McGrath method. These new tables will, we understand, list current capacities for soil thermal resistivities of 60, 90, and 120 thermal ohms.

We are indebted to Mr. Barnes for furnishing the information on the British Electricity Board's specification on cable jackets. Of particular interest is the clause requiring the jacket to pass a 10-kv d-c test after laying. This is definitely a step in the right direction.

Mr. Barnes asks for amplification of our reasons for choosing the 695-mil insulation offer by the British supplier instead of their 600-mil insulation alternative when both cables were guaranteed to pass the AEIC voltage tests. While the authors are aware that the trend in European cable engineering practice is to thinner insulations with correspondingly higher electrical stresses, the AEIC specification calls for 835 mils of insulation in the 230-kv voltage class. For our first 230-kv cables the 695-mil insulation seemed a reasonable compromise between American and European standards. We are now of the opinion that a review of the insulation thickness in the AEIC specification should be undertaken.

Mr. Barnes also raises the question of the disparity in installation costs apparent in Table VI. The splicing portion of the installation contract was virtually on a unit-price-per-manhole basis. The same unit price held for both the Canadian and the British splices. There are 32 splicing manholes on the 4.2 circuit miles of Canadian cable as compared to 29 splicing manholes on 9.9 circuit miles of British cable. Thus the installation cost per mile for the Canadian cable was about twice the installation cost per mile for the British cable, as shown in Table VI.

Mr. Short asks for clarification of the 695 mils given as the British insulant thickness. This is the nominal insulation thickness excluding the conductor and the insulant screens. The minimum insulation thickness assumed for design purposes is 680 mils. The routine factory tests showed no thicknesses this low. Mr. Short refers to the limitation of the ionization voltage test to 100 kv on the British 1,900-foot length because of limitations of capacity of factory test transformers. On lengths under 1,200 feet they were able to apply the 160 kv stipulated by the AEIC specification and a sufficient number of shorter lengths were included in the contract to provide a satisfactory quality evaluation for the British cable. Answering Mr. Short's specific questions, we do not consider that the AEIC ionization factor test is more severe than necessary; nor do we consider that a d-c routine high-voltage test is as acceptable as the a-c test.

Mr. Hatcher has commented on the use of Lucite as the joint casing insulator for the Canadian cable. The Lucite insulator has performed very well so far and, in the authors' opinion, is definitely superior to any former design of sheath insulator. These insulators have been in service for 8 months at pressures up to 200 psi and no leaks have developed to date. With regard to Mr. Hatcher's query on the power factor for the Canadian cable, the value 0.38% given in Table II is the guaranteed value. Further data on power factor for the Canadian cable are contained in Mr. Short's discussion. In the British joint, antimony lead wire shielding is used as a stress control cone to the top of the joint insulation slope. In the Canadian joint design the lead wire shielding is brought across the joint to the vicinity of the sheath insulator. Metallized paper shielding is carried across the joint insulation under the sheath insulator, the shielding from one side being overlapped with, but insulated from, the shielding from the other side.

Mr. Del Mar is correct in his comments on the losses given in Table II. The $I^2R$ watt loss for the Canadian cable is based on 700 amperes. The dielectric loss of 2,150 watts per 1,000 feet is computed for a power factor of 0.45%. The authors regret these errors in Table II.

We have had no experience with the polyethylene jacket containing butyl rubber recommended by Mr. Del Mar. The difficulty of obtaining a good bond of polyethylene to any material has caused us to hesitate in specifying polyethylene for a jacket over aluminum sheath in wet locations. Perhaps the addition of butyl rubber overcomes this objection to polyethylene. We intend to make further investigations of suitable jackets for future lines.

Horne Payne and Ingledon are receiving points for 230-kv power from distant hydrogenerating stations. The main generating station at Bridge River is approximately 130 miles from Horne Payne. In Fig. 8 the lengths of aerial lines are: Horne Payne to Hill terminal, 5.4 miles; Hill terminal to Ingledon, 11.7 miles; and Ingledon to Kidd, 15.2 miles. The longest individual 230-kv cable section now planned will be approximately 14 miles in length.

Cable movement was definitely not determined on the basis of rigid rod expansion. In the section "British Cable" of the paper it is stated that 75% of each section length would contribute to duct mouth movement. Mr. Hollingsworth covers this point fully in his discussion.

The authors agree with Mr. Atkinson that the duct arrangement accepted for the British cable system did increase appreciably the duct bank costs. In the light of the experience gained on this first installation, the cost of future installations can be reduced. We cannot comment on the joint and terminal details for the Los Angeles 138-kv cable installations as we are not familiar with them.

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# A Transformer Differential Relay with Second-Harmonic Restraint

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HIGH-SPEED transformer differential relays are concerned not only with faults within the differential zone of the transformer, but also with faults external to this zone. External faults can saturate one or more of the main current transformers to such a degree that a false differential current flows in the operating coil of the relay. Operation occurs if the relay does not discriminate between this false differential current and the true differential current of an internal fault.

