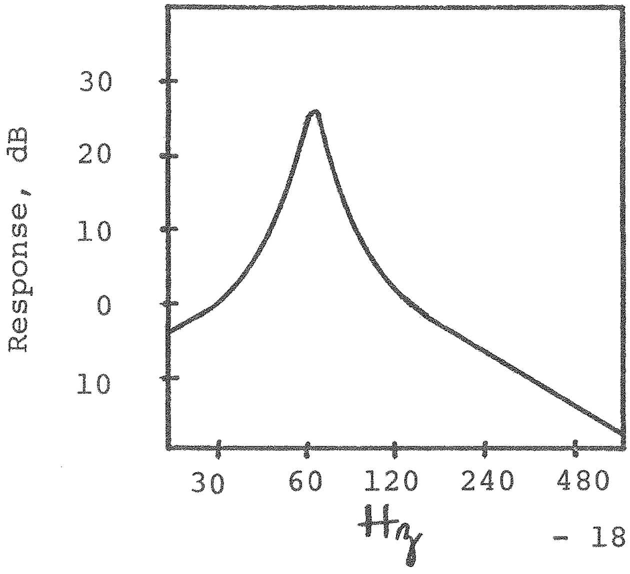


FIGURE 10
Frequency Response
60 Hz. Pass Filter

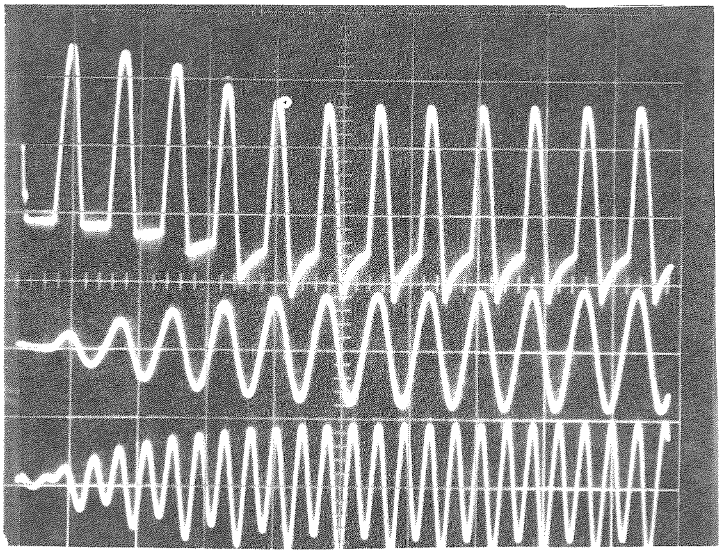


FIGURE 11
Filter Response to Inrush

