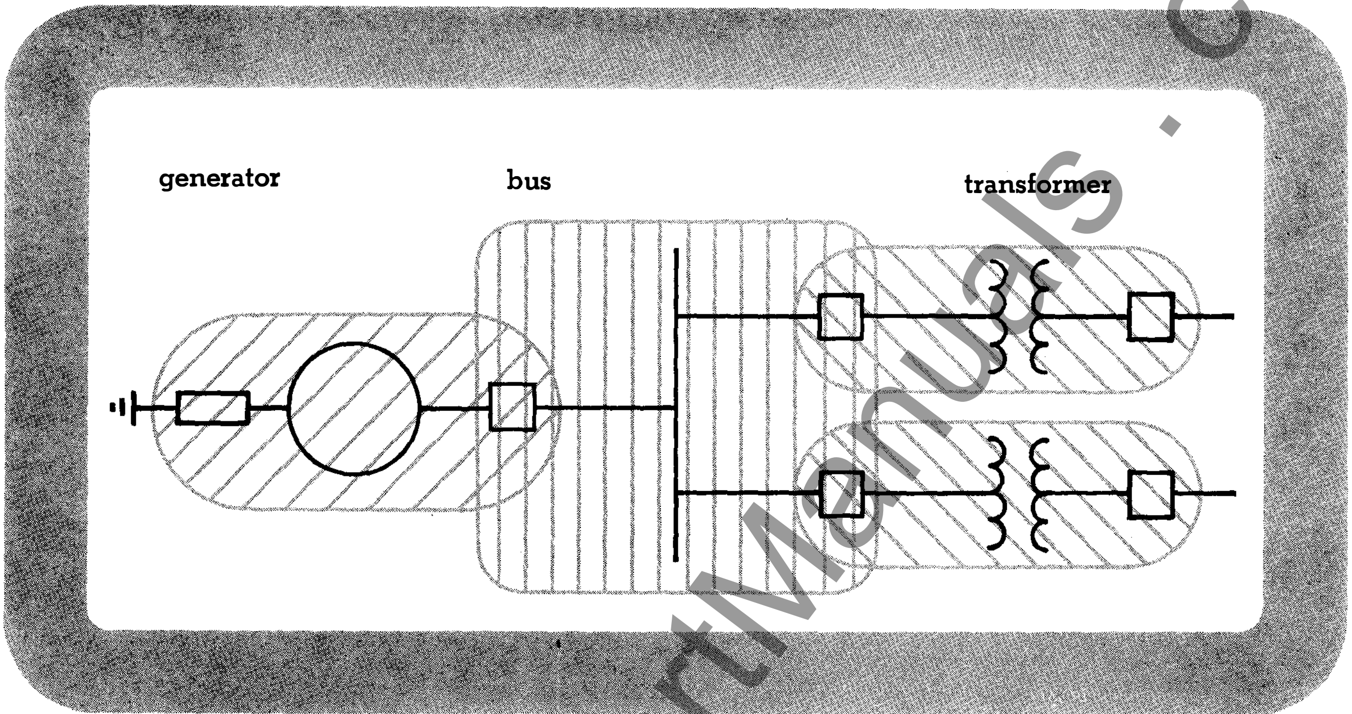
differential relays

percentage differential • linear coupler

for internal fault protection of a-c generators, transformers, and station bus



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mailed to: E/1147/DB; D/821/DB; C/373/DB

principles of differential protection

general information

Differential relaying systems are universally used for the protection of generators, transformers, station buses, and transmission lines. These differential systems are all based on the principle of balancing or comparing the secondary currents in the current transformers at the terminals of equipment. Due to the distance between terminals of a transmission line, the comparison cannot be made directly, and transmission line relaying therefore is a separate and distinct type of differential relaying. This subject is treated elsewhere.

The basic differential scheme is shown diagrammatically in figure 1. Under normal load conditions, current flows through the protected equipment (generator, bus, or transformer) and the current transformer secondary currents I_1 and I_2 will circulate through path I_A.

With a protective relay connected between points 1 and 2, no current will flow through the relay under normal conditions. Should a fault occur external to the equipment, current flow will be increased but will be in the same relative direction as under normal conditions, and the relay will not operate for this external fault condition.

When a fault occurs in the protected equipment, the current flow on one side is reversed, upsetting the normal balance and causing current I_D to flow through the relay from point 1 to point 2.

As long as the current transformer secondary currents are nearly equal, no appreciable current will flow through the relay operating circuit. Any leakage current, however, to other phases or to ground, will upset the balance and send current through the relay operating coil. If this current exceeds the pickup setting of the relay, it will operate to trip the breaker and disconnect the faulty apparatus.

Generator differential relays are usually arranged to trip the generator, field circuit, and neutral breakers simultaneously . . . using a manually reset lockout auxiliary relay. In some applications the differential relay also trips the throttle and admits CO_2 to the generator for fire protection.

In transformer differential protection, the high voltage circuit breaker is often located at the remote end of the line serving the transformer. In this application the differential relay initiates a remote trip signal over a pilot wire, tone or carrier channel to the breaker location. See application data 41-940 (carrier) or application data 41-960 (audio tone) for further discussion of this application.

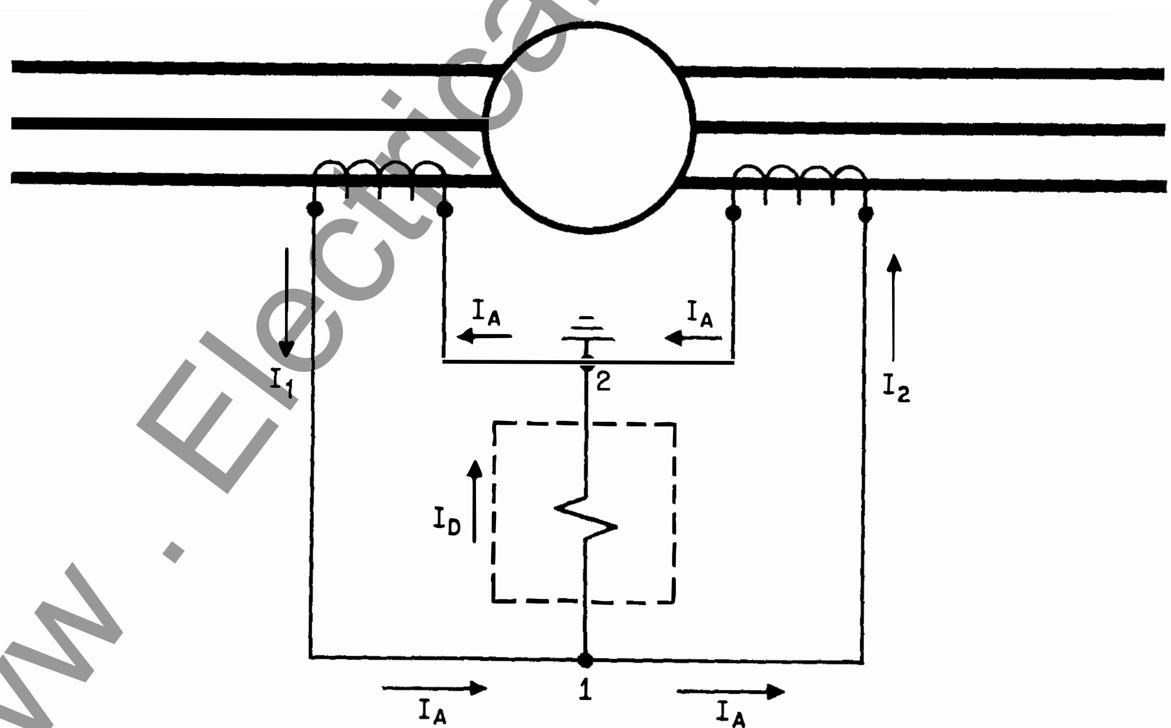


fig. 1: Basic differential relay connections.

differential protection using overcurrent relays

differential protection using percentage differential relays

external fault

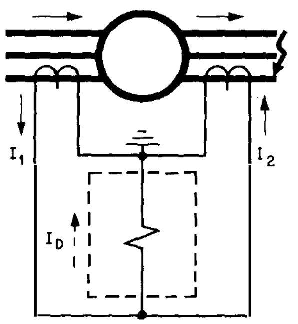


fig. 2

internal fault

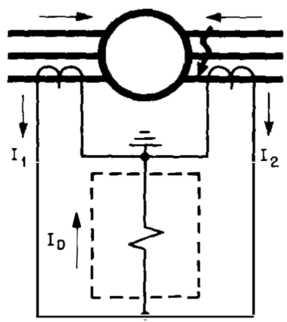


fig. 3

external fault

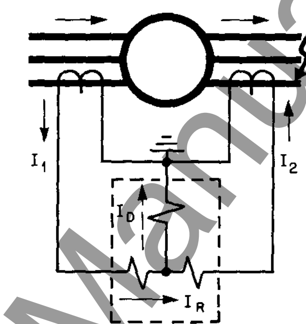


fig. 4

internal fault

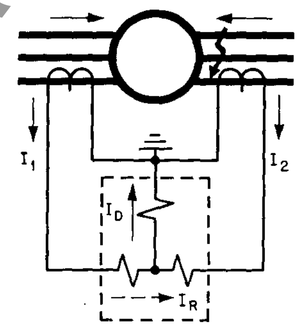


fig. 5

While standard overcurrent relays have been used in differential schemes (figures 2 and 3), the rapid increase in the complexity and loading of integrated power systems has created a more selective line of differential relays . . . each with its own operating characteristic.

Sensitive relay settings are required to detect ground faults which may develop into phase-to-phase or three-phase faults. The neutral impedance of a generator limits the magnitude of the ground fault current.

However, relay selectivity requirements may prevent the use of low-current or fast-time settings.

Phase-to-phase overcurrent protection has definite limitations from the consideration of sensitivity, selectivity, and speed of operation, since overcurrent relays must be set above maximum load current and must also have time settings which select with other relays on the system.

The use of restraining windings in differential relay design permits more sensitive relay settings, affording greater protection than is possible with plain overcurrent relays whose trip settings must be high enough to prevent undesired operation due to current transformer performance under heavy through-fault current.

Since current transformers of the same type and rating perform differently due to variations in magnetic construction, loading, degree of saturation, etc., differential relays are designed which operate on either a **fixed** or **variable** percent of differential current between the incoming and outgoing currents. The variable percentage relay is particularly adaptable to applications involving transformers where the low and high side current transformers have different current and voltage ratings.

Percentage differential relays have two (or more) additional windings called restraining windings. The restraining torque is in the contact opening direction and is proportional to the vector sum of the incoming and outgoing currents. On an external fault, this contact-opening torque is strong and tends to prevent false tripping due to the differential current (I_D) caused by saturation effects of the current transformers.

On internal faults, most of the current in the restraining windings is in opposite directions so that the total restraint torque is much less than in the case of the external fault.

The relay will trip when the operating torque (created by I_D) is greater than the restraining torque, that is, when the operating current is higher than a certain percentage of the smaller of the two restraining currents.

Some relays are designed to trip when a constant percentage of unbalance exists between the two restraining currents. Other relays operate over a variable range of differential current. These have a "variable percentage" characteristic and, as the magnitude of the restraining current increases, a greater amount of operating, or differential current is required to trip the relay.

The **variable** percentage relay is more sensitive than a **constant** percentage relay on light internal faults, but less sensitive on heavy external faults; due to the variable percentage characteristic. It is particularly suitable where heavy saturation currents are encountered.

differential protection using linear coupler relays

external fault

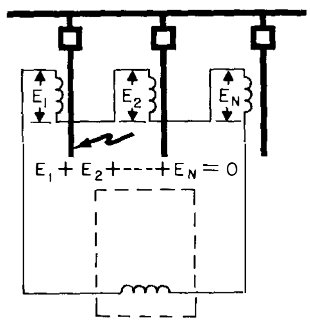


fig. 6

internal fault

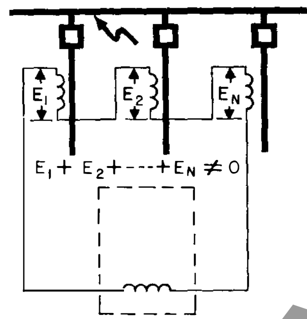


fig. 7

Linear coupler transformers produce secondary voltages proportional to the applied primary currents.

The linear coupler method of differential protection is essentially a voltage differential scheme and, consequently, a series circuit is used in contrast to the parallel circuit employed with current transformer schemes. In the case of an external fault as shown in figure 6, the sum of the voltage induced in the linear coupler is zero. $E_1 + E_2 - E_N = 0$.

This occurs because the sum of the currents flowing to the bus is equal to the sum of the currents flowing out to the system . . . and the relay does not trip. In the case of an internal fault, see figure 7, the above voltage cancellation does not exist, and the difference voltage appears at the terminals of a high speed, low energy, linear coupler relay which trips instantaneously. The linear couplers are in effect air core mutual reactors. They are similar to current transformers in general appearance and structural detail, except that the secondary coil winding has an air core with a permeability of 1.0; thus will not saturate or cause error currents even when heavy primary currents exist.

This type of protection is particularly applicable to the protection of station buses where the d-c component of short circuit current has a long time constant and causes saturation in current transformers of conventional design.

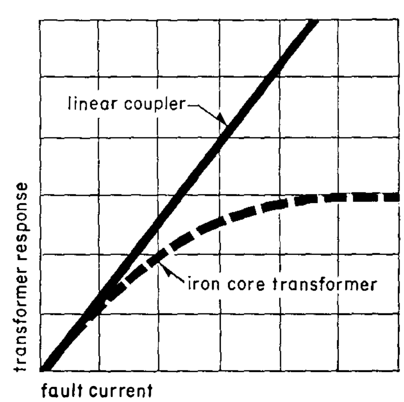


fig. 8

generator differential relays

The relays described in this section are percentage differential types. The magnitude of the differential current required to operate them increases as the external fault (or through) current increases.

In the type CA inverse timing relay the percentage is constant, and in the type HA instantaneous 3-phase relay the percentage is variable.

These relays are extremely sensitive, yet they will not trip on a through fault unless the difference current expressed as a percent of the smaller restraint current exceeds the percent sensitivity of the relay.

The burden of the current transformers used in a generator differential relaying scheme is of importance in maintaining the proper relationship between the two sets of current transformers.

Burden on the current transformers external to the differential relay burden should not exceed $(N_P V_{CL})/133$ ohms. Where:

N_P = proportion of total number of current transformer turns in use

V_{CL} = current transformer 10L accuracy class voltage

For example, if the 400/5 ampere tap of a 600/5 multi-ratio current transformer is used, $N_P = 400/600 = 0.67$. If this current transformer has a 10L200 rating, $V_{CL} = 200$. The external burden should therefore not exceed:

$$(N_P V_{CL})/133 \text{ ohms} = (0.67 \times 200)/133 = 1.0 \text{ ohm}$$

In calculating the burden use the one way load burden.

type CA single phase, inverse timing, constant percentage

The basic connections for this relay are shown in figure 9.

Connected as shown, under normal conditions current passes through the current transformers, relay restraining coils R_1 and R_2 and back to the current transformers. The current in the relay restraining coils produces a restraining, or contact opening torque.

An internal fault in the protected machine will unbalance the secondary currents, forcing a differential current I_D through the relay operating coil O. The amount of differential or operating current required to overcome the restraining torque and close the relay contacts is a fixed (constant) percentage of the smaller restraining current.

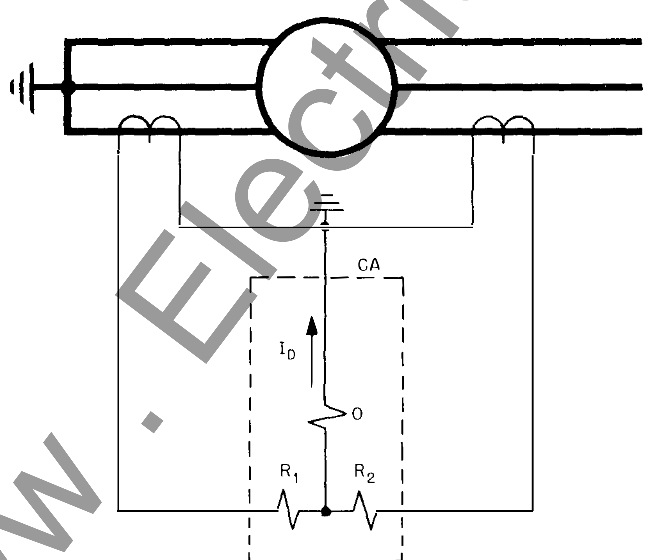


fig. 9

characteristics

single phase, 60 cycles, spst-cc contacts, FT-21 Flexitest case
inverse time characteristic
operating time: see figures 12 and 13
two restraining and one operating circuit
no ratio taps
constant percentage differential
sensitivity: 10% or 25% unbalance
minimum trip
0.18 amperes for 10% relay
0.45 amperes for 25% relay
burden: see figures 15 and 16
thermal capacity
restraint circuits: 10 amperes continuous
operating circuits: 10% relay, 2.5 amperes continuous, 70 amperes for 1 second; 25% relay, 5.0 amperes continuous, 140 amperes for 1 second

relay settings

No setting is required for the percentage differential unit except the setting of the time dial, which should be on the number 1 position.