Another factor that concerns high-speed transformer differential relays is magnetizing inrush currents. These currents flow into a transformer when it is originally energized, when an external fault is cleared, and when an energized bank is paralleled with a second bank. Since inrush currents flow in one side of a transformer only, they appear as an internal fault to a relay. Consequently the relay operates if means are not provided to desensitize the relay during an inrush.

High-speed transformer differential relays are further complicated by the connections of the transformer bank and the main current transformers on each side of the bank. These current transformers may have different characteristics as well as different ratios. As a result, under load conditions of the power transformer bank, one set of current transformers may produce a greater secondary current than the other set. The difference in the two secondary currents appears in the operating circuit of the relay and may cause a relay operation if not properly compensated.

This paper describes a high-speed differential relay that discriminates between true internal fault currents and false

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The authors wish to acknowledge with thanks the co-operation of the Cleveland Electric Illuminating Company for a series of inrush tests made on the 2-winding transformer differential relay.

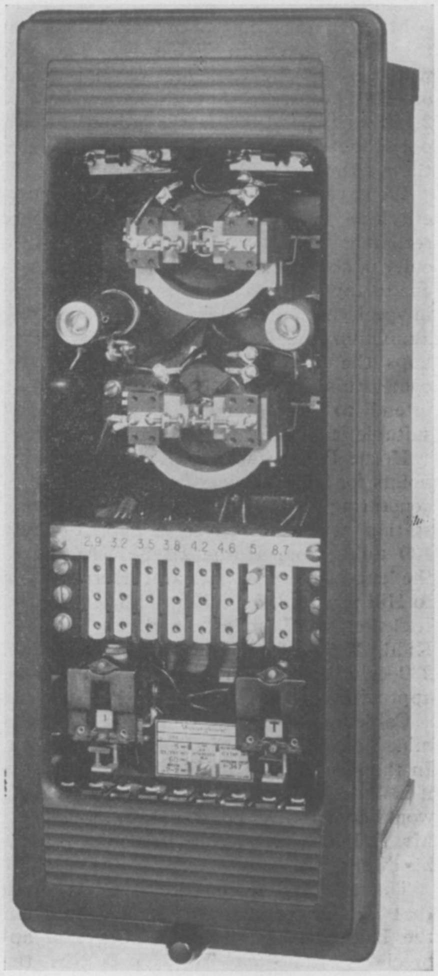

Fig. 1. Three-winding transformer differential relay

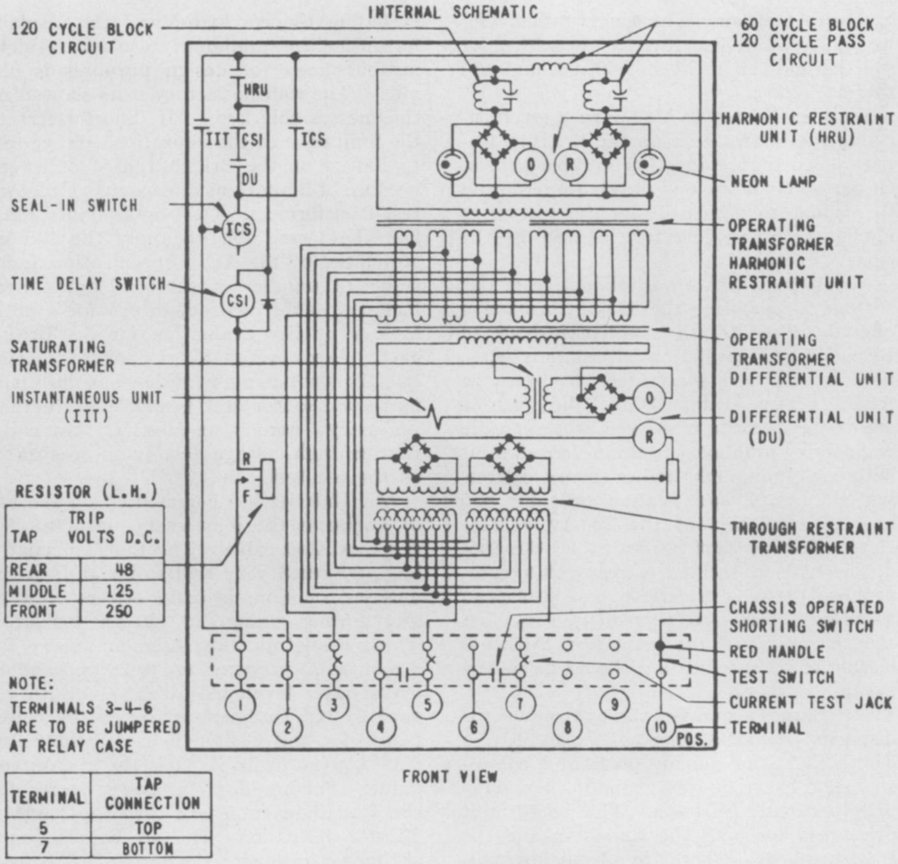

Fig. 2. Schematic diagram of 2-winding differential relay