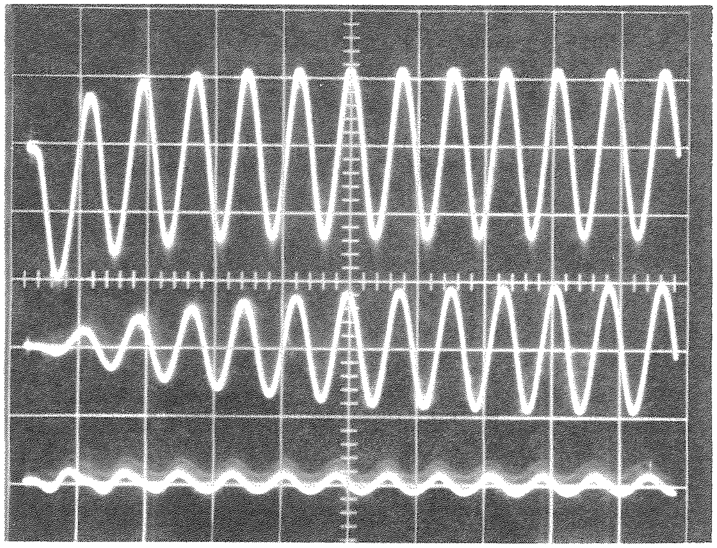


FIGURE 12
Filter Response to
Offset Fault Current

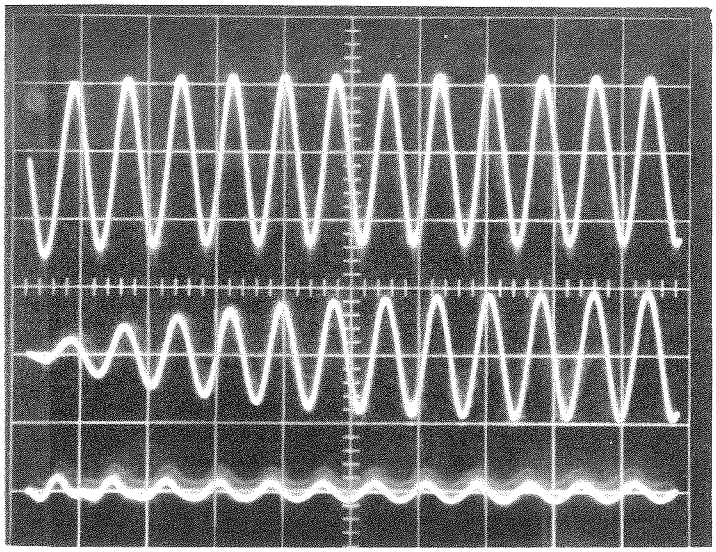


FIGURE 13
Filter Response to
Non-Offset Fault Current