Each relay is designed for a specific sensitivity and once the correct relay is chosen for a given application, no adjustment is necessary. If, for some reason, adjustment becomes necessary, the spring tension controlling minimum operating current may be altered slightly.

In general, for generator protection, a study of the current transformer characteristic curves under short circuit conditions should indicate whether the high sensitivity (10%) or the low sensitivity (25%) relay should be used. The 25% relay should be used if a-c saturation causes more than 1% ratio error in either set of current transformers.

generator differential relays continued

type CA single phase, inverse timing, constant percentage

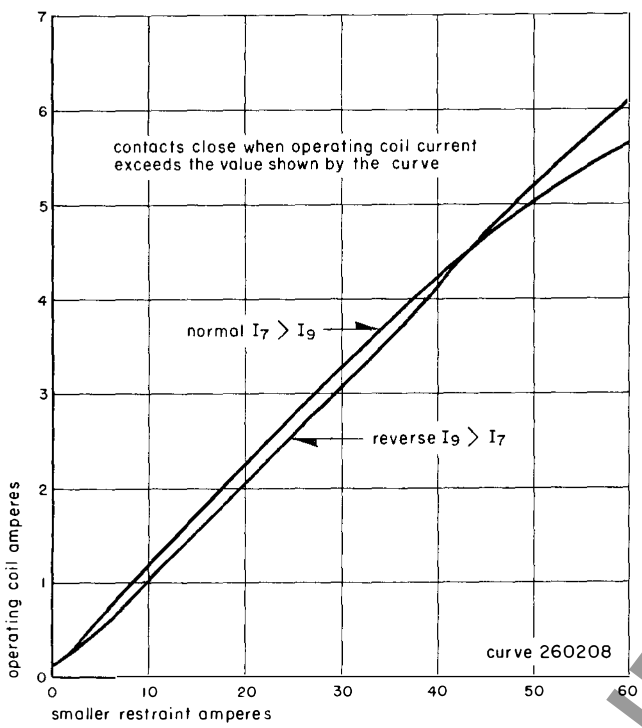


fig. 10: Typical operating curves, 10% CA relay.

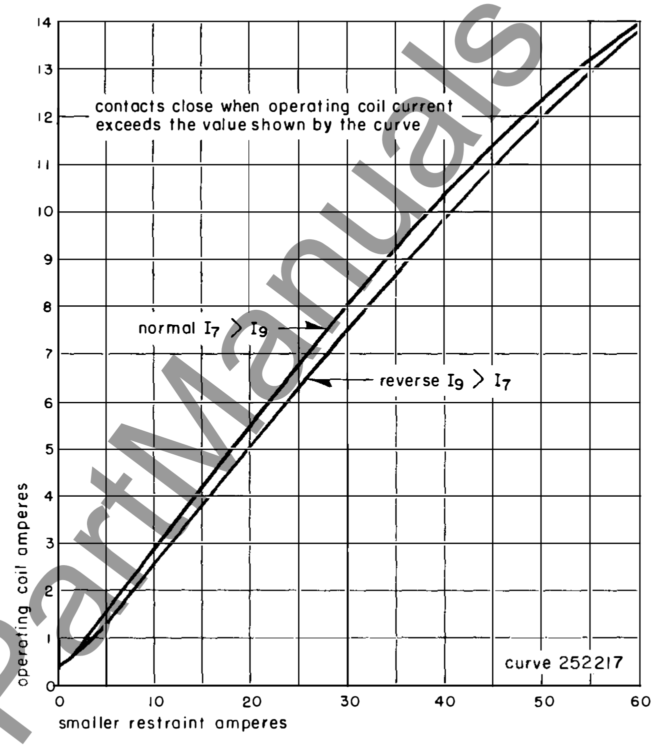


fig. 11: Typical operating curves, 25% CA relay.

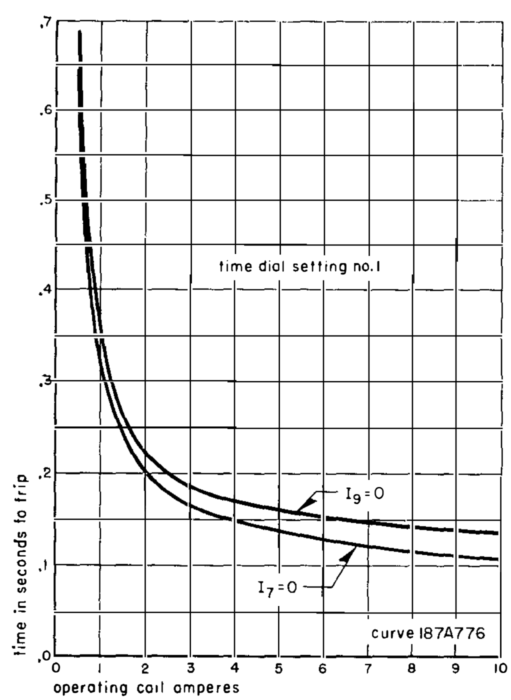


fig. 12: Typical operating curves, 10% CA relay.

further information

product bulletin 41-330A1
instruction leaflet 41-331.2

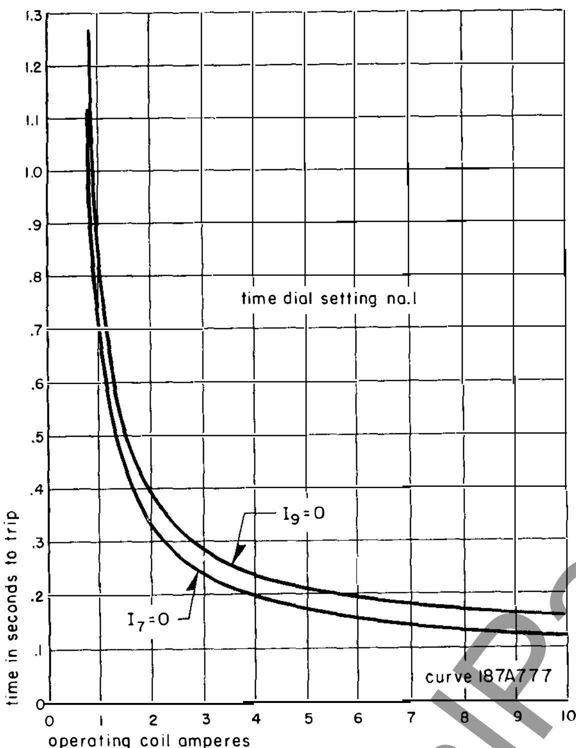


fig. 13: Typical time curves, 25% CA relay.

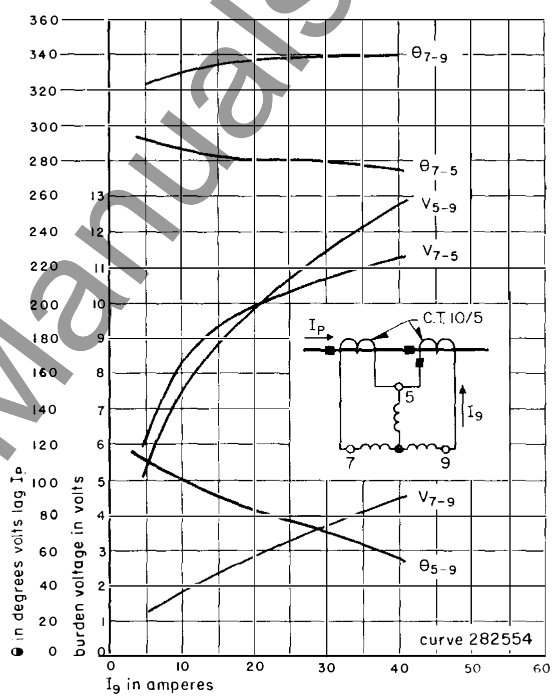


fig. 15: Typical burden curves, 10% CA relay.

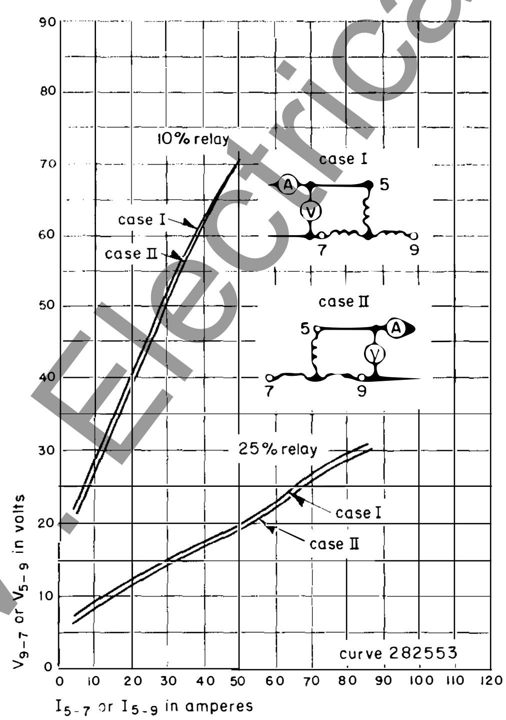


fig. 14: Typical saturation curves, all CA relays.

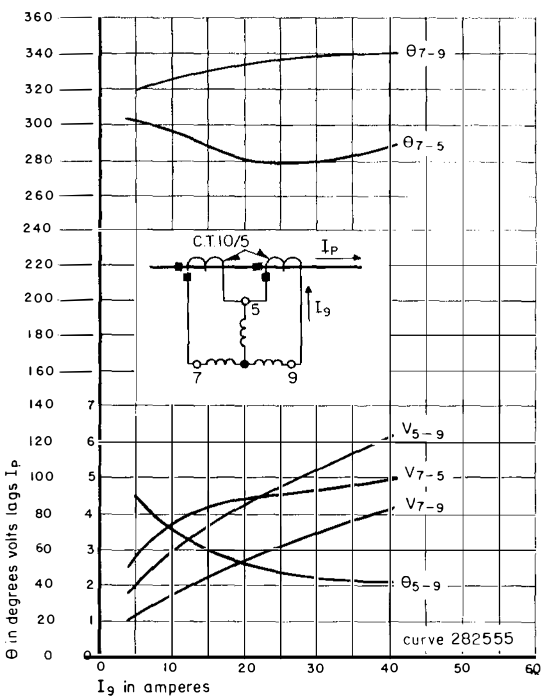


fig. 16: Typical burden curves, 25% CA relay.

generator differential relays continued

type HA three phase, instantaneous, variable percentage

This relay provides complete three-phase high speed differential protection for a-c rotating machines. Each phase element has two restraint and one operating coil with a saturating transformer to limit the energy supplied to the relay elements.

The HA relay will operate in one cycle (60 cycle basis) and has a variable percentage differential characteristic designed so as to be unaffected by d-c transients associated with asymmetrical external fault currents.

The variable percentage characteristic provides sensitive operation on light internal faults and, in addition, provides a large factor of safety against false tripping on heavy external faults. This characteristic is shown in figure 17.

External connections for the HA relay are shown in figure 19.

characteristics

3-phase, 60 cycles, 5 amperes
variable ratio characteristic: see figure 17.
operating time: see figure 18.
minimum pickup: 0.14 amperes

burden:

	restraint circuit	operating circuit
volt-amperes at .5 ampere	...	13.0
volt-amperes at 5.0 amperes	.20	...
volt-amperes at 60.0 amperes	...	4200
continuous rating	5.0 amps	5.0 amps
1-second rating	200 amps	200 amps

relay settings

There are no taps on the relay, and no settings are required.

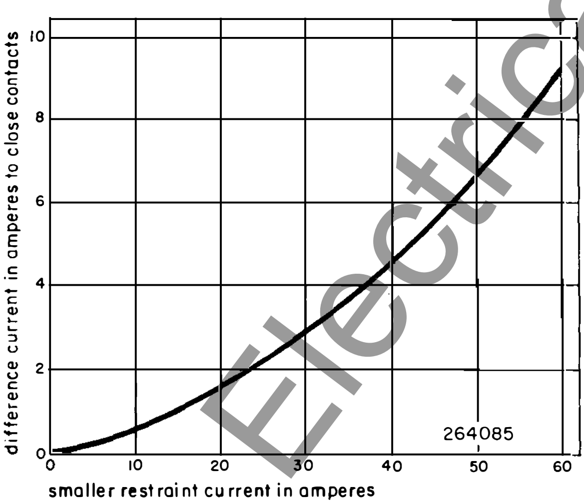


fig. 17: Variable percentage slope curve, HA relay.

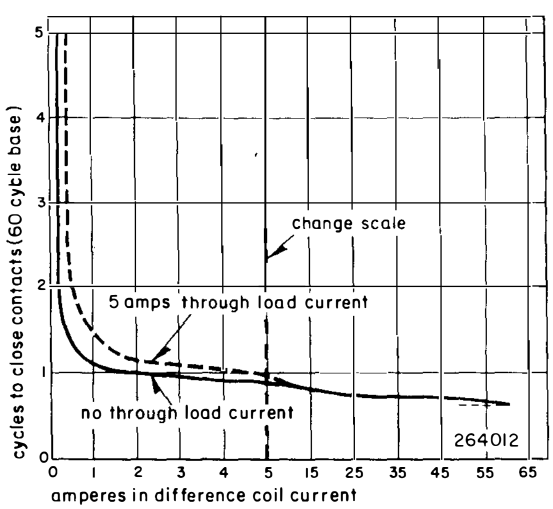


fig. 18: Typical time curve, HA relay.

external wiring diagram

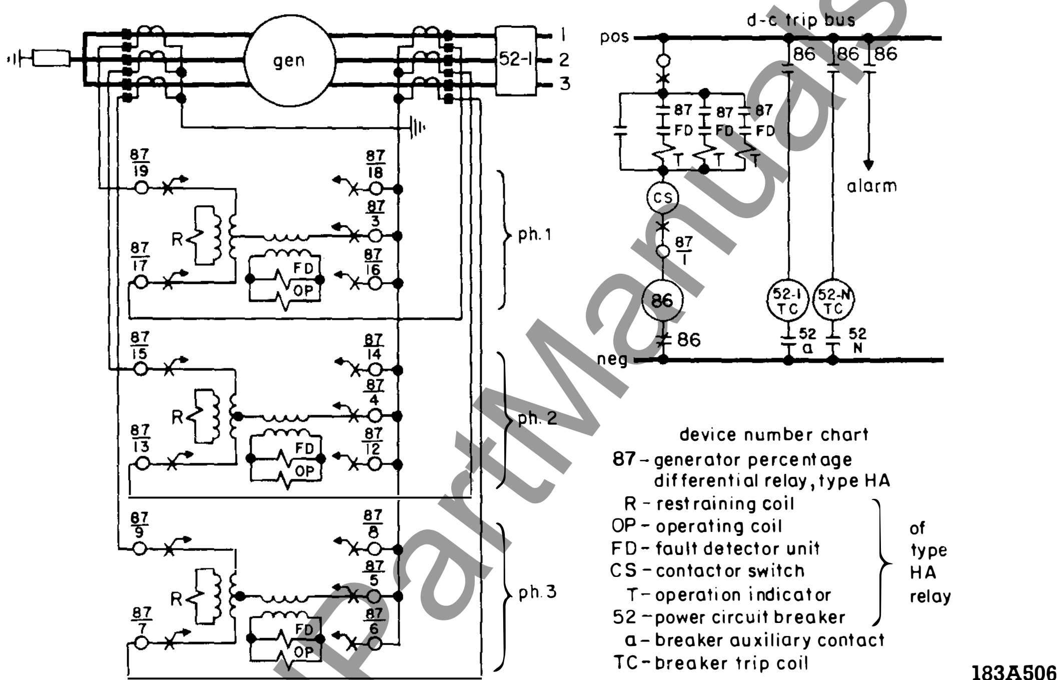


fig. 19: External wiring, HA relay for high speed generator protection.

further information

product bulletin 41-330A2
instruction leaflet 41-341.1

bus differential relays

In generating stations and sub-stations there are usually several incoming and outgoing lines connected to the bus; all of which must be included in the bus differential protection zone. The differential scheme must provide a restraining circuit for each source of power connected to the bus so that there will be no external fault location under any system condition where the output of the current transformers would not produce sufficient restraint in the differential relay. In addition, the relay should be sensitive at low current values to operate on a light internal fault, yet relatively insensitive at high values of current to prevent tripping on heavy external faults when the current transformer characteristics might vary.