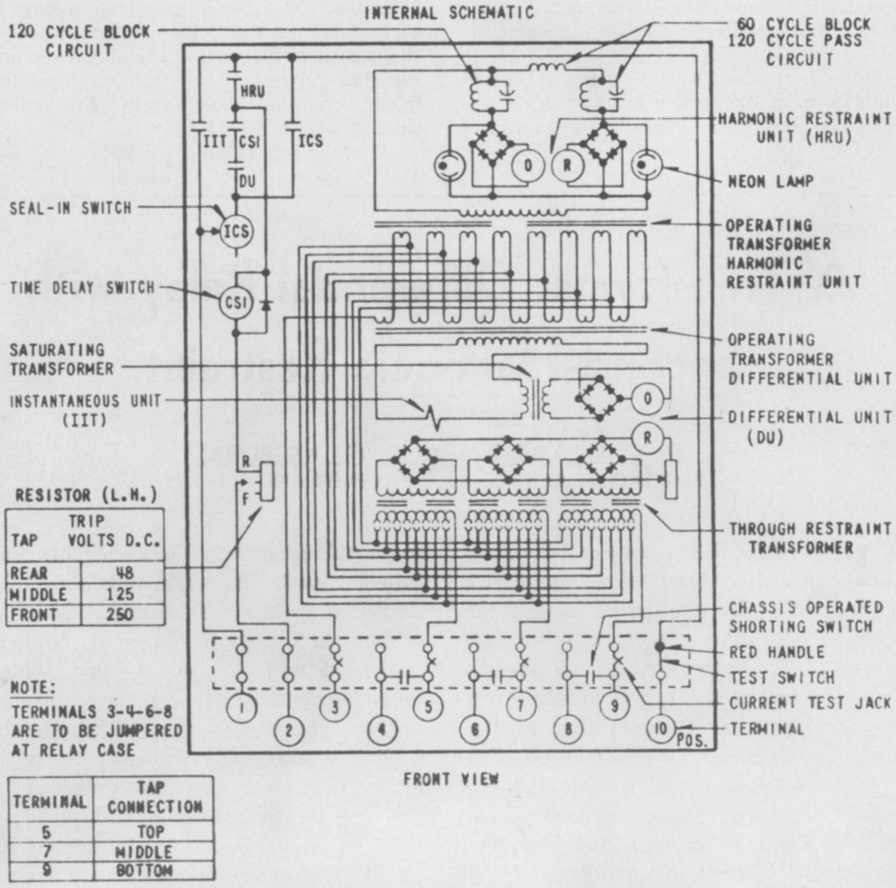

Fig. 3. Schematic diagram of 3-winding differential relay

differential currents of an external fault and an inrush. This is accomplished by the addition of a harmonic-restraint unit to a differential relay. This unit either operates or restrains on the harmonics present in the operating current of the relay. Thus, the relay of this paper consists of a differential unit and a harmonic-restraint unit. Ratio-matching taps are provided on each unit to compensate for main current-transformer ratio mismatch. The relay is shown in Fig. 1.

## Construction

The relay for 2-winding transformer protection is shown schematically in Fig. 2 and the relay for 3-winding transformer protection is shown in Fig. 3. The 3-winding transformer relay can also be used for protection of a 2-winding transformer.

As seen in Fig. 2, the differential unit of the 2-winding transformer relay consists of two air-gap restraint transformers, an operating transformer, a saturating transformer, three full-wave rectifiers, and a sensitive-type d-c polar unit. An in-

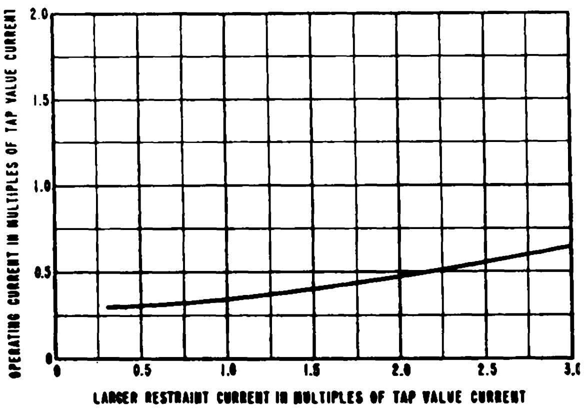

**Fig. 4 (left). Typical operating characteristics at low values of restraint current**

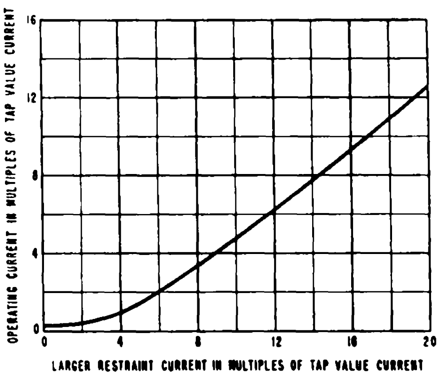

**Fig. 5 (right). Typical operating characteristics at high values of restraint current**

dicating instantaneous trip is connected on the secondary side of the operating transformer. The differential unit of the 3-winding transformer relay, in addition to the foregoing components, has a fourth full-wave rectifier and a third air-gap restraint transformer.