FIGURE 14
Percentage Differential Circuit

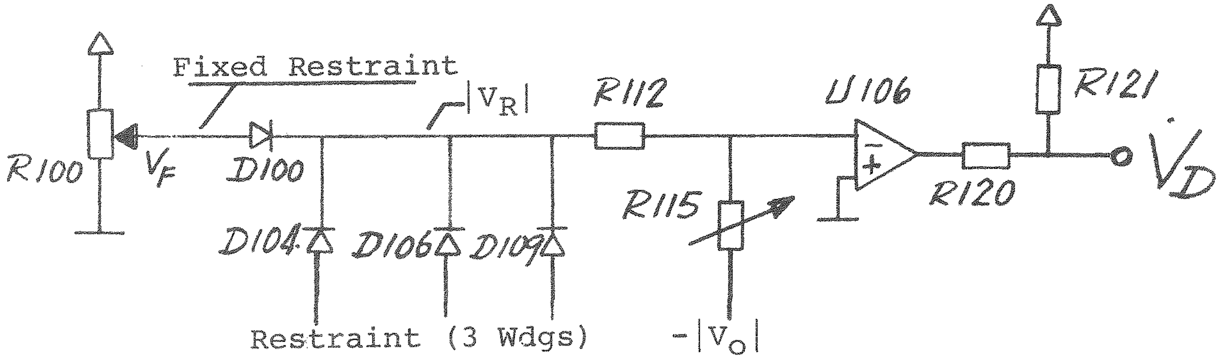
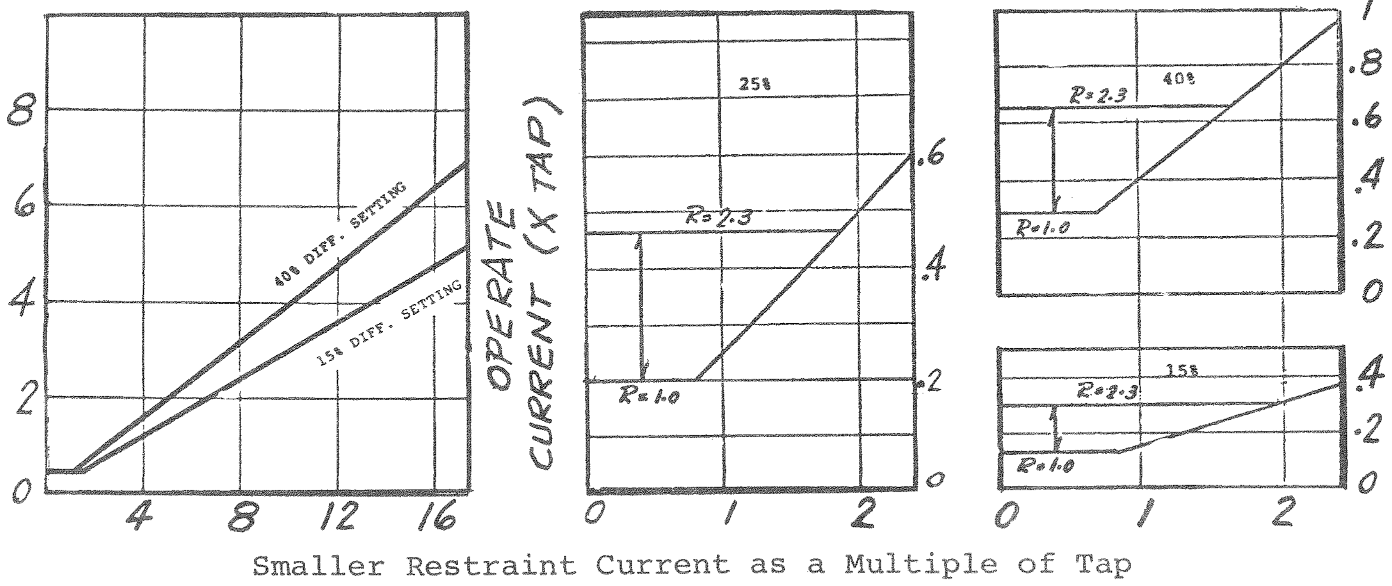
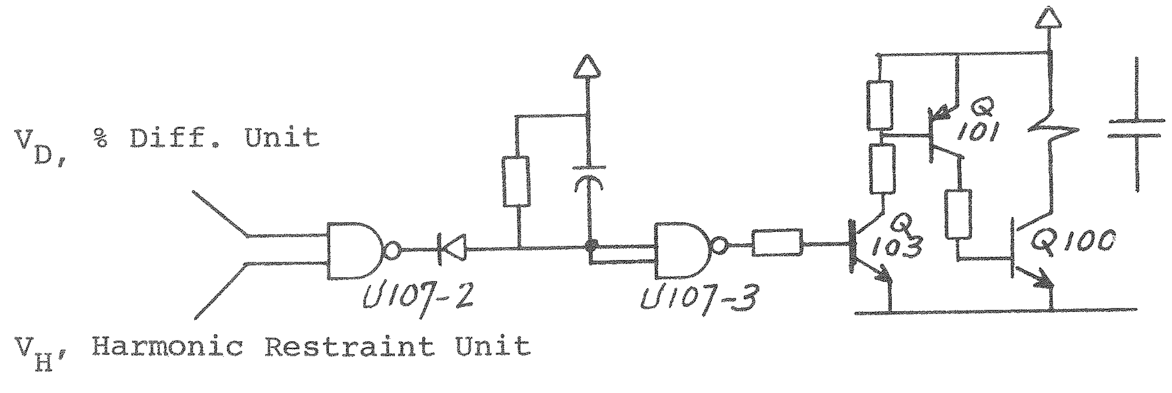