Bus differential relays characteristically use several restraining circuits with a single operating circuit. The linear coupler system, however, uses a series connection between all the linear couplers in the protected zone with a simple low energy high speed relay.

This system is described more fully on pages 14 through 21.

type CA-16 single phase, inverse timing, variable percentage

The CA-16 is designed for the differential protection of multi-circuit buses up to a total of six circuits. The variable percentage characteristic provides the desirable high sensitivity at small current magnitudes and relative insensitivity at high currents. It will therefore detect light internal faults in the protected bus section and, conversely, will not trip incorrectly on heavy external faults.

characteristics

single phase, 60 cycle, spst-cc contacts, FT-32 Flexitest case

operating time: see figure 22
six restraint circuits, one operating circuit
no ratio taps

variable percentage characteristics: see figures 20 and 21

minimum trip: 0.15 amperes

burden:

each restraint circuit: 0.75 volt-amperes at 5 amperes
14 amperes continuous rating
460 amperes 1 second rating

operating circuit: burden, see figure 23
8 amperes continuous rating
280 amperes 1 second rating

relay settings: none required

performance curves: see figures 20 to 23

further information

product bulletin 41-330B1
instruction leaflet 41-337.2

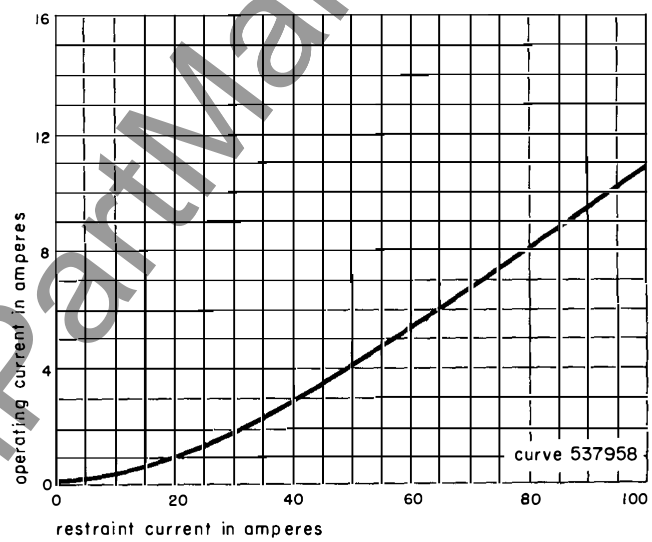


fig. 20: Variable percentage slope curve, CA-16 relay with one restraint winding.

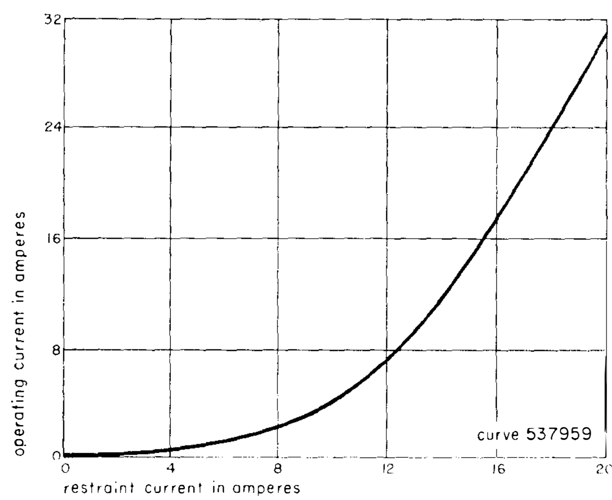


fig. 21: Variable percentage slope curve, CA-16 relay with six restraint windings in series.

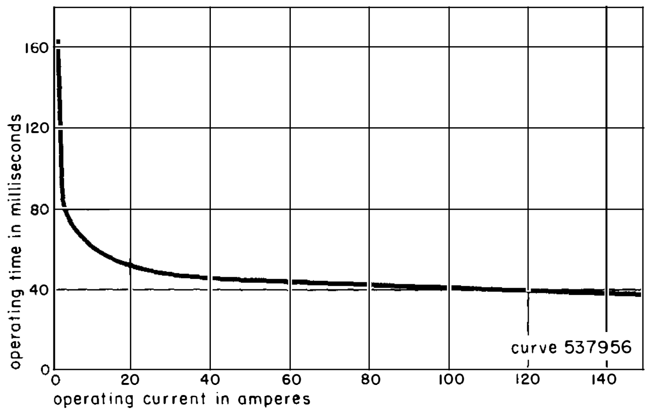


fig. 22: CA-16 relay typical time curve.

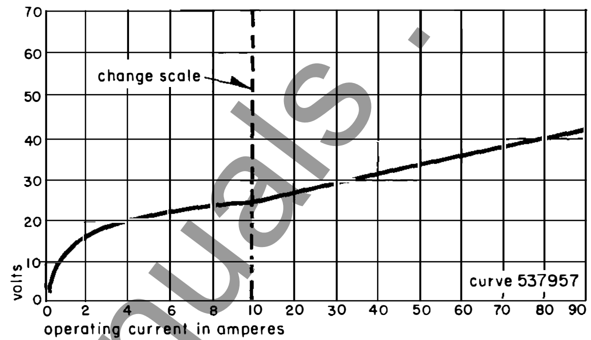


fig. 23: CA-16 relay typical burden operating curve.

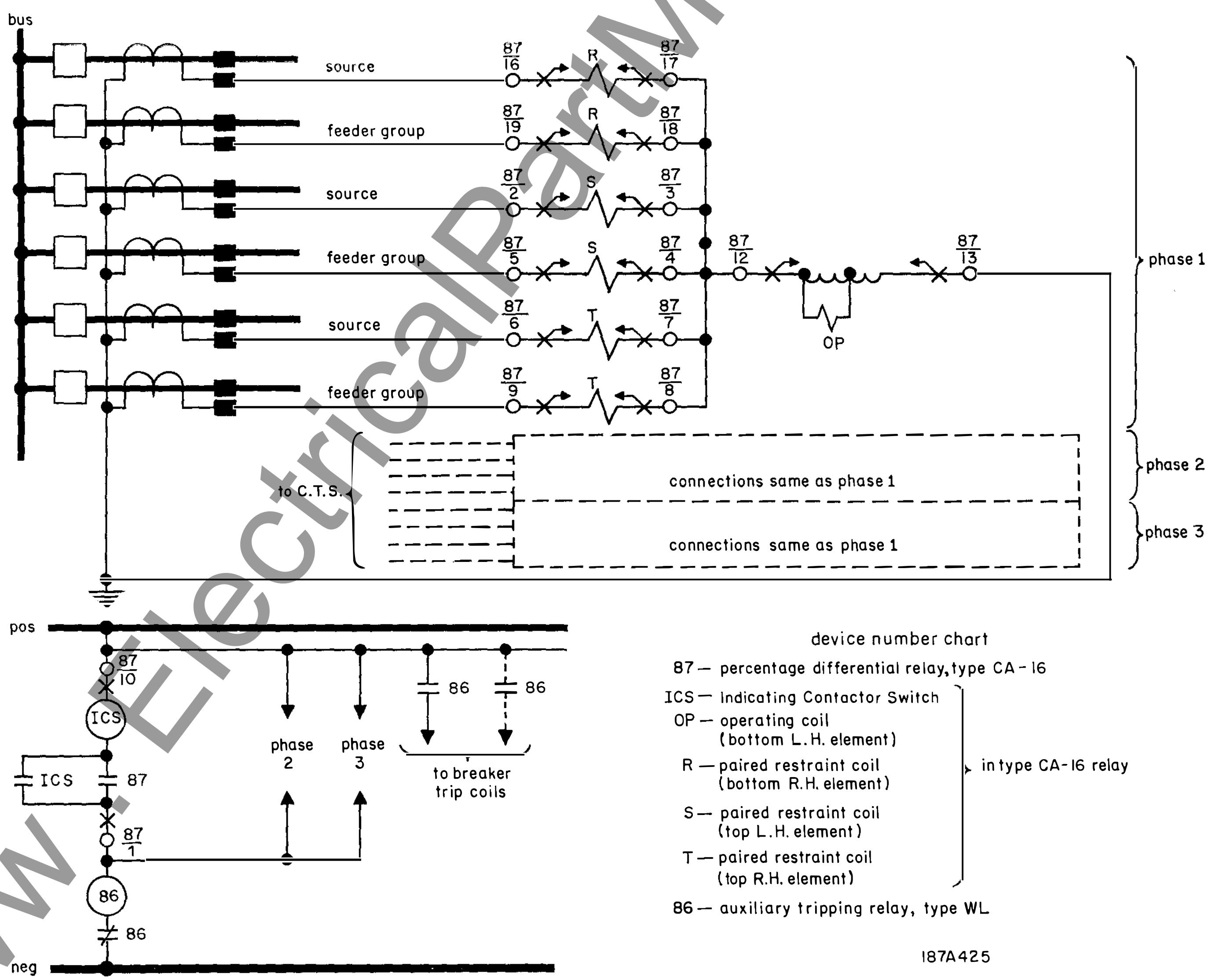


fig. 24: External wiring—one set of CA-16 relays for the protection of a six circuit bus with three feeder groups.

bus differential relays continued

type HU-4 single phase, instantaneous, variable percentage

This relay is a high speed unit with four restraint circuits and one operating circuit. In addition, it has a second harmonic restraint unit for use where a transformer is associated with the bus differential scheme. The harmonic restraint provides security against false tripping on magnetizing inrush associated with the transformer energization.

The variable percentage characteristic provides high sensitivity at high currents. It will therefore detect light internal faults and will not trip incorrectly on heavy external faults.

The type HU-4 may be applied to any bus circuit where the external fault current through the bus in twenty times tap value secondary current or less, i.e.—100 amperes on 5 ampere tap.

External connections are similar to those of the CA-16, with the relay input limited to four restraint circuits including transformer circuit. Occasionally an auxiliary current balance transformer is used on the line side of the power transformer to adjust the current transformer secondary currents to the bus sections included in the protected zone.

characteristics

single phase, 60 cycle, spst-cc contacts, FT-42 Flexitest case
operating time: see figure 26
four restraint circuits, one second harmonic restraining circuit, and one operating circuit
ratio taps: 2:9, 3.2, 3.5, 3.8, 4.2, 4.6, 5.0, 8.7 amperes
variable percentage characteristics: see figure 25
minimum trip: 30% or 35% of tap value

relay settings: Same as those for types HU and HU-1 relays, pages 31 to 34. (HU-4 is similar to HU and HU-1, except that it has four restraint circuits.)
performance curves: see figures 25 to 27

burden data:

tap	continuous rating	power factor angle*	at tap value current	volt-amperes@ at 8 times tap value current	volt-amperes@ at 20 times tap value current
burden of each restraint circuit					
2.9	10	71	.88	50	191
3.2	12	70	.89	51	211
3.5	13	66	.90	51	203
3.8	14	65	.91	53	220
4.2	15	58	.91	53	235
4.6	16	57.5	.91	55	248
5.0	18	52.5	.92	59	280
8.7	22	30	1.28	94	340
burden of operating current					
2.9	10	35	2 26	76	487
3.2	12	34	2.30	78	499
3.5	13	33	2.30	81	504
3.8	14	33	2.30	83	547
4.2	15	31	2.30	84	554
4.6	16	30	2.40	88	598
5.0	18	29	2.50	92	640
8.7	22	23	3.18	132	850

* Degrees current lags voltage at tap value current.
@ Voltages taken with Rector type voltmeter.

thermal rating: one second—300 amperes

(Thermal capacities for short times other than one second may be calculated on the basis of time being inversely proportional to the square of the current.)

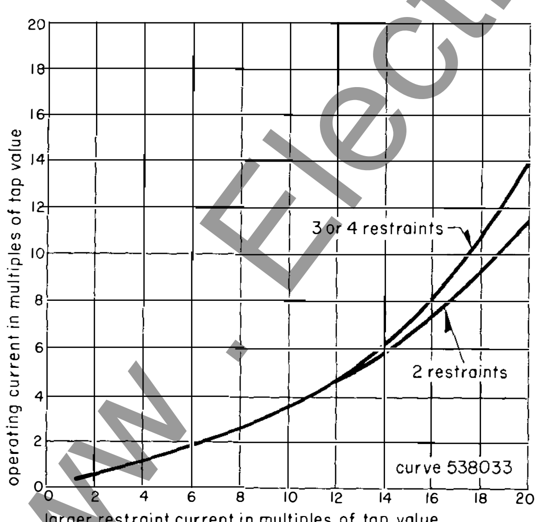


fig. 25: Variable percentage slope curve, HU-4 relay.

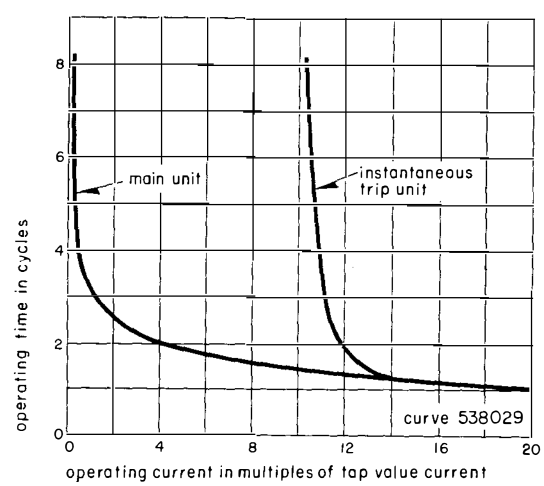


fig. 26: Typical time curve, HU-4 relay.

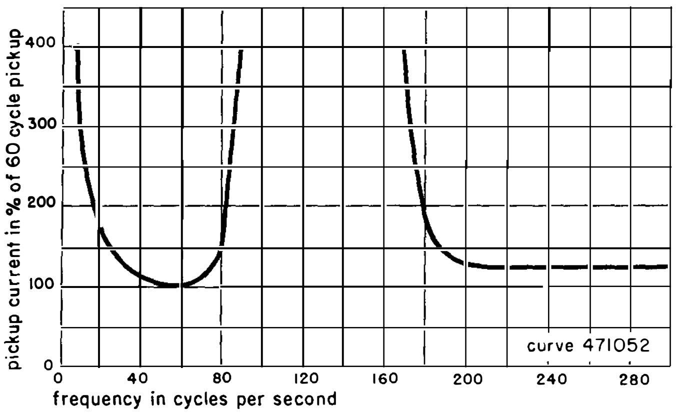


fig. 27: Frequency response curve, HU-4 relay.

further information

product bulletin41-330C5
instruction leaflet 41-347.1

types LC-1, LC-2 single phase, instantaneous, linear coupler

The linear coupler method of bus protection utilizes air core mutual reactors known as linear couplers, instead of the usual current transformers. It employs the voltage output of the couplers in a series voltage differential circuit. The energy output of the couplers makes possible the use of low-energy, high speed relays, types LC-1 and LC-2. Each is provided with impedance taps so that the impedance of the relay can be more closely matched to the impedance of the linear couplers when such is required for maximum sensitivity.

When the relay and coupler impedances are matched, there is a maximum amount of operating energy transferred from the coupler to the relay. Since the standard linear coupler induces 5 volts secondary per 1000 amperes primary, the couplers (unlike current transformers) can be safely open-circuited. Danger to personnel from high voltages is eliminated.

relays used

type LC-1: Consists primarily of an impedance matching transformer and solenoid unit which has trip contacts. It covers an ohmic range of 30 to 80 ohms in four steps and is adjustable to operate at energy levels rated from 0.5 to 8.0 volt-amperes.

type LC-2: The use of a permanent magnet polarized d-c operating unit energized by a rectifier from the saturating impedance-matching transformer makes the LC-2 more sensitive than the LC-1.

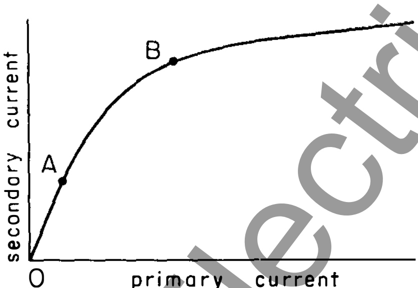


fig. 28: Current transformer saturation curve.

current transformers and linear couplers

current transformers

In differential protective schemes, the relays and current transformers function as a team. The current transformers must interpret, in their secondary windings, the a-c current conditions existing in the power circuit . . . and transmit this information to the relays. The typical saturation curve shown below (figure 28) indicates that secondary currents are proportional to primary currents along the curve portion OA of the curve corresponding to the nominal rating of the transformer. When large short circuit currents occur, the secondary current of the heavily saturated current transformer is indicated on the upper portion of the curve, portion AB, and the ratio of transformation is rarely equal for two different types of current transformers. It is necessary to know the magnitude of the error-current, so that relays and their settings can be chosen to compensate for the current transformer errors.