The harmonic-restraint unit of both relays consists of an air-gap operating transformer, a 120-cycle block filter, a 60-block 120-cycle pass filter, two full-wave rectifiers, two neon lamps, and a sensitive-type d-c polar unit.

The contacts of the two units are connected in series to either the trip coil of a circuit breaker or an auxiliary tripping relay. Before an operation can occur, both units, as well as a time-delay switch, must close their contacts.

## Operation and Characteristics

Each of the units of the two relays has a separate function to perform in the over-all protection of a transformer. The differential unit prevents false operation on external faults, and the harmonic-restraint unit prevents false operation on magnetizing inrush currents. Both units close their contacts for internal faults in the transformer.

### EXTERNAL FAULTS

When a fault occurs outside the differential zone of a transformer, the fault can affect the performance of the main current transformers connected to the differential relay. This is true for both symmetrical and asymmetrical fault currents, but as far as relay performance is concerned, the asymmetrical fault affects the relay the most.

The severity of asymmetrical fault currents depends upon the location of the fault in the system and the location of the transformer in this system. Fault currents are possible that have a large d-c component with a long time constant. The direct current can saturate one or both of the main current transformers used with the differential relay to such an extent that a false differential current flows. This differential current will be the greatest when one main current transformer saturates completely and the other main current transformer does not saturate at all.

Operation of the relay is prevented on such a fault by the variable-percentage characteristic of the differential unit of the relay. This characteristic is shown in Figs. 4 and 5. As seen in Fig. 4, the differential unit has a high sensitivity at low values of restraint current. This is to allow tripping on light internal faults. Fig. 5 shows that the unit has a low sensitivity at high values of restraint current. This allows the main current transformers to depart from their true ratio, to a large degree, at high values of through fault current and not to operate the relay.[1]

The variable-percentage characteristic is obtained by restraining the relay with the linear output of the air-gap restraint transformers and operating the relay with the output from a saturating transformer. Current flowing in the restraint transformers produces a voltage on the secondary of the transformers. This voltage is applied to a full-wave rectifier which is connected to the restraint coil of the sensitive-type d-c polar unit. As can be seen from the schematic diagram of the relay, this restraint coil is connected to the output of parallel rectifiers. This is a maximum voltage network in that the greatest voltage applied to the a-c side of any rectifier determines the amount of current flowing to the restraint coil of the polar unit. Thus, with the same tap setting on each restraint transformer, the transformer with the largest current flowing determines the restraint on the polar unit. Hence, the characteristics of Figs. 4 and 5 are plotted in multiples of larger restraint current.

On external faults, the harmonic-restraint unit may or may not close its contact depending upon the harmonic content of the false differential current.