FIGURE 15
Percentage Differential Characteristic


15a
High Currents

15b
Expanded at the Origin; 15, 25 and 40%

FIGURE 16
Nand, Filter, and Output Circuit



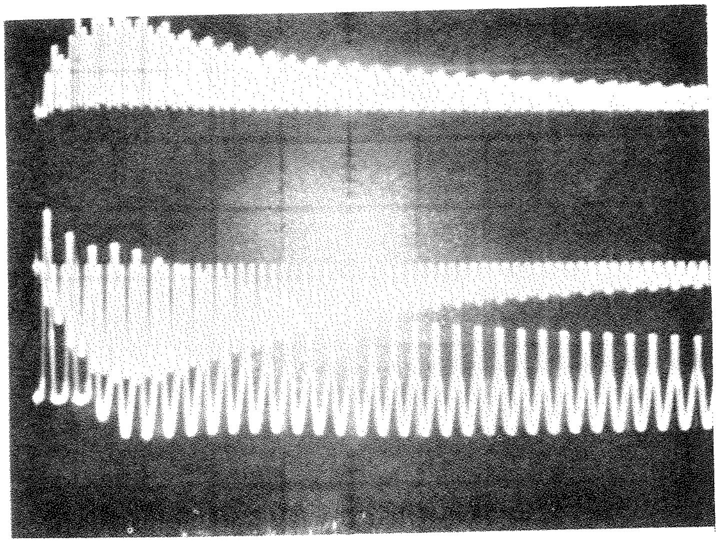


FIGURE 17

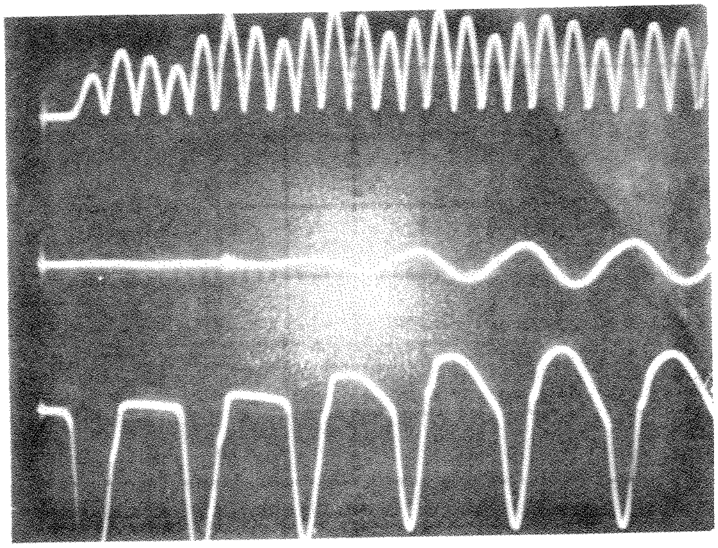


FIGURE 18

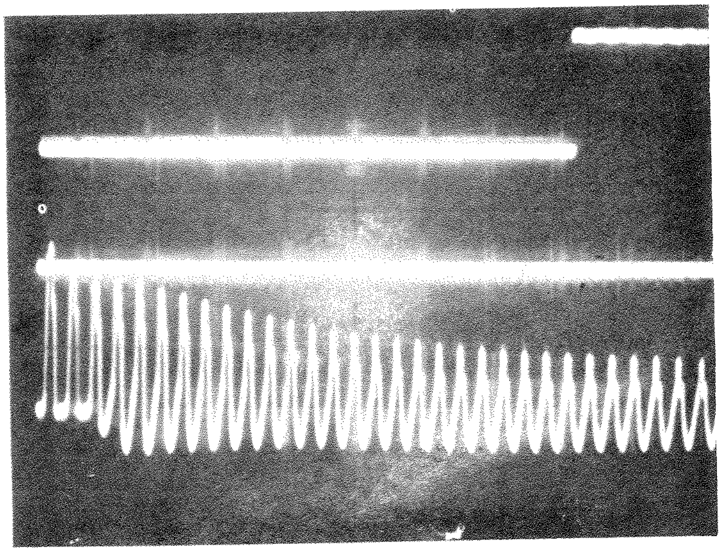


FIGURE 19

Type ITE-87T
Transformer Differential Relay

Relay and Circuit-Board Extender
Showing Solid-State Circuitry