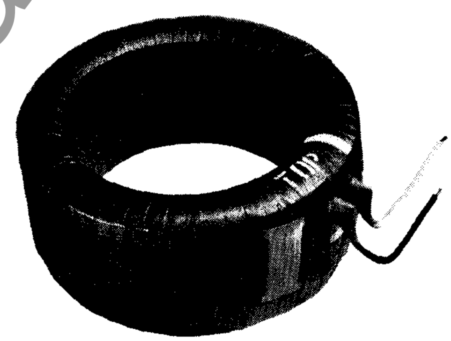


fig. 29: Typical bushing type linear coupler.

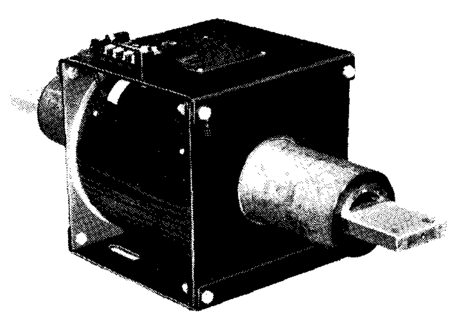


fig. 30: Typical bar type linear coupler.

saturation from a-c component of fault current

A-c saturation is not particularly troublesome since it can be calculated, and compensation made for the resulting errors in secondary current. For a given current, saturation results from: (a) insufficient cross section of iron in the transformer core, (b) too few secondary turns, (c) too high a secondary burden; or a combination of all three. The degree of saturation due to the maximum a-c current can be calculated from the formula:

$$B = \frac{IZ_s\ 10^8}{4.44\ nfa}$$

when:

B = Flux density in the core in lines per square inch.

I = Maximum secondary short-circuit current in RMS amps.

Z_s = Total secondary circuit impedance including current transformer secondary in ohms.

n = Number of secondary turns.

f = Frequency.

a = Iron cross section in square inches.

Thus, for a given short-circuit current and a given transformer, both decreasing the secondary impedance and increasing the secondary turns will improve the performance of the transformer by requiring a lower flux density to supply the burden. It is therefore recommended that the highest rated available current transformer ratios be used, consistent with the requirement that the minimum internal fault can be safely tripped. If some saturation results, it may be possible to raise the relay setting to provide a sufficient margin of safety. The minimum trip requirement must not be extended, however.

saturation from d-c component of fault current

If the fault current is asymmetrical, a d-c component is present. When it decays slowly because of long d-c time constant (large L/R ratio), transient saturation of the current transformer results. This condition occurs more frequently in the protection of generating station buses when the d-c time constant of the circuit is apt to be long. For most substation buses, the time constant is short and no appreciable effect from d-c saturation results.

The presence of a prolonged d-c component will produce a severe transient saturation. Even though it would be technically possible to design a current transformer that would not saturate, calculations show that such current transformers would require a cross section of iron as much as one hundred times larger than current transformers of standard construction.

linear couplers

The problems associated with the saturation of the core of current transformers are eliminated when linear couplers are used.

The linear coupler consists of a toroidal or ring type secondary winding on a non-magnetic core. It is usually mounted in a circuit breaker or transformer bushing and can be designed to fit into the space available for a conventional current transformer. See figures 29 and 30.

The single conductor in the bushing forms the primary of the linear coupler reactor and, because of the absence of iron, avoids problems due to saturation and provides a definite linear relationship between primary currents and secondary voltage. The system employs a series circuit in contrast to the parallel circuit used with current transformers. All of the linear coupler secondaries of a particular phase are connected in series with one type LC relay to form a closed loop. Under normal conditions, or when external faults occur, the induced voltages in all the linear couplers are cancelled out. On internal faults, a net voltage is available for relay operation. The scheme is fast in operation, simple, and easily checked while in service.

The ratio between maximum external fault current and minimum internal fault current is limited to 25/1 (except when a separate ground LC relay is used), not because of the relay, but because of the economic manufacturing tolerances of the couplers. Couplers are made to plus or minus 1-percent accuracy. The possibility exists that one coupler may be +1% and another in the same circuit −1%, with maximum current flow. This gives a 2-percent accuracy spread which, combined with a 2/1 safety factor, limits the relay pickup to not less than 4-percent of the maximum through fault current of a ratio of 1/25 between minimum internal and maximum external fault currents.

example: Assuming a 5000-ampere maximum external fault current, the LC relay should not be set to pick up on less than 4-percent of 5000 or 200 amperes primary current. Therefore, 200 amperes primary current is the minimum internal fault the relay can be set to detect.

When systems are grounded through a current limiting impedance, the ground fault current on the single phase to ground fault is so much less than interphase fault current that a fourth or ground type LC relay may be required. This relay is set much more sensitively than the phase relays, and to prevent it from picking up on error current during a heavy external phase fault, a type HVS supervisory relay is required. The HVS relay operates on zero sequence voltage and has its contacts connected in series with the ground type LC relay contacts.

When even more sensitive ground fault detection is required, LC-2 ground relays are connected in series with the LC phase relays and one HVS relay is used to supervise the contact circuits of the three LC-2 ground relays.

The calculations for settings and performance involve a simple application of Ohm's Law.

bus differential relays continued

types LC-1, LC-2 single phase, instantaneous, linear coupler

one line diagram illustrating application of linear coupler and type LC relays

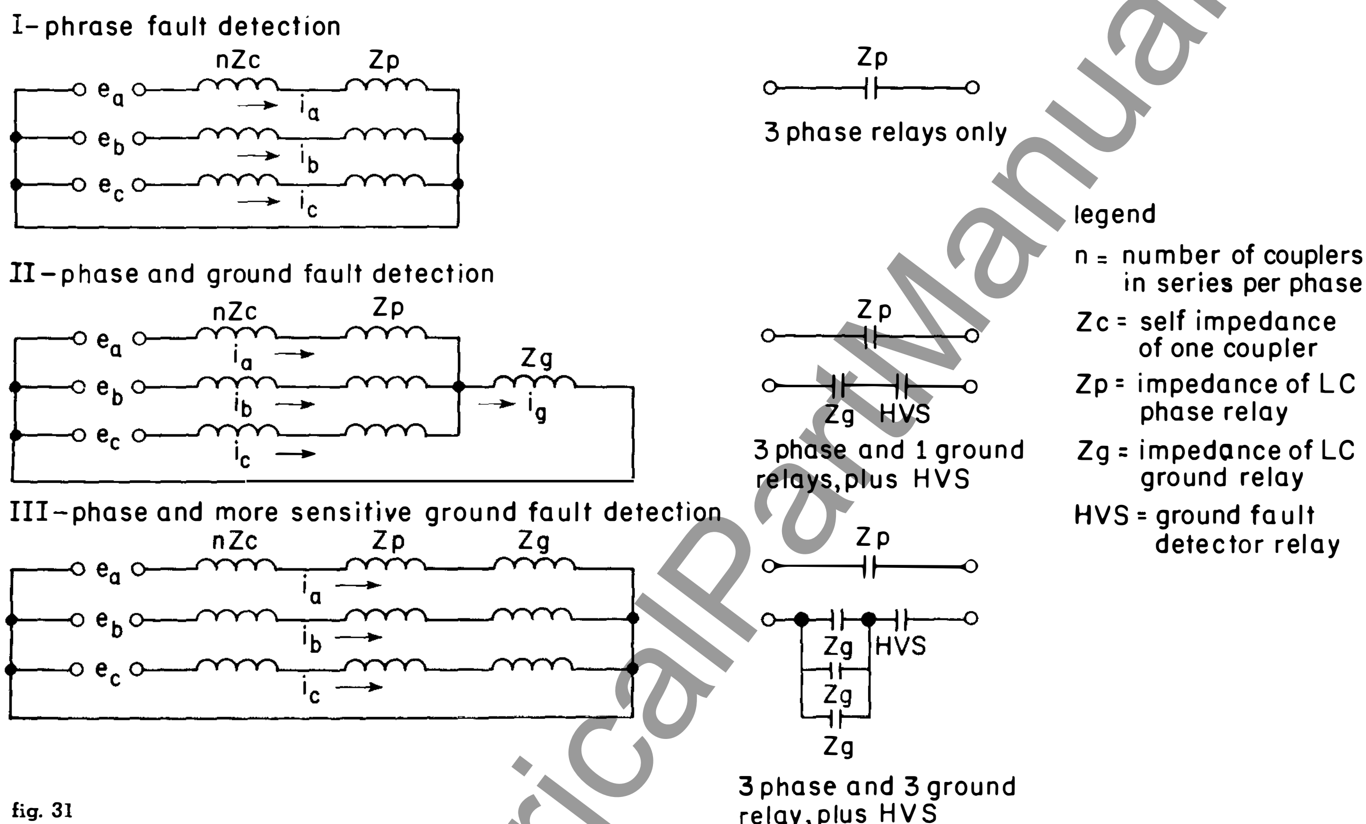


fig. 31

selection of LC-1 or LC-2

The anticipated relay current is calculated by the following formula:

$$I\ relay = \frac{I_{ext} \times E_M}{25 \times 2 \times Z_C \times N}$$

This gives the approximate value

I_{ext} = Maximum external primary fault current in amps.

E_M = 5 volts/1000 amps = Mutual impedance of one coupler.

25 = 25/1, which is ratio of maximum external to minimum internal fault current. Includes coupler tolerance and safety factor details.

2 = Reduction factor: If coupler series impedance (Z_C) is 60 ohms, then double (2) this value because the relay would be set on the 60 ohm tap and adds 60 ohms additional impedance to relay circuit.

Z_C = Impedance of one coupler—average of 10 ohms each.

N = Number of series couplers in one phase.

for relay currents:	use relay type
5- 80 ma	LC-2
80-200 ma	LC-2 plus external series resistor*
200-400 ma	LC-1

* The external series adjustable resistor assembly 0-300 ohms, used with the LC-2 relay reduces the relay current (Ir) to a value within the recommended operating range of the relay. In setting the LC-2, the resistor is used for coarse adjustment, and the flux shunts on the polar unit are used for more exact calibration.

required information

maximum external fault current: phase and ground
minimum internal fault current: phase and ground
number of couplers per phase
coupler impedance (estimate at 10 if unknown)

application guide

1. Are separate ground relays required?

   Yes, if minimum internal line-to-ground fault current is less than 8% of the maximum external fault current.

2. How many ground relays are required?

   If answer to (1) is yes, refer to curve A fig. 32, use solid curves, VA = 0.0085 if possible. (Special care required in setting relays to get more sensitive settings.)

3. Selection of LC-1 or LC-2

   If three ground relays are used, refer to curve B, fig. 33. Otherwise use curve C, fig. 34.

4. Is 300 ohm adjustable resistor required?

   If LC-2 phase relays are to be used, refer to curve C or B to determine if resistor is required.

When applications involving the LC-2 relay require a sensitivity between 0.0085 and .0025 volt-amperes, it may be necessary to adjust the flux shunts on the polar unit of the relay to obtain the desired sensitivity. If the adjustable resistor is required, a resistor should be connected in parallel with each of the LC-2 phase relay coils, so as not to decrease the sensitivity of the series connected LC-2 ground relays.

curve B

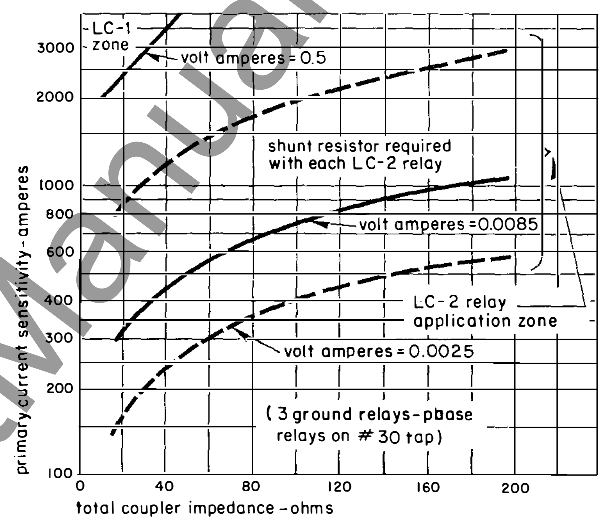


fig. 33: Approximate phase relay sensitivity, 3 ground relays (phase relays on #30 tap).

curve A

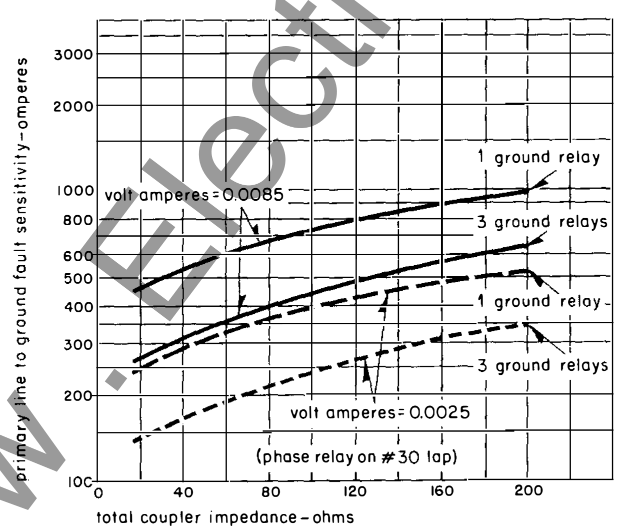


fig. 32: Approximate LC-2 ground relay sensitivity (phase relay on #30 tap).

curve C

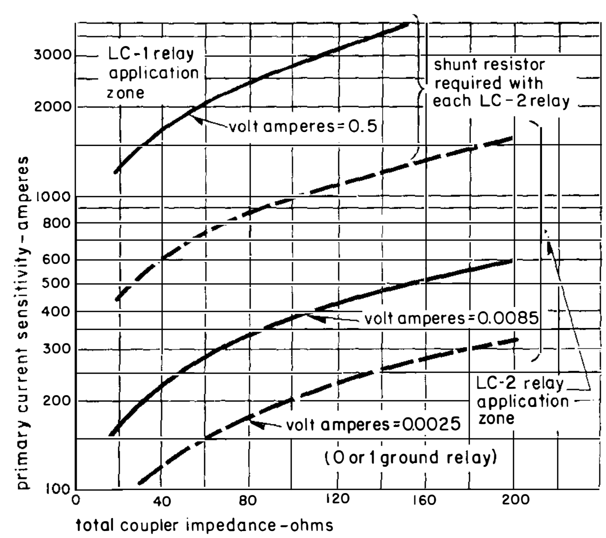


fig. 34: Approximate phase relay sensitivity, 0 or 1 ground relay.

bus differential relays continued

types LC-1, LC-2 single phase, instantaneous, linear coupler

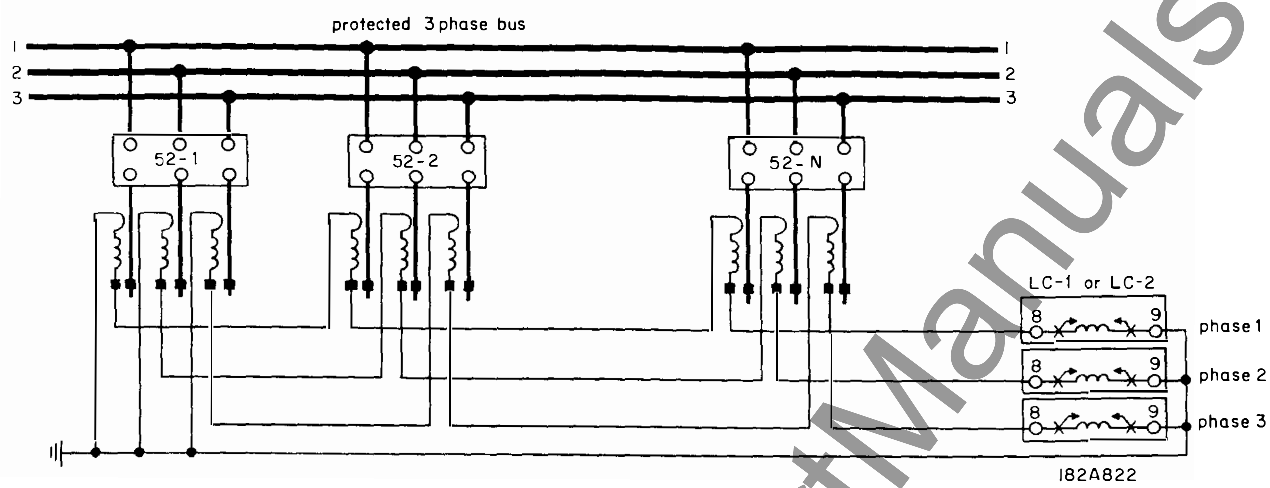


fig. 35: External wiring, LC-1 and LC-2 relays.