### MAGNETIZING INRUSH CURRENT

When a transformer bank is first energized, an magnetizing inrush current

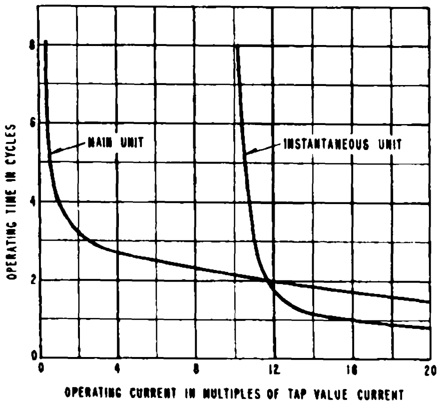

**Fig. 6 (left). Typical operating time of differential relay**

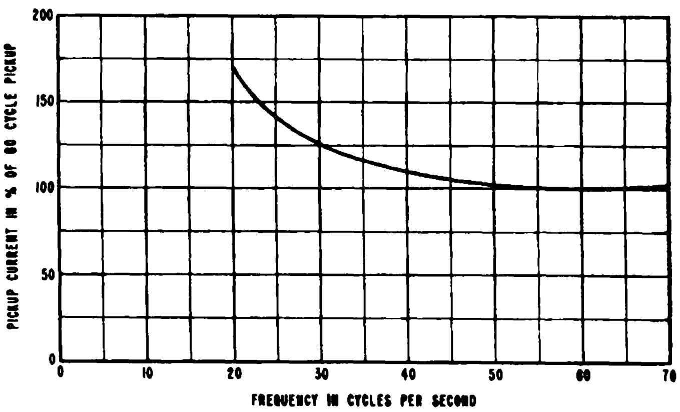

**Fig. 7 (right). Frequency response of differential relay**

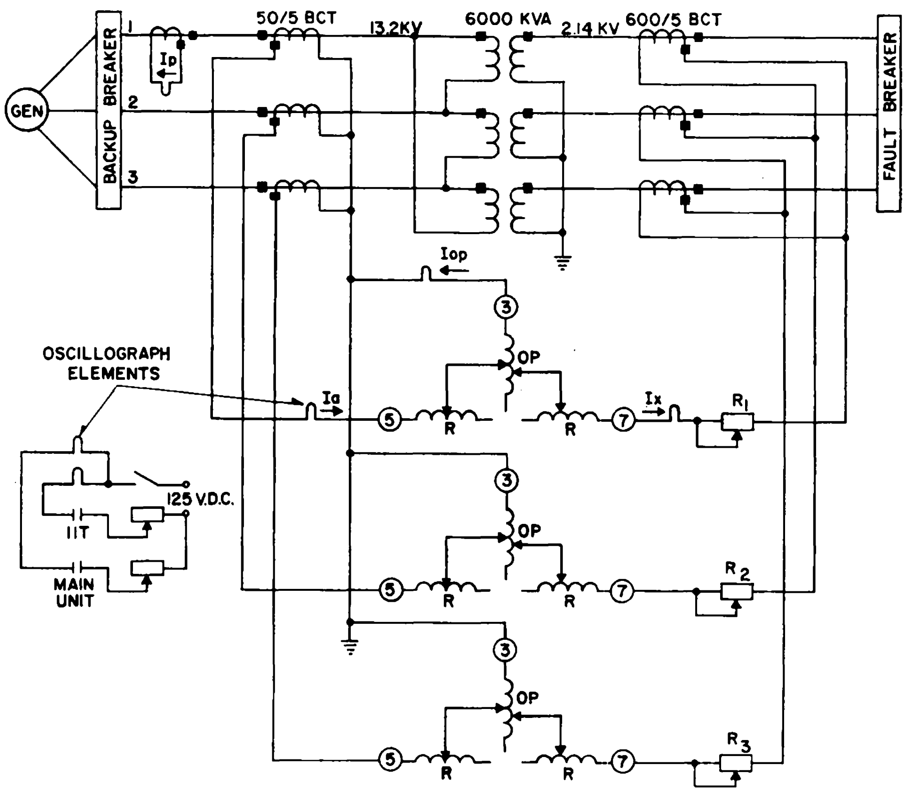

**Fig. 8. Schematic diagram of test connections. $R_1$, $R_2$, and $R_3$ are variable resistors used to produce saturation of delta-connected current transformers**

may flow into one side of the transformer. As stated in another paper,[3] the waveshape of any inrush always has a second-harmonic component which is transmitted to the relay regardless of current-transformer connections. Thus, the harmonic-restraint unit of the relay was made to restrain on the second-harmonic component of the current wave in the operating circuit of the relay.

When an inrush wave is applied to the relay, the differential unit may or may not close its contact, depending upon the magnitude of the inrush. However, operation of the relay is prevented by the harmonic-restraint unit of the relay. The d-c component of the inrush wave is blocked by the air-gap operating transformer while the other components of the wave are passed to the tuned circuits connected in parallel on the secondary of the operating transformer. The second-harmonic component of the wave is filtered out of the wave by the 60-cycle block 120-cycle pass circuit. This harmonic is rectified and applied to the restraint coil of the sensitive-type polar unit. The remaining harmonics of the inrush wave are passed into the 120-cycle block filter. They are rectified and applied to the operating coil of the polar unit. Component parts of the filters are selected such that approximately 15% or more second harmonic will prevent operation of the harmonic-restraint unit.

Operation of the harmonic-restraint unit does not occur for inrushes associated with the initial energization of a transformer or for inrushes associated with the clearing of an external fault. However, when parallel banks are included in the same differential zone, relay operation probably will occur for those inrushes encountered when one bank is energized while the other bank is in normal operations. The waveshape of this sympathetic inrush appears as a sine wave to the operating circuit of the relay.[3] To avoid unnecessary outages of the transformers, each bank of transformers must have its own relays.

Some inrushes have a very high peak and a very wide base. The second-harmonic content of such a wave is very low. When this wave is suddenly applied to the relay, the harmonic-restraint unit may temporarily close its contact as a result of a spurious pulse. This pulse occurs because it takes a small part of a cycle for the tuned circuits to become stable. Thus, for very high inrush currents with bases that are approaching the theoretical limit, a transient is presented to the harmonic-restraint polar unit, and this transient may impart an operating pulse to the unit. After decay of the transient in a very small part of a cycle, normal restraint is established and the contacts will remain open. To avoid an operation, a time-delay switch is added to the trip circuit of the relay. If the harmonic-restraint unit closes its contact as a result of the pulse, it will open before the time-delay switch has had time to pick up to complete the trip circuit.