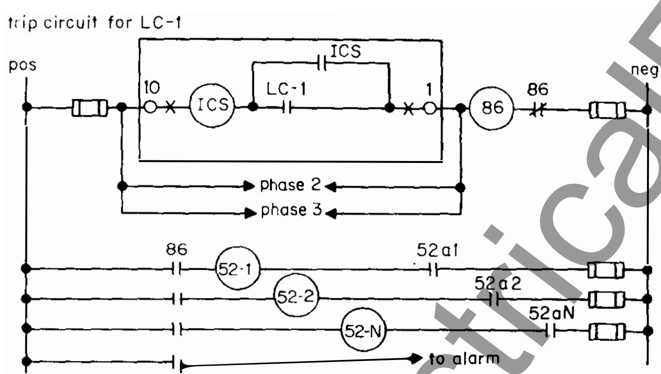


fig. 36a: Trip circuit for LC-1.

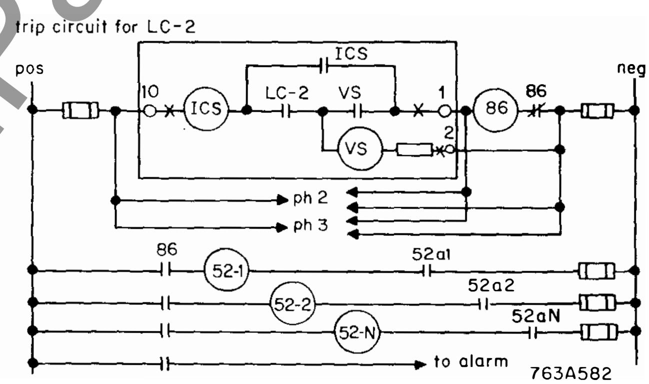


fig. 36b: Trip circuit for LC-2.

device number chart

87 —linear coupler bus differential relay, type LC-1 or LC-2.
86 —auxiliary tripping relay, type WL
52 —power circuit breaker
52a —breaker auxiliary contact
52TC—breaker trip coil

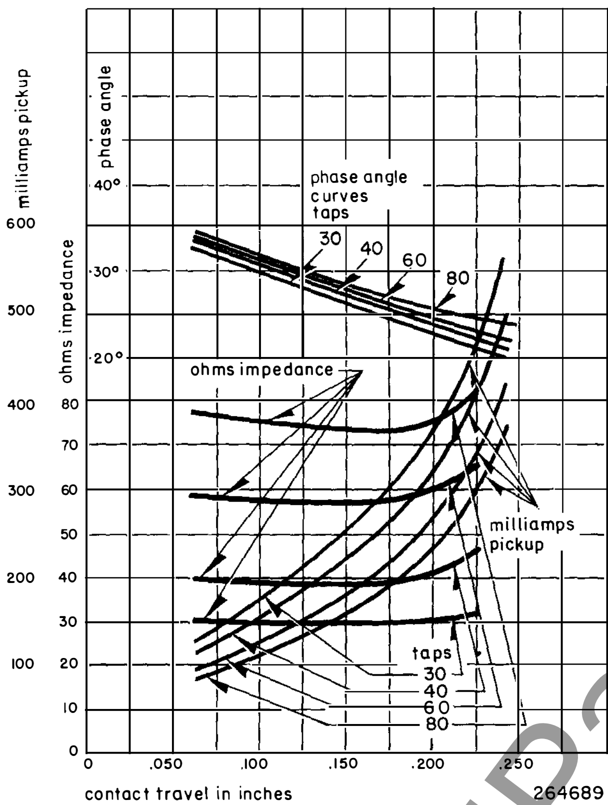


fig. 37: LC-1 characteristic curve.

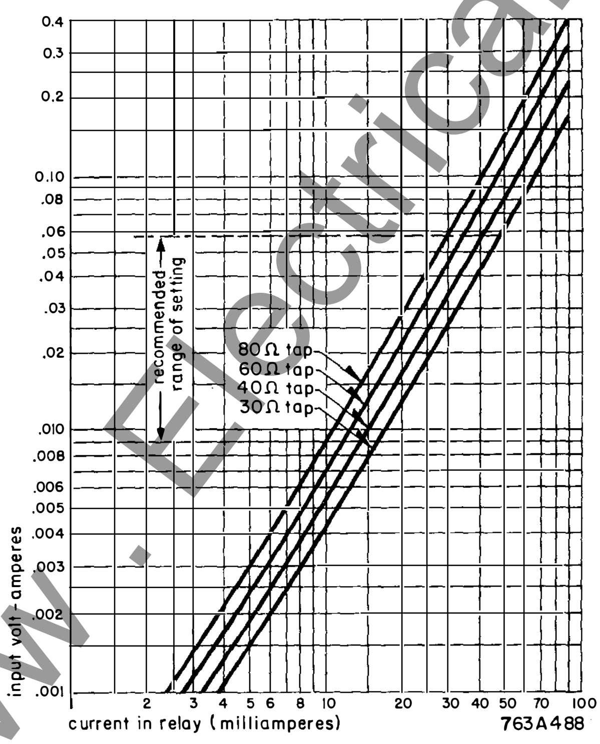


fig. 38: LC-2 volt-ampere curve.

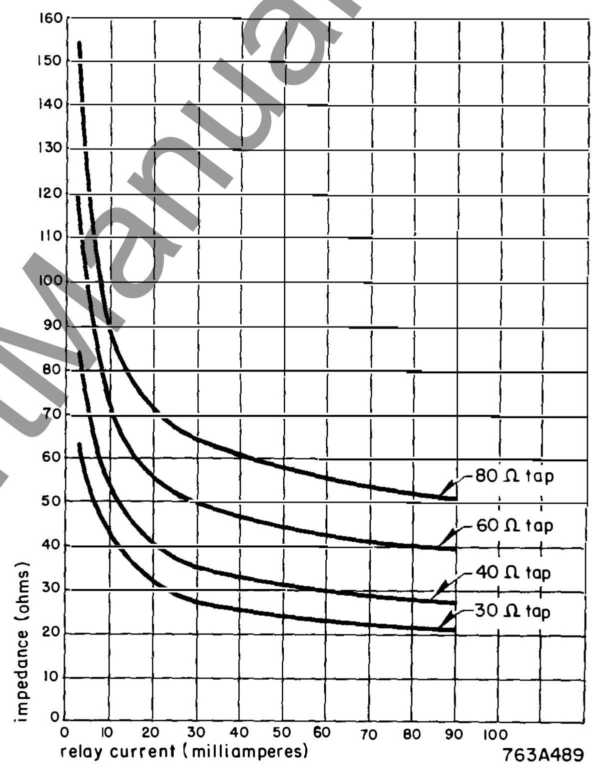


fig. 39: LC-2 impedance curve (impedance at 22° angle).

bus differential relays continued

types LC-1, LC 2 single phase, instantaneous, linear coupler

characteristics

LC-1 relay

single phase, 60 cycle, spst-cc contacts, FT-11 Flexitest case
operating time: 1 cycle or less above 150% of pickup
ratio taps: 30, 40, 60, 80 ohms
sensitivity: 0.5 volt-amperes

LC-2 relay

single phase, 60 cycle, spst-cc contacts, FT-11 Flexitest case
operating time: 1¼ to 1¾ cycles including time for VS contactor
ratio taps: 30, 40, 60, 80 ohms
sensitivity: .0085 to .062 volt-amperes

LC-1 and LC-2 settings

The following fundamental equations apply:

$$E = I_p M \qquad (1)$$

$$I_r = \frac{E}{Z_s} \qquad (2)$$

$$I_r = \frac{I_p M}{Z_s} = \frac{I_p M}{NZ_c + Z_r} \qquad (3)$$

$$I_p = \frac{I_r Z_s}{M} = \frac{I_r(NC_c + Z_r)}{M} \qquad (4)$$

where:

E = voltage induced in linear coupler secondary
I_p = primary current in linear coupler
M = mutual impedance of linear coupler = .005 ohm for 60 cycles
I_r = relay current
Z_s = impedance of secondary circuit
N = number of secondary circuit = number of linear coupler secondaries in series per phase
Z_c = self-impedance of linear coupler secondary
Z_r = relay impedance

Equation (3) is used to determine the current at which the relay trips for an internal fault of magnitude I_p on the bus. Equation (4) is used to determine the primary current necessary to trip the relay when it has been adjusted to trip at a known value of relay current.

It should be noted, however, that the relay impedance is not constant, but varies with relay current as indicated in figures 37 and 39. Therefore, in using equation (3) it is desirable to assume a value of relay impedance equal to the impedance tap and make a first calculation of the relay current. When this is obtained, a new value of relay impedance should be selected from figure 37 or 39 and a second value of relay current calculated. Usually, it will not be necessary to continue the calculation any further, as the values resulting from the second calculation will be sufficiently accurate.

LC-1 setting example

Assume a six circuit bus for which the linear couplers have a self-impedance of $Z_c = 3.7 + j8.9 = 9.64\angle 67.4°$. Three type LC-1 relays are used, one per phase, to obtain phase and ground fault protection. The maximum external fault current is 60,000 amperes rms symmetrical. It is desired to set the relays to trip on a minimum internal fault of 5000 amperes. However, since the linear couplers and relays will operate over a 25/1 range to 2 to 1 factor of safety, the relays may as well be set for 2400 amperes, which is 1/25 of 60,000.

The self impedance of the linear coupler secondaries is determined first, as follows:

$$NZ_c = 6(3.7 + j8.9) = 22.2 + j53.4 = 57.8\angle 67.4°.$$

For any given primary current, the relay receives maximum energy when the impedance Z_r is made equal to NZ_c. This feature is utilized by matching Z_r and NZ_c as closely as possible in those cases where it is desirable to obtain the lowest possible minimum tripping current. In other cases, the relay impedance and Z_p and the total linear coupler self impedance NZ_c may be deliberately mismatched in order to extend the range of adjustment to a higher current value. In this example, a first trial calculation will be made on an approximate basis by assuming that the relay impedance is 60 ohms (60 ohm tap) and that this adds arithmetically to the 57.8 ohms of the couplers (leads being neglected).

$Z_s = 57.8 + 60 = 117.8$ ohm approximately

$E = I_p M = 2400 \times .005 = 12.0$ volts

$I_r = \frac{E}{Z_s} = \frac{12.0}{118.8} = .102$ ampere, approximately

Reference to figure 37 indicates that the relay can be set to operate at .102 (or 0.100 ampere) on either the 60 ohm or 80 ohm tap. Since the desired value is near the minimum obtainable, choose the 60 ohm tap as being the closest match to the value of 57.8 for NZ_c and make a second more accurate calibration. Using the 60 ohm tap and a contact travel of .075 inches. Values read from the curve give a pickup current $I_r = 0.100$; $Z_r = 58.3$ ohms, and an impedance angle of 33° for Z_r.

$$Z_r = 58.3\angle 33° = 48.9 + j31.75$$

$$NZ_c = 57.8\angle 67.4° = 22.2 + j53.4$$

$$Z_r + NZ_c \qquad 71.1 + j85.15 = 111\angle 50.1°$$

From equation (2), $I_r = \frac{E}{Z_s} = \frac{12.0}{111} = .1081$ ampere

This current is higher than the original assumed current because the calculations were more accurately made, taking into consideration the vector addition of Z_r and NZ. Changing the contact travel to .080 inch to obtain the pickup current, $I_p = .107$, makes an inconsequential change in the relay ohms, $Z_r = 59$, and a change of approximately 0.5 in the phase angle of the relay impedance. Another trial calculation is therefore unnecessary from a practical standpoint.

LC-2 setting example

Assume a six circuit bus has linear couplers with a self-impedance of $Z_C = 3.7 + j8.9 = 9.64\underline{/67.4^\circ}$. Three type LC-2 relays are used, one per phase, to obtain phase and ground fault protection. The maximum external fault current is 12,000 amperes rms symmetrical. Since the linear couplers and relays will operate over a 25/1 range with 2 to 1 factor of safety the relays may be set for 480 amperes, which is 1/25 of 12,000.

The LC-2 relay operates with maximum energy when its impedance equals the impedance of the linear coupler circuit $NZ_C = 6(3.7 + j8.9) = 22.2 + j53.4 = 57.8\underline{/67.4^\circ}$. Therefore, choose a tap setting $Z_r = 60$ for the relay, which is an approximate match. Since the phase angle of Z_r is substantially constant (within 3%) at 22°, $Z_r = 60\underline{/22^\circ} = 55.6 + j22.5$.

$NZ_C = 22.2 + j53.4$
$Z_r \; = 55.6 + j22.5$
$Z_s \; = 77.8 + j75.9 = 108.8$ ohms
$I_pM = 480 \times .005 = 2.4$ volts

From equation (3) page 20,

$$I_r = \frac{I_pM}{Z_s} = \frac{2.4}{108.8} = .0221 \text{ amperes}$$

This is within the recommended setting range of the relay as indicated in figure 38.

On the 60 ohm tap, at $I_r = .0221$ $Z_r = 54.5\underline{/22^\circ} = 50.6 + j20.4$.

This new value of Z_r should be used in equation (3).

$NZ_C = 22.2 + j53.4$
$Z_r \; = 50.6 + j20.4$
$Z_s \; = 72.8 + j73.8 = 103.6$ ohms

$$I_r = \frac{I_pM}{Z_s} = \frac{2.4}{103.6} = .0232 \text{ amperes}$$

At $I_r = .0232$ on the 60 ohm tap, figure 39 indicates that $Z_r = 54$ ohms. Since a value of $Z_r = 54.5$ was used in the above calculation, it is not necessary to carry the calculation any further.

The relay should be adjusted to trip at $I = .0232$ amperes on the 60 ohm tap using the magnetic shunts at the rear of the polar element assembly.

in service test facilities for LC relay schemes

The linear coupler differential circuit can be provided with a test scheme to check the differential circuit while the bus is carrying load. Defects such as short circuited linear coupler transformers, ground faults and open circuits in the secondary loop, wrong polarity or phasing connections in the linear couplers, and severe steady state stray voltage effects from foreign sources can be detected. For further details, refer to instruction leaflet 41-342.1.

further information

product bulletin 41-330B2
instruction leaflet 41-342.1

transformer differential relays

Power transformers have a high and a low voltage winding (2-winding), with some having an intermediate voltage winding (3-winding), and the current transformers associated with each winding will have different ratings and operating characteristics, particularly on heavy overloads and short circuit conditions. For this reason, transformer differential relays are usually provided with "ratio" taps to balance the difference in current transformer characteristics. In some applications, auxiliary auto-balancing transformers are used.

In addition to the problem of matching the high and low side current transformer characteristics, the problem of magnetizing inrush to the power transformer must also be considered.

2 and 3-winding transformers require different differential protective relay schemes, and a regulating transformer still another. Each of the relays covered in this section has its specific field of application, and proper selection and application may be easily made from the following information.

type CA single phase, 2-winding, inverse timing, constant percentage

Basic external connections for the CA relay are shown in figure 40.

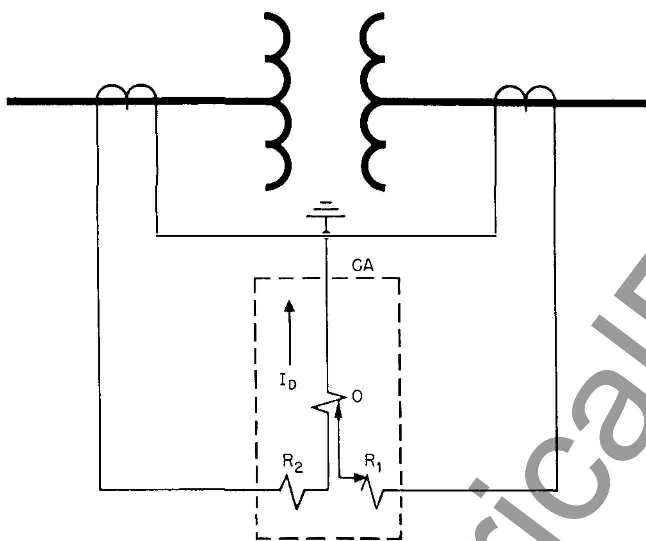


fig. 40

Connected as shown, under normal conditions current passes through the current transformers, relay restraining coils R_1 and R_2, and back to the current transformers. This current in the relay restraining coils produces a restraining, or contact opening torque.

An internal fault in the protected power transformer will unbalance the secondary currents, forcing a differential current I_D through the relay operating coil 0. The amount of differential or operating current required to overcome the restraining torque and close the relay contacts is a fixed percentage of the smaller restraining current.

External wiring diagrams are shown in figures 41 and 42.

characteristics

single phase, 60 cycle, spst-cc contacts, FT-21 Flexitest case
2-winding transformer protection
inverse time characteristics

operating time: see fig. 45
2 restraining and 1 operating circuit

ratio taps: 5-5, 5-5.5, 5-6, 5-6.6, 5-7.3, 5-8, 5-9, 5-10
constant percentage differential

sensitivity: 50% unbalance

minimum trip: on 5-5 tap, terminals 9 and 5-2.7 to 2.8 amperes
on 5-5 tap, terminals 7 and 5-2.9 to 3.2 amperes

burden: see figures 47 and 48

thermal rating:

restraining circuits—10 amperes continuous (the untapped winding should be limited to 5 amperes to prevent overloading of the operating winding)
operating circuit—5 amperes continuous.

relay settings

To determine the correct tap setting, calculate the current delivered to the relay at full load on the transformer bank, taking into consideration not only the current transformer ratios, but also any delta connections which may be used. These currents will be in a certain ratio and the relay taps should be chosen to match this as closely as possible.

For example, assume that the currents are 7.8 and 4.6 amperes, and the relay is properly connected so that the higher current (7.8 amperes) flows in the tapped restraining winding. The ratio 4.6/7.8 is equal to 5/8.47. The nearest tap ratio on the relay is 5-8, and this pair of taps would be used.

The time dial should be set on the number 1 position.

fig. 41: CA relay external wiring for wye-delta bank.

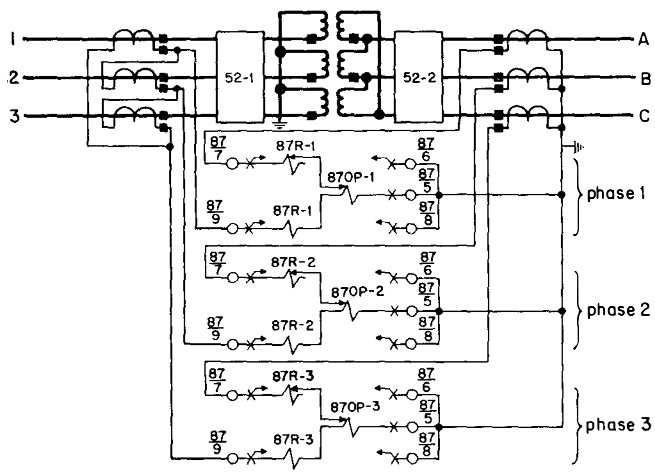
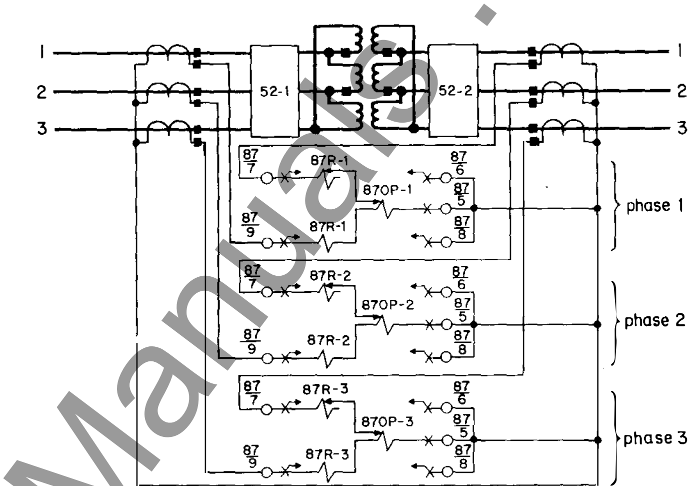
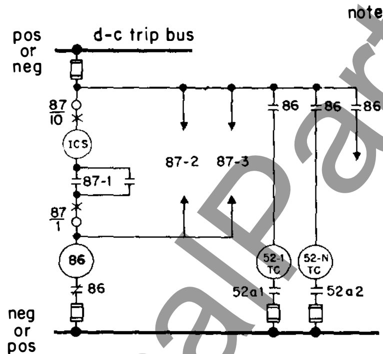


fig. 42: CA relay external wiring for delta-delta bank.



note: always connect terminal 7 to high current and terminal 9 to low current



87 – transformer percentage differential relay, type CA
87R – restraining coil of type CA
87OP – operating coil of type CA relay
86 – auxiliary tripping relay, type WL
52 – power circuit breaker
a – breaker auxiliary contact
TC – breaker trip coil
ICS – Indicating Contactor Switch

transformer differential relays continued

type CA single phase, 2-winding, inverse timing, constant percentage

Operating characteristics of the CA relay for normal through load current and through fault current are shown in figures 43 and 44. When the currents flowing in and out of the relay are plotted on these curves and the point falls outside of the inoperative area the relay will trip.

In figures 43 and 44, the two curves going with the 5-5 tap are tied together with a bracket to indicate that these two curves go together. Similarly, the two curves for the 5-10 tap are also tied together. The center lines between pairs of curves are shown for all taps. The paired curves bounding the inoperative areas are not shown for the 5-5.5 through 5-9 taps. These curves may be approximately determined by using the following formula:

for the upper curve: $I_9 = \frac{7.517}{T}$ (1)

for the lower curve: $I_7 = .3TI_9$ (2)

In these formulas, T is the larger number of the tap pair. For example, if the relay is set on the 5-7.3 tap, then T = 7.3.

As an example of the accuracy of the formula, consider the point $I_7 = 43.5$ and $I_9 = 30$, and read from the lower curves for the 5-5 tap in figure 43. Applying the formula, equation (2), the calculated value of I_7 is found to be 45, which is fairly close to the curve value I_7 of 43.5.

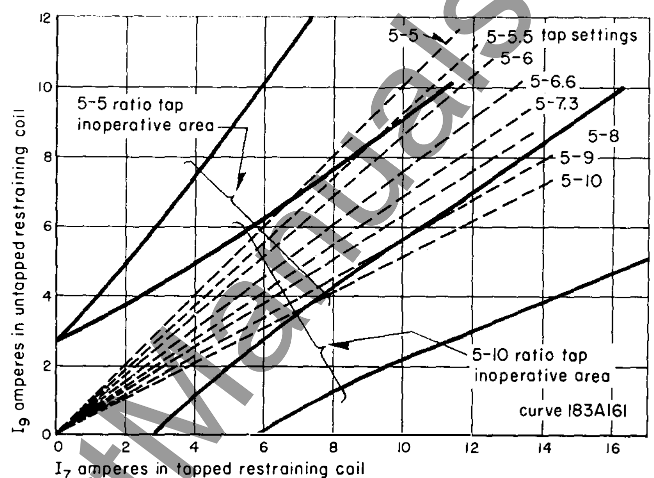


fig. 43: CA relay typical operating curves, low current values.

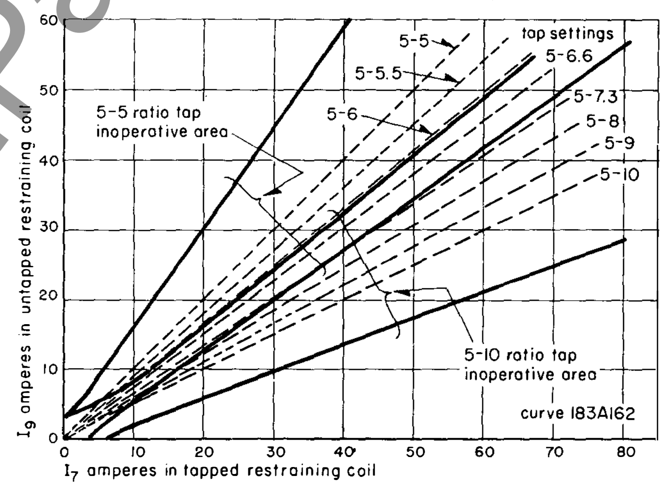


fig. 44: CA relay typical operating curves, high current values.

further information

product bulletin 41-330C1
instruction leaflet 41-332.2

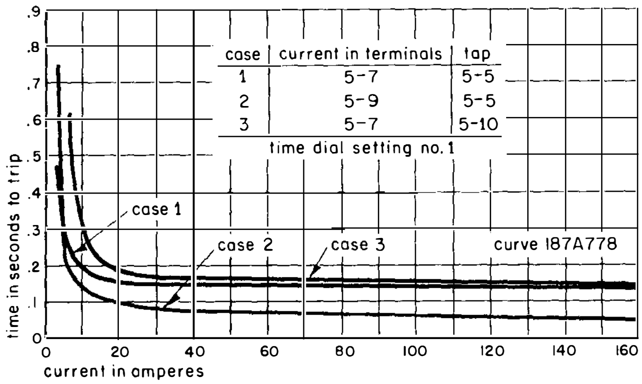


fig. 45: CA relay typical time curves.

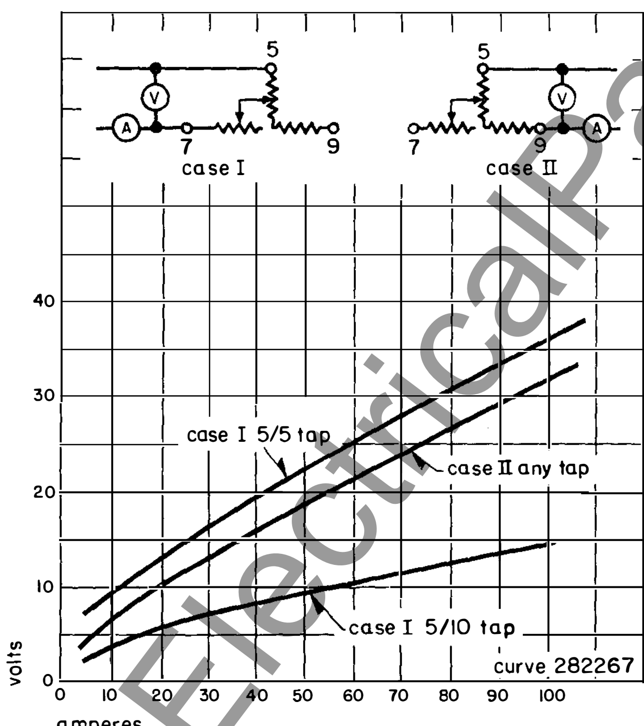


fig. 46: CA relay typical saturation curves.

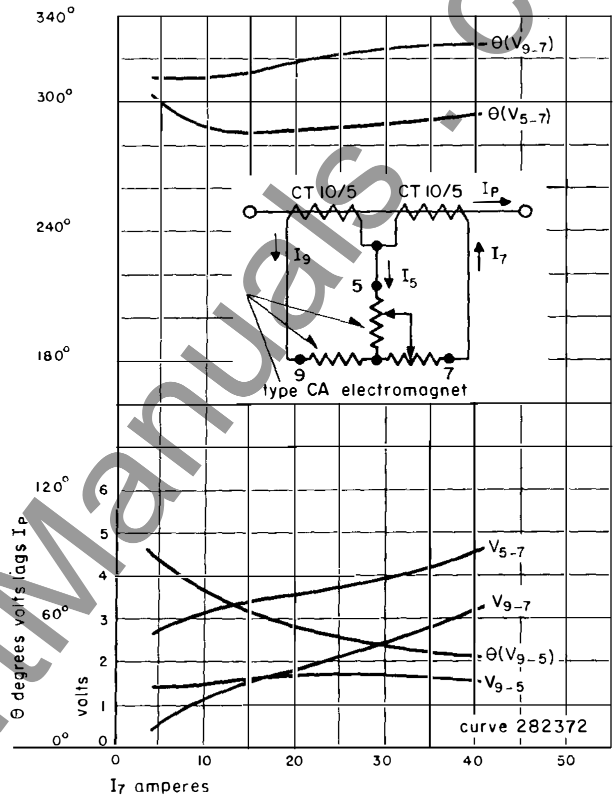


fig. 47: CA relay typical burden curve, 5/5 tap.

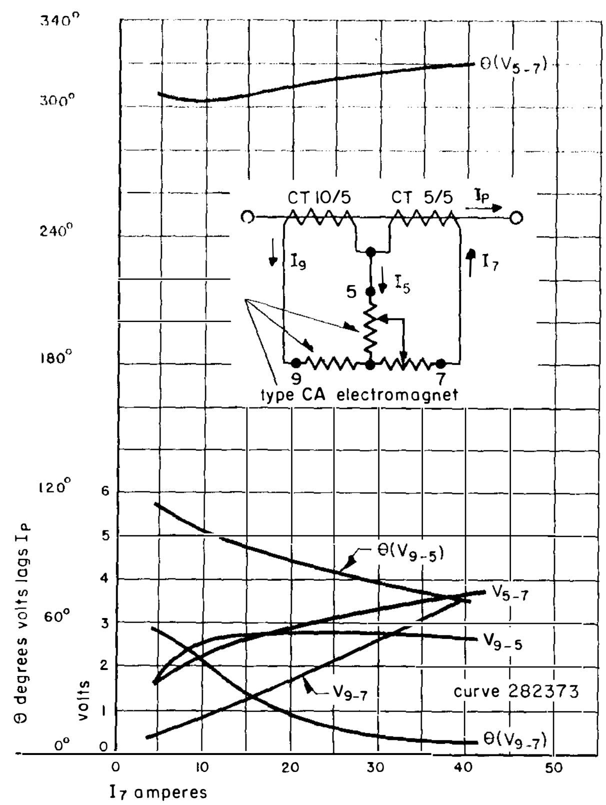


fig. 48: CA relay typical burden curve, 5/10 tap.

type CA-26 single phase, 2 or 3 winding, inverse timing, variable percentage

The CA-26 may be used for differential protection of either a 2 or a 3-winding power transformer. It has three restraining circuits for use in either of these applications.

The variable percentage ratio characteristic provides high sensitivity at low current magnitudes, with an increase in percentage ratio at the higher currents. It will therefore detect light internal faults within the transformer and at the same time allows for variation in current transformer performance at high external fault currents thereby preventing false tripping on heavy external faults. This characteristic is particularly desirable when severe saturation of the current transformers occurs due to the d-c component of asymmetrical short circuits.

The CA-26 may be used on circuits where the external fault current through the transformer is 100 amperes rms secondary or less.

A typical external connection diagram is shown in figure 53, page 28.