Neon lamps are connected across each rectifier in the harmonic-restraint unit. These lamps protect the rectifiers from excessive voltage and current. The lamps

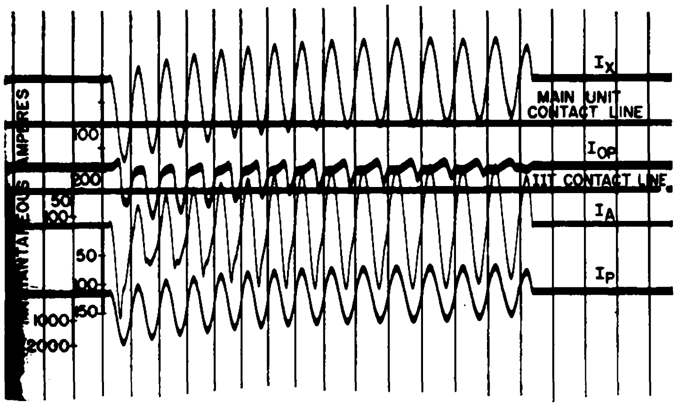

**Fig. 9. Test oscillogram for external fault**

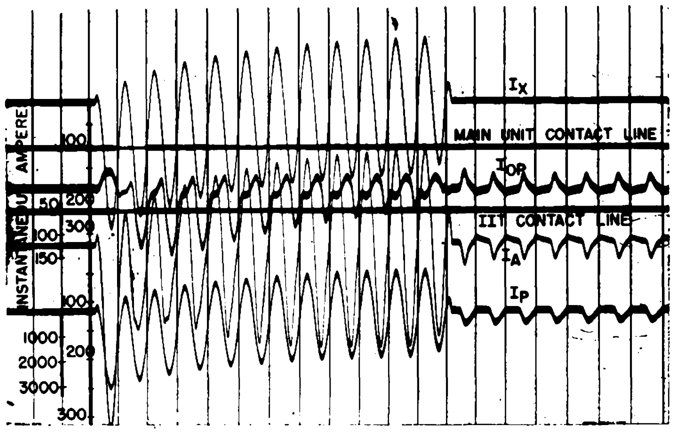

**Fig. 10. Test oscillogram for external fault and recovery inrush**

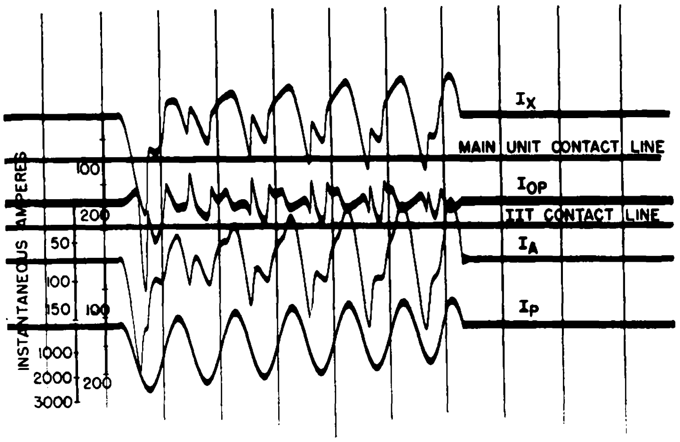

Fig. 11. Test oscillogram for external fault

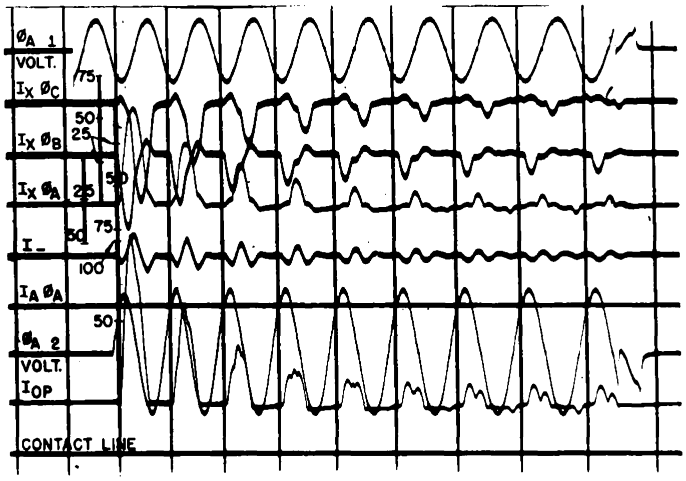

Fig. 12. Test oscillogram for magnetizing inrush current

$\phi_{A1}$—Phase voltage to closing breaker on transformer
$\phi_{A2}$—Phase voltage to transformer
I—Current in tertiary winding of transformer bank

break down and limit the voltage across the rectifiers to a value well below their rating. At the same time, they bypass the excessive current that otherwise would flow through the rectifiers. The lamps break down at high values of internal fault current and do not affect the performance of the harmonic-restraint unit on inrushes.