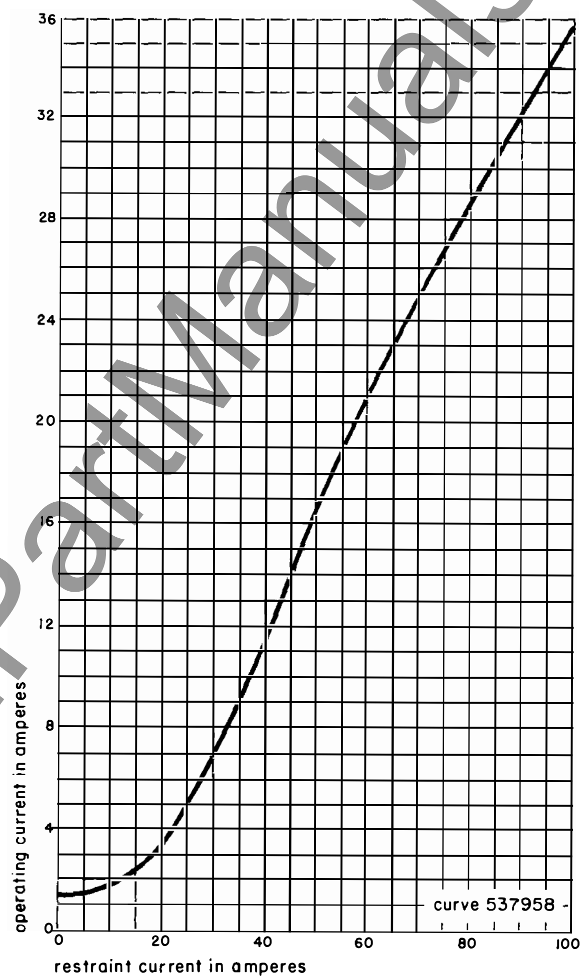


fig. 49: CA-26 relay variable percentage slope curve with one restraint winding.

characteristics

single phase, 60 cycle, spst-cc contacts, FT-32 Flexitest case

operating time: see figure 52
three restraint circuits, one operating circuit
no ratio taps

variable percentage characteristics: see figures 49 and 50

minimum trip: 1.25 amperes

burden:
each restraint circuit---0.75 volt-amperes at 5 amperes, 14 amperes continuous rating; 460 amperes 1 second rating
operating circuit—see figure 51, 8 amperes continuous rating; 280 amperes 1 second rating

relay settings: none required, except to select the proper tap on the Indicating Contactor Switch (ICS)

performance curves: see figures 49 to 52

further information

product bulletin 41-330C2
instruction leaflet 41-337.2

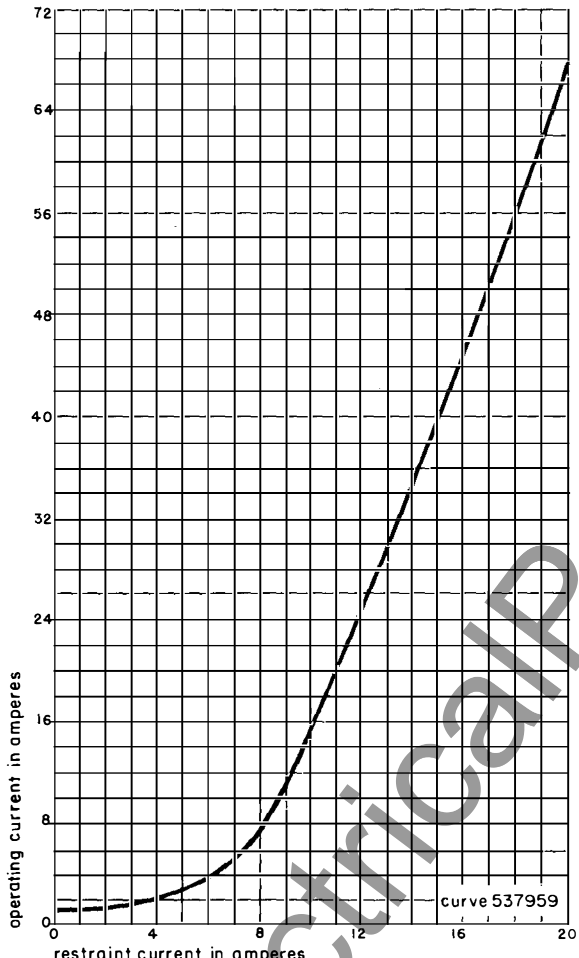


fig. 50: CA-26 relay variable percentage slope curve with six restraint windings in series.

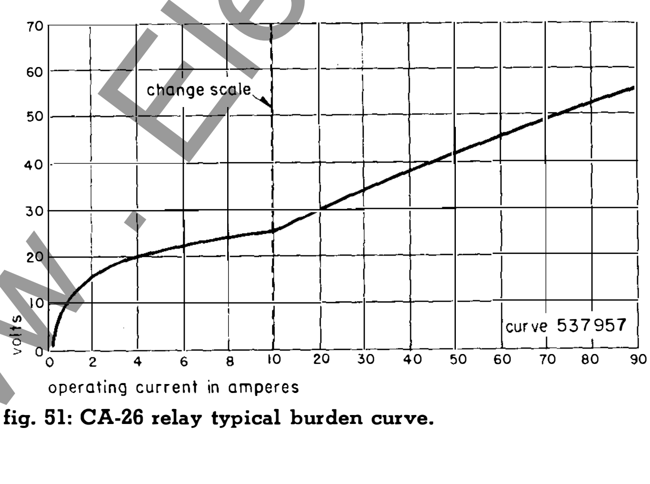


fig. 51: CA-26 relay typical burden curve.

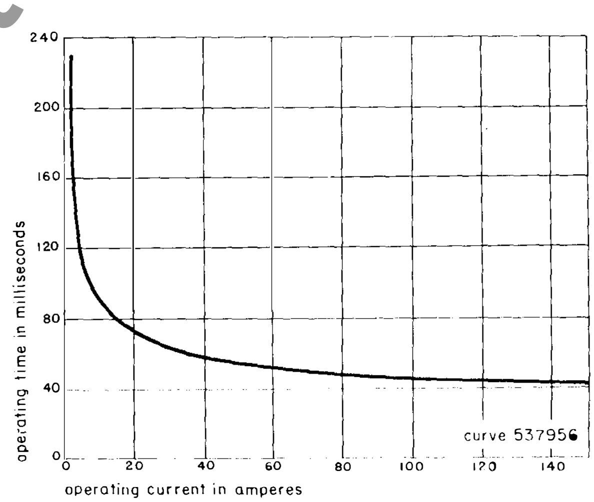


fig. 52: CA-26 relay typical time curve.

transformer differential relays continued

type CA-26 single phase, 2 or 3 winding, inverse timing, variable percentage

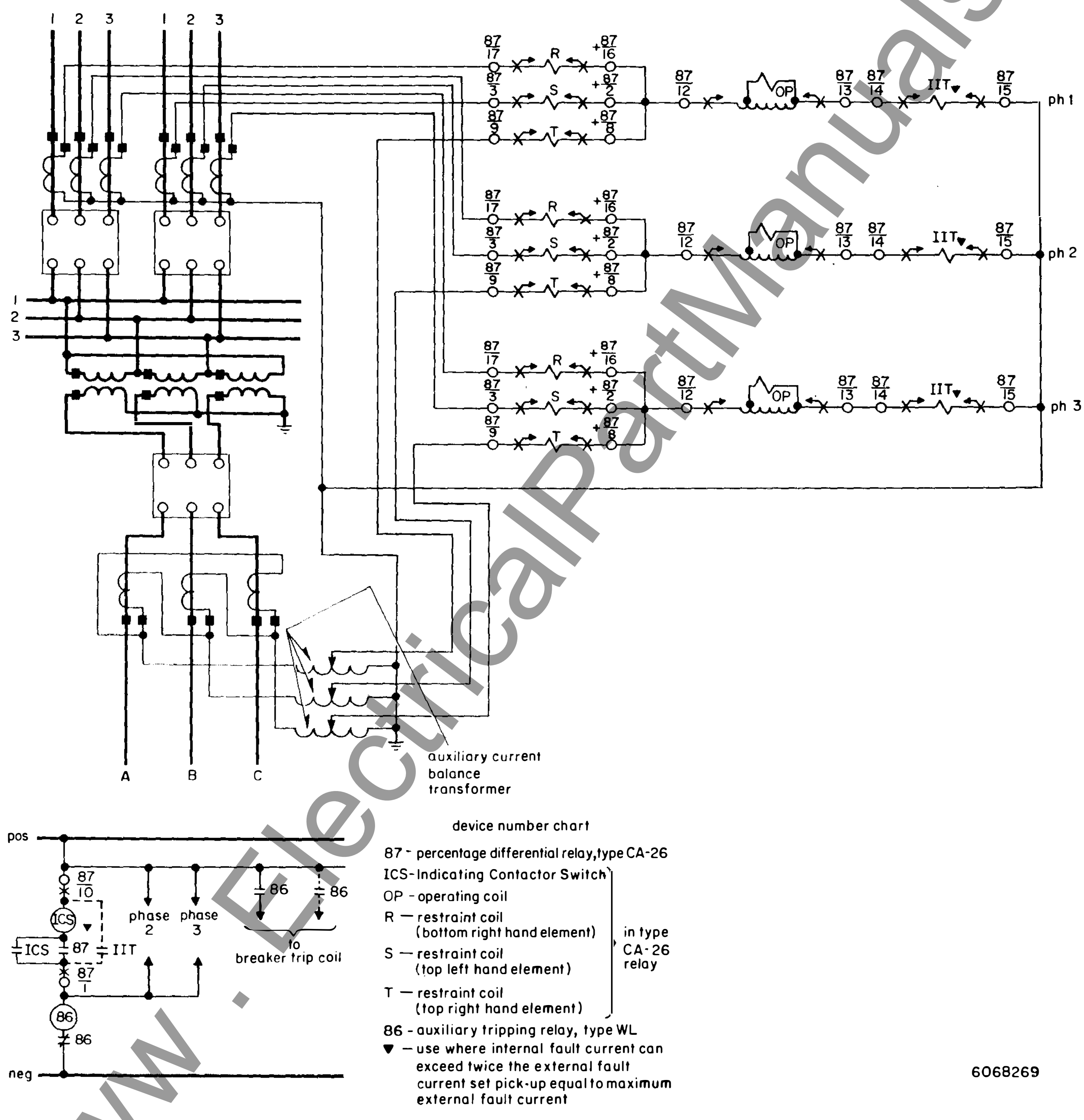


fig. 53: CA-26 relay external wiring.

types HU, HU-1, HU-4

single phase, 2 or 3 winding, instantaneous, variable percentage

These relays are high speed differential units with two, three or four restraint circuits respectively; all incorporating a harmonic restraint circuit to prevent false tripping on magnetizing inrush current.

They are all designed with a variable percentage ratio characteristic which provides high sensitivity at low current magnitudes, with an increase in percentage ratio at the higher currents. Each relay will, therefore, detect light internal faults within the transformer and at the same time prevent false tripping on heavy external fault currents which may cause variation in the current transformer performance at high currents. This is particularly desirable when severe saturation of the current transformers occurs due to the d-c component of asymmetrical short circuits.

The harmonic restraint feature prevents false tripping on magnetizing inrush currents which appear at the relay as an internal fault. These inrush currents are rich in harmonics, with the second harmonic predominant. Since the second harmonic is always present in magnetizing inrush currents, and not in internal fault current waves, the second harmonic is used in these relays to restrain the relay on inrush.

Normal application of these relays is as follows:
- **2-winding transformer:** type HU
- **3-winding transformer:** type HU-1
- **4-winding transformer:** type HU-4
- **4-circuit bus:** type HU-4

All HU type relays are available with a sensitivity of either 0.30 or 0.35 times tap rating. The 30% sensitivity relay satisfactorily handles up to 15% mismatch (e.g. ± 10% transformer tap changing, plus 5% current transformer mismatch). The 35% unit handles up to 20% mismatch. See figures 57 and 58 for comparison of these two sensitivity characteristics.

Either characteristic may be obtained on any one of these relays by recalibration in the field.

Taps are provided in each restraint and operating circuit to compensate for current transformer mismatch. These tap settings are marked in terms of secondary amperes and these values are listed in "characteristics" below.

A typical external connection is shown in figure 62 on page 35.

characteristics

(Type HU-4 characteristics are the same as those for types HU and HU-1 except where noted otherwise).

single phase, 60 cycle, spst-cc contacts, HU, HU-1—FT-31 Flexitest case, HU-4—FT-42 Flexitest case
operating time: see figure 59
restraint circuits: 2 in HU, 3 in HU-1, 4 in HU-4, plus one harmonic restraint and one operating circuit in each
ratio taps: 2.9, 3.2, 3.5, 3.8, 4.2, 4.6, 5.0, 8.7 amperes
variable percentage characteristics:
types HU and HU-1—see figures 54 and 55
types HU-4—see figure 56
minimum trip: 30% or 35% of tap value
performance curves: see figures 54 to 60

burden

tap	continuous rating	power factor angle*	at tap value current	volt-amperes@ at 8 times tap value current	volt-amperes@ at 20 times tap value current
burden of each restraint circuit					
2.9	10	71	.88	50	191
3.2	12	70	.89	51	211
3.5	13	66	.90	51	203
3.8	14	65	.91	53	220
4.2	15	58	.91	53	235
4.6	16	57.5	.91	55	248
5.0	18	52.5	.92	59	280
8.7	22	30	1.28	94	340
burden of operating circuit					
2.9	10	35	2.26	76	487
3.2	12	34	2.30	78	490
3.5	13	33	2.30	81	504
3.8	14	33	2.30	83	547
4.2	15	31	2.30	84	554
4.6	16	30	2.40	88	598
5.0	18	29	2.50	92	640
8.7	22	23	3.18	132	850

* Degrees current lags voltage at tap value current.
@ Voltages taken with Rector type voltmeter.

thermal rating: 300 amperes 1 second (thermal capacities for short times other than one second may be calculated on the basis of time being inversely proportional to the square of the current).

transformer differential relays continued

types HU, HU-1, HU-4 single phase, 2 or 3 winding, instantaneous, variable percentage

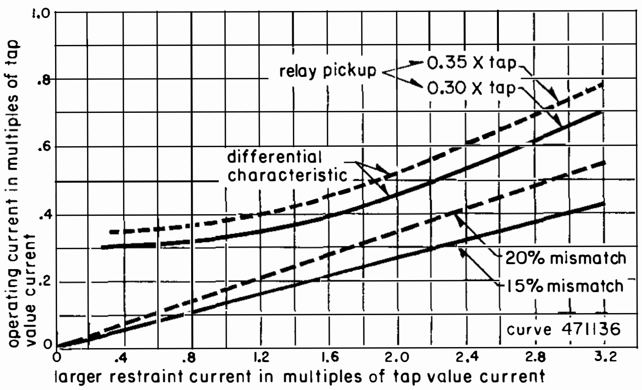


fig. 54: Types HU, HU-1 differential unit characteristics, smaller current values.

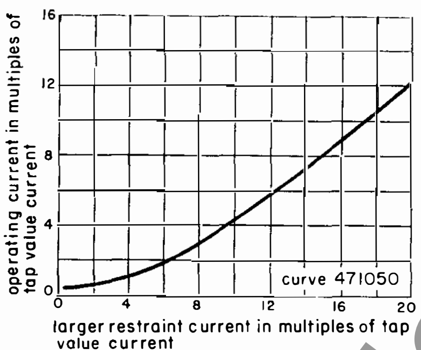


fig. 55: Types HU, HU-1 differential unit characteristics, larger current values.

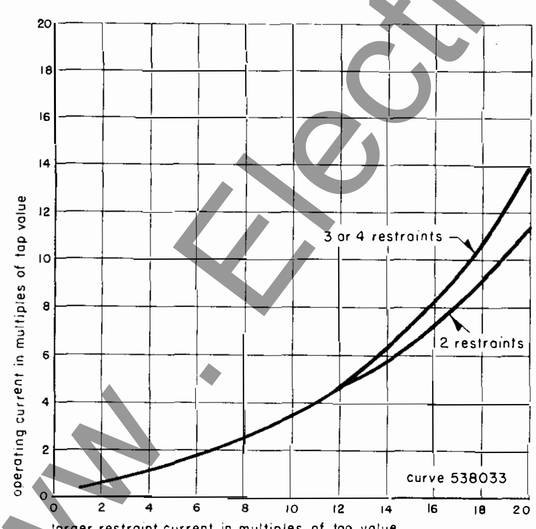


fig. 56: Type HU-4 relay differential unit characteristics of DU unit.

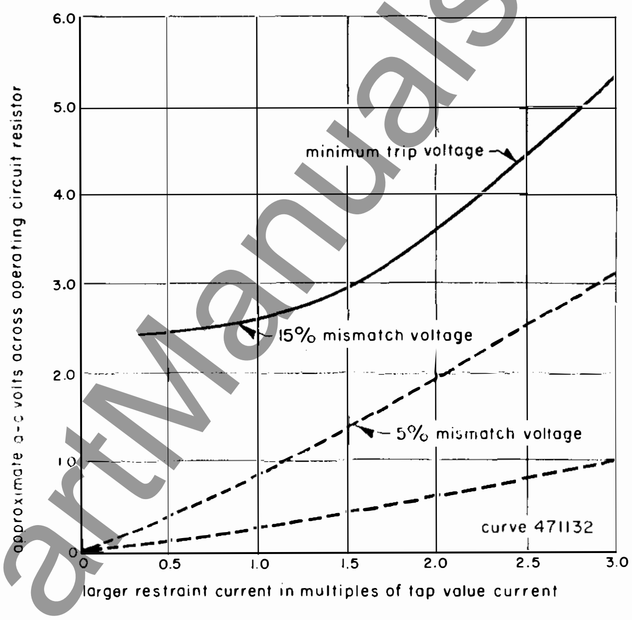


fig. 57: Types HU, HU-1 differential voltage characteristics of DU unit, .03 times tap value pickup.