### Internal Faults

Upon the occurrence of an internal fault in the transformer being protected, both units operate. Pickup of both the differential unit and the harmonic-restraint unit is 30% of tap-value current. Thus, the relay has a high sensitivity for light internal faults.

Internal faults normally appear as a sine wave with possibly a decaying d-c component. Since this wave has very little second harmonic, the harmonic-restraint unit operates. On the other hand, the differential unit operates in conformance with the variable-percentage characteristic curves of Figs. 4 and 5.

The time of operation of the relay is shown in Fig. 6. An instantaneous-trip attachment is provided to give a faster time of operation than that obtained by the polar units. The pickup of this unit is set at ten times tap-value current. This is high enough to override the peak of inrushes and still give a fast time of operation on severe internal faults.

The relay has very good operating characteristics for frequencies below 60 cyles. These frequency conditions exist during reduced-frequency operation of generators and are of particular importance in transformer protection on unit systems. As can be seen from Fig. 7, the pickup of the relay at 20 cycles is only 170% of the normal 60-cycle value. As a result of this tolerable reduction in sensitivity at reduced frequencies, the relay will protect a transformer of a unit system without the use of supplementary relays.

## Confirmation Tests

Tests were conducted on a 13,200/2,140-volt 6,000-kva bank of transformers as shown in Fig. 8. The high-voltage side of this bank was connected in delta and the low-voltage side of the bank was connected in star. Current transformers used on the high-voltage side of the bank were 50/5-ampere bushing-type transformers connected in star. Bushing-type current transformers rated 600/5 amperes and connected in delta were used on the low-voltage side of the bank. Normally such current transformers would not be applied to a bank of transformers of this rating. However, to study the relay's performance on external faults the ratings of the current transformers were made low on purpose. This allowed the relay to be tested with a very good set of current transformers and a very bad set of current transformers. The relay was set on the 4.6- and 5-ampere taps. Three-phase, phase-to-phase, and line-to-ground external faults were applied to determine the behavior of the relay.

As seen in Fig. 9, the 600/5-ampere current transformer reproduced the external fault current faithfully, while the 50/5-ampere current transformer did not. As a result, a large differential current was presented to the relay. As can be seen, neither the indicating instantaneous trip nor the main units operated.

In Fig. 10, the relay did not operate for either the external fault or the recovery inrush when the external fault was cleared. For such a condition, the fault breaker was opened with the resulting inrush current flowing into the bank.

Next, the 600/5-ampere bushing-type current transformers were loaded with

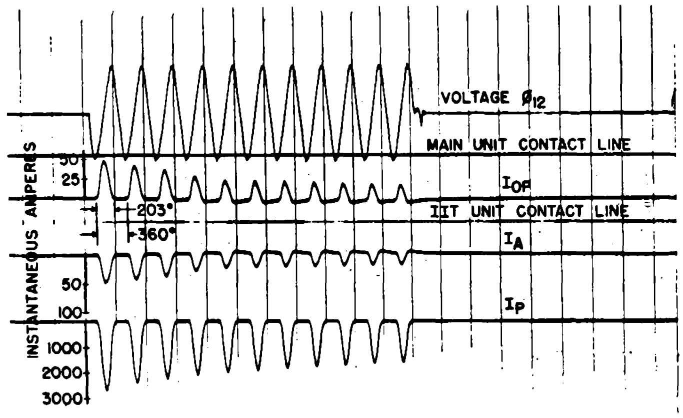

Fig. 13 (left). Test oscillogram for magnetizing inrush current

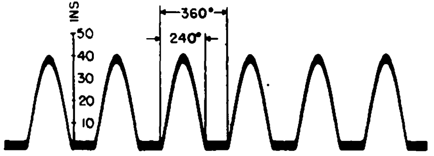

Fig. 14 (right). Test oscillogram for artificially derived inrush wave

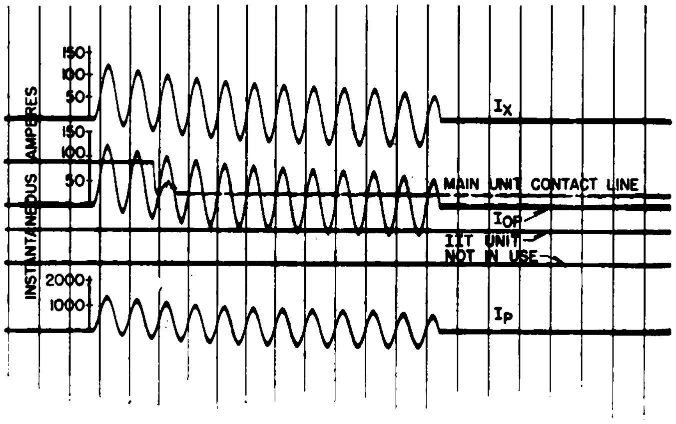

**Fig. 15.** Test oscillogram for internal fault

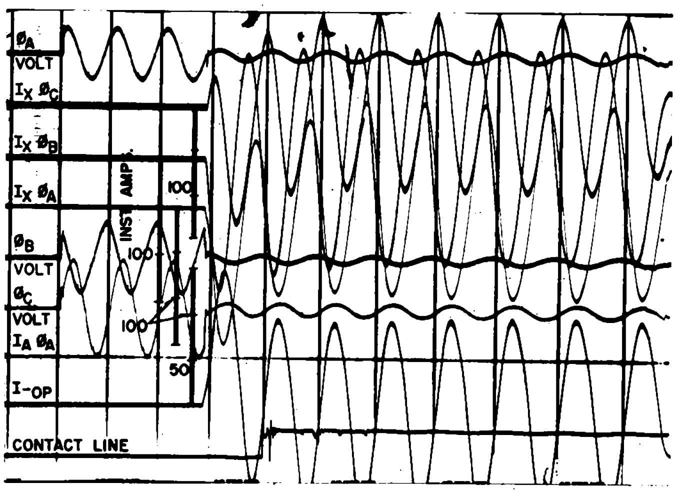

**Fig. 16 (right).** Test oscillogram for internal fault

approximately 1.1 ohms. This made the performance of the 600/5-ampere current transformers approximately the same as that of the 50/5-ampere current transformers. As seen in Fig. 11, neither of the main transformers reproduced the fault current. Both transformers saturated and produced the operating-coil current shown in the figure. Neither the main units nor the instantaneous-trip unit of the relays operated.

To verify the performance of the relay on magnetizing inrush currents, the relay was applied to a 240/240-volt 45-kva distribution transformer bank. The source side of the bank was connected in star, and the line side of the bank was connected in delta. Delta-connected 200/5-ampere bushing-type current transformers were used on the star side of the bank.

A high inrush current was obtained on this bank of transformers by controlling the residual flux in the bank. This was accomplished by applying direct current to the three transformers in such a manner that one transformer had residual flux in the positive direction and the other two transformers had residual flux in the negative direction. The transformers were connected on their 219-volt tap and 300 volts was applied to each transformer. The voltage on the transformer with the positive residual flux was applied at the instant that the voltage wave was going through zero. To obtain the maximum effect of the inrush on the relay, it was set on the 2.9-ampere tap. As shown in Fig. 12, the first peak of the inrush current was approximately 103 amperes with a a base of 206 degrees. However, due to a low *R-X* ratio of the bank, the amplitude and base of the second peak was considerably reduced. The remaining peaks of the inrush were further reduced by this low *R-X* ratio and the inrush subsided after a few cycles. The contact line of Fig. 12 verified the fact that the relay performed properly for this inrush.

To obtain an inrush current that was maintained for a longer period of time, the relay was tested on the transformer bank of Fig. 8. The multiratio bushing-type current transformers were set on their 300/5-ampere tap, and magnetizing inrush currents applied to the relay by energizing the high-voltage side of the bank with the fault breaker open. As seen in Fig. 13, the first peak of inrush current was approximately 50 amperes with a base of 203 degrees. The second peak of inrush was approximately 37 amperes with a base of 190 degrees. After the second peak of inrush, the 300/5-ampere current transformers saturated on the d-c component of the wave. This is shown by the dipping of the "flat" portion of the inrush below the zero line. After 9 cycles the inrush current was still appreciable, having a peak of approximately 20 amperes. Even though the inrush was maintained for a considerable length of time, the relay performed properly.

In order to test the relay on an inrush with a theorical maximum base, a special test circuit was devised. This circuit was such that successive peaks of the wave were not reduced. As seen in Fig. 14, all the peaks had a base of 240 degrees with a value of approximately 40 amperes. Since the relay did not trip on this wave, it can be stated that the relay would not trip on actual inrush waves that have the same first peak followed by successively lower peaks and narrower bases.

Internal faults were applied to the system and, as can be seen in Fig. 15, the relay tripped correctly. The particular fault applied to the relay was below the pickup of the instantaneous-trip unit, and the tripping time was approximately 2 cycles. A more severe fault was applied to the relay as shown by Fig. 16. As can be seen, the relay tripped out in approximately 1 cycle.

## Conclusions

A high-speed variable-percentage differential relay for 2- and 3-winding transformer protection has been developed that will not trip on external faults and magnetizing inrush currents, but will trip for internal faults.

The design uses second harmonic only for restraint of the inrush supervision unit, as this harmonic will always be presented to the relay during an inrush, and is much less predominant for internal faults. The new relay retains the basically simple principle and design of the variable-percentage differential unit. It also provides inrush supervison through second-harmonic restraint of a simple sensitive overcurrent unit connected in the differential current circuit of the main current transformers. The tuned circuits of the inrush supervision unit were selected not only to provide the proper response of the unit for inrush and fault conditions, but also to provide a very good response under reduced-frequency conditions.

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