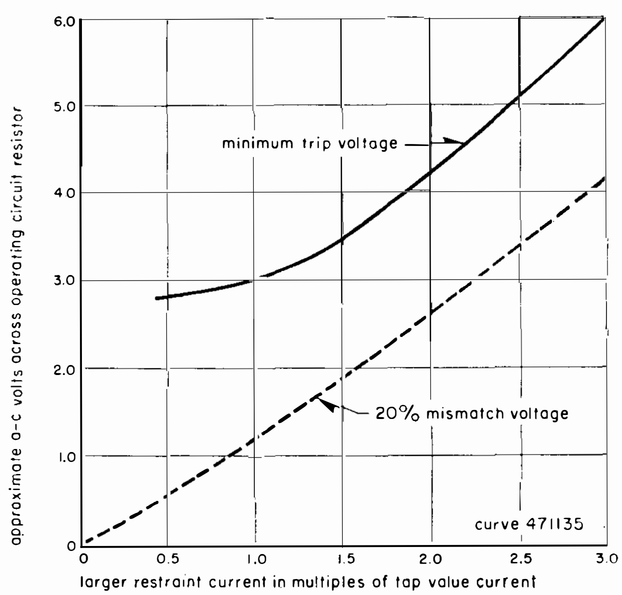


fig. 58: Types HU, HU-1 differential voltage characteristics of DU unit, 0.35 times tap value pickup.

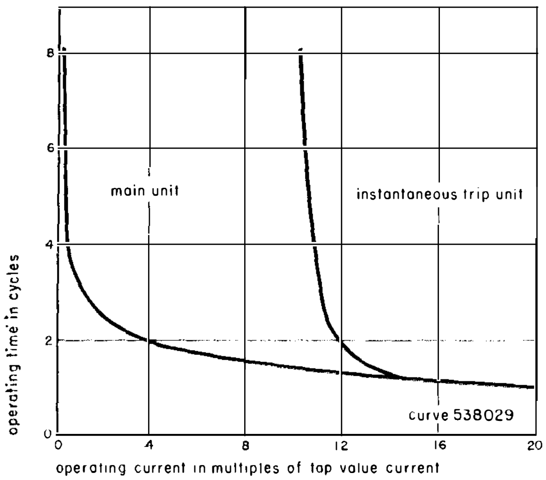


fig. 59: Types HU, HU-1 relay typical time curve.

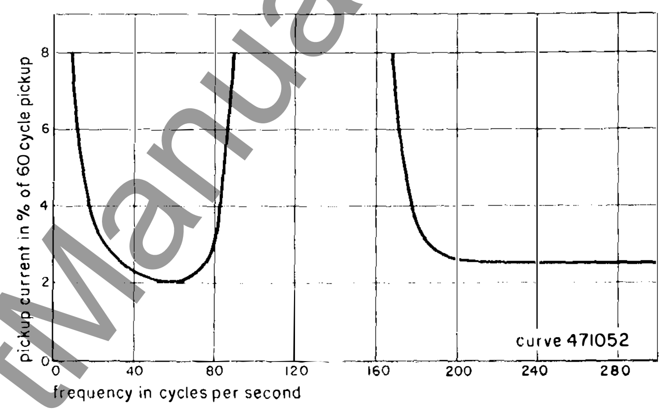


fig. 60: Types HU, HU-1 relay typical frequency response curve

relay settings

Select the ratio in matching taps. No other settings are necessary. In order to calculate the required tap settings and check current transformer performance, the following is required:

required information

1. maximum transformer power rating $(KVA)_M$
2. maximum external fault currents
3. voltage ratings of power transformer (V_H, V_I, V_L)
4. current transformer ratios, full tap (N_T)
5. current transformer 10L accuracy class voltage (or excitation or ratio-overcurrent curve)
6. one way current transformer lead resistance at 25°C (R_L) (when using excitation curve, include current transformer winding resistance)
7. current transformer connections (wye or delta)

definition of terms

I_p = primary current at $(KVA)_M$
I_R = relay input current at $(KVA)_M$
I_{RH}, I_{RL}, I_{RI} are same as I_R except for high, low, and intermediate voltage sides, respectively.
I_S = current transformer secondary current at $(KVA)_M$
T_H, T_L, T_I = relay tap settings for high, low, and intermediate voltage windings, respectively
N = number of current transformer turns that are in use
N_P = N/N_T (proportion of total turns in use)
N_T = current transformer ratio, full tap
V_{CL} = 10L accuracy class voltage
Z_A = burden impedance of any devices other than HU or HU-1 relays with maximum phase-to-phase or 3 phase current flowing
Z_T = total secondary burden in ohms (excluding current transformer winding resistance, except when using excitation curve)

calculation procedure

1. select current transformer taps where multi-ratio types are used

I_R should be more than 2.9 amperes for high sensitivity and should not exceed the relay continuous rating (see burden information, page 29).

For determining the required continuous rating of the relay, use the expected two-hour maximum load, since the relay reaches final temperature in this time.

2. select relay taps in proportion to the relay currents, I_R

I_R should not exceed relay continuous rating. Also, the maximum external fault current should not exceed 20 times relay tap.

3. determine mismatch (not to exceed 15%)

for 2-winding banks:

$$\%\ \text{mismatch} = 100\ \frac{(I_{RL}/I_{RH}) - (T_L/T_H)}{S} \quad (1)$$

for 3-winding banks:

$$\%\ \text{mismatch} = 100\ \frac{(I_{RH}/I_{RT}) - (T_H/T_I)}{S} \quad (2)$$

where S is the smaller of the two terms (I_{RH}/I_{RT}) or (T_H/T_I).

transformer differential relays continued

types HU, HU-1, HU-4 single phase, 2 or 3 winding, instantaneous, variable percentage

Equations similar to equation (2) apply for mismatch from the high to low and from the intermediate to low voltage windings.

Where tap changing under load is performed, the relays should be set on the basis of the middle or neutral tap position. The total mismatch, including the automatic tap changes should not exceed 15% with a 30% sensitivity relay, and 20% with a 35% sensitivity relay. Note from figure 54 that an ample safety margin exists at these levels of mismatch.

4. check current transformer performance

Ratio error should not exceed 10% with maximum symmetrical external fault flowing or with 8 times relay tap current flowing. An accurate method of determining ratio error is to use ratio-correction-factor curves (RCF).

A less accurate, but satisfactory method is to utilize the ASA relaying accuracy classification. If the 10L accuracy is used, performance will be adequate if . . .

$$\frac{N_P V_{CL}}{100} \text{ is greater than } Z_T \qquad (3)$$

for wye-connected current transformers

$$Z_T = \text{lead resistance} + \text{relay burden} + Z_A$$

$$= 1.13\ R_L + \frac{0.15}{T} + Z_A \text{ ohms} \qquad (4)$$

R_L multiplier, 1.13, is used to account for temperature rise during faults. $\frac{0.15}{T}$ is an approximation, where T = relay tap.

Z_A is an additional burden, when maximum external 3-phase fault current is flowing.

for delta connected current transformers

$$Z_T = 3(1.13\ R_L + \frac{0.15}{T} + Z_A) \text{ ohms}$$

$$= 3.4\ R_L + \frac{0.45}{T} + 3Z_A \qquad (5)$$

(The factor of 3 accounts for conditions existing during a phase-to-phase fault. Z_A is any additional burden, when maximum external phase-to-phase fault current is flowing.)

5. examples

Refer to pages 33 and 34 and figure 61 for setting examples. Note in both examples that the 8.7 tap was selected as the first step in selecting relay taps. If a lower tap, such as 5 had been the first selection, a proper balance would have been impossible.

On page 33, for the 2-winding bank . . .

$$\frac{I_{RL}}{I_{RH}} = \frac{8.05}{4.18} = 1.92.$$

With tap 5 for the low side, the maximum current ratio that can be matched by the taps is

$$\frac{5}{2.9} = 1.73.$$

With tap 8.7 selected for the low side, a 3 to 1 current ratio can be matched.

On page 34, for 3-winding bank . . . . .

$$\frac{I_{RL}}{I_{RH}} = 3.02$$

This current can be accommodated by the 8.7 and 2.9 taps without excessive mismatch.

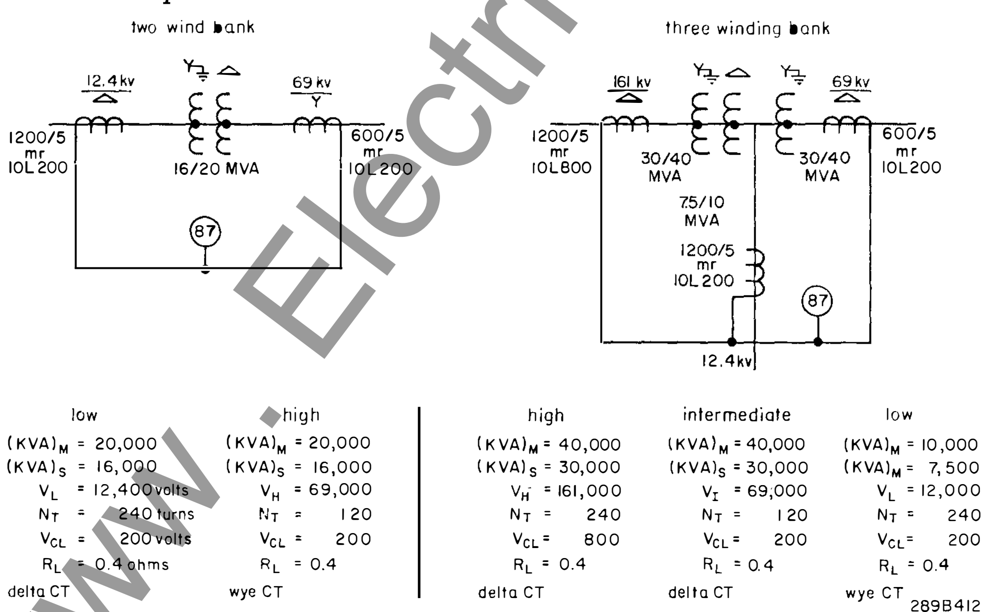


fig. 61: Types HU, HU-1, HU-4 example for setting calculations.

2 winding transformer calculation (see figure 61)

	low	**high**
1. Select CT Ratio:		
$I_P = \frac{(KVA)_M}{\frac{V\sqrt{3}}{1000}} =$	$\frac{20{,}000}{12.4\sqrt{3}} = 930$ Amp.	$\frac{20{,}000}{69\sqrt{3}} = 167$ Amp.
Select Ratio	1000/5 (N = 200)	200/5 (N = 40)
2. Select Relay Taps:		
$I_S = \frac{I_P}{N} =$	$\frac{930}{200} = 4.65$ Amp.	$\frac{167}{40} = 4.18$ Amp.
$I_R =$	$I_{RL} = 4.65\sqrt{3} = 8.05$ Amp.	$I_{RH} = 4.18$ Amp.
Select Tap	$T_L = 8.7$	$T_H = \frac{4.18}{8.05} \times 8.7 = 4.64$
Desired Tap		$T_H = 4.6$

3. Determine Mismatch:

% Mismatch =

$$100\,\frac{(I_{RL}/I_{RH}) - (T_L/T_H)}{T_L/T_H} = \quad 100\,\frac{(8.05/4.18) - (8.7/4.6)}{8.7/4.6} =$$

$$100\,\frac{1.92 - 1.89}{1.89} =$$

1.6%

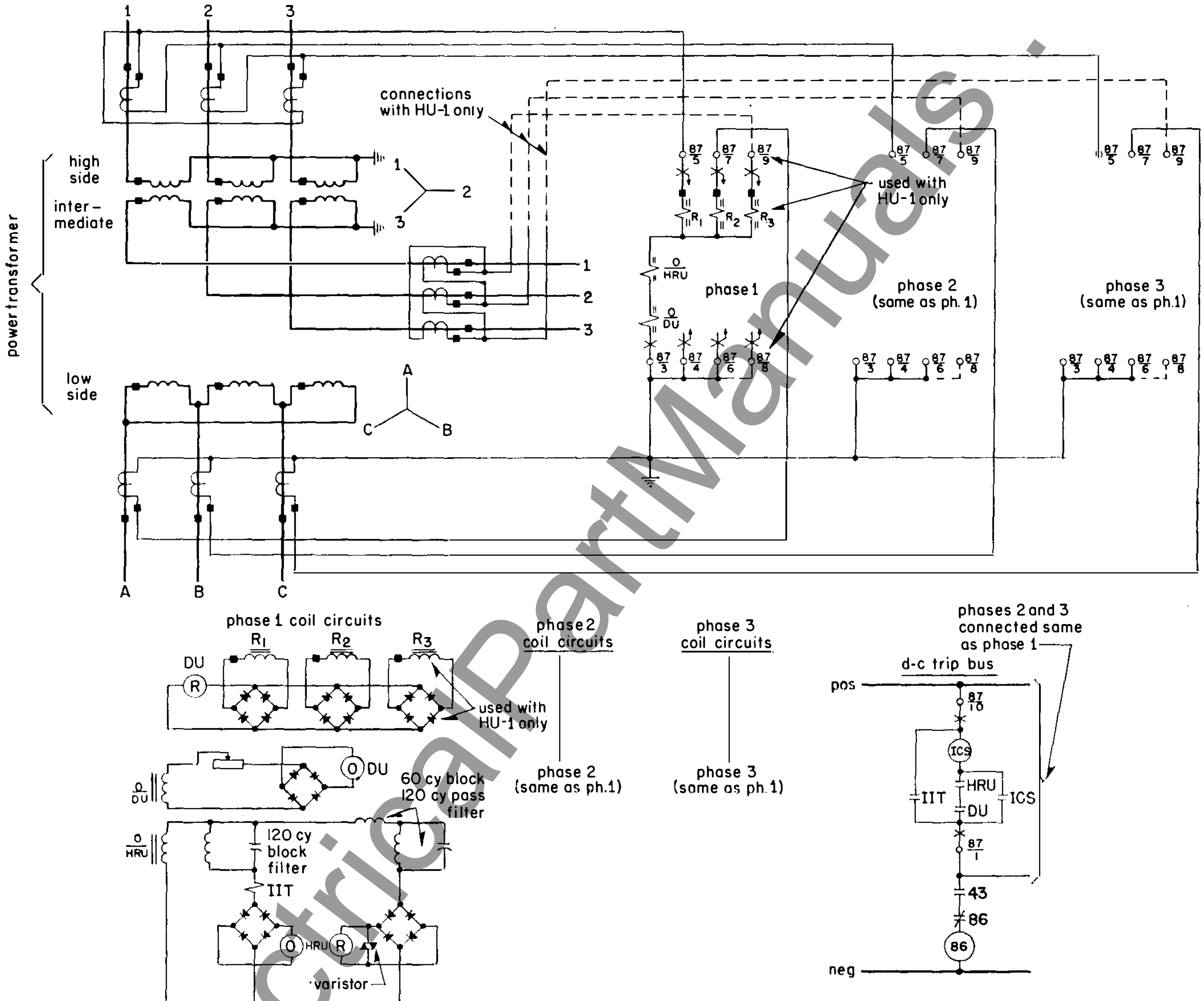
	low	**high**
4. Check CT Performance:		
$Z_T =$	$3.4\,R_L + \frac{0.45}{T} =$	$1.13\,R_L + \frac{0.15}{T} =$
	$3.4 \times 0.4 + \frac{0.45}{8.7} = 1.36 + 0.05 =$	$1.13 \times 0.4 + \frac{0.15}{4.6} = 0.45 + 0.03 =$
	1.41 ohms	0.48 ohms
$N_P = \frac{N}{N_T} =$	$\frac{200}{240} = 0.833$	$\frac{40}{120} = 0.333$
$\frac{N_P V_{CL}}{100} =$	$\frac{0.833 \times 200}{100} = 1.67$	$\frac{0.333 \times 200}{100} = 0.67$
$(N_P V_{CL}/100) > Z_T$	Yes	Yes

transformer differential relays continued

types HU, HU-1, HU-4 single phase, 2 or 3 winding, instantaneous, variable percentage

3 winding transformer calculation (see figure 61)

	high	**intermediate**	**low**
1. Select CT Ratio:			
$I_P = \frac{(KVA)_M}{\frac{V\sqrt{3}}{1000}} =$	$\frac{40,000}{161\sqrt{3}} = 143$ Amp.	$\frac{40,000}{69\sqrt{3}} = 334$ Amp.	$\frac{10,000}{12.4\sqrt{3}} = 465$ Amp.
Select Ratio	400/5 $(N = 80)$	600/5 $(N = 120)$	1000/5 $(N = 200)$
2. Select Relay Taps:			
$I_S = \frac{I_P}{N} =$	$\frac{143}{80} = 1.78$ Amp.	$\frac{334}{120} = 2.78$ Amp.	$\frac{465}{200} = 2.32$ Amp. (At 10 MVA)
I_R (At 40 MVA) =	$I_{RH} = 1.78\sqrt{3}$ $= 3.08$ Amp.	$I_{RI} = 2.78\sqrt{3}.$ $= 4.82$ Amp.	$I_{RL} = \frac{40}{10} \times 2.32$ $= 9.3$ Amp.
Select Tap			$T_L = 8.7$
Desired Tap	$T_H = 8.7\frac{3.08}{9.30}$ $= 2.88$	$T_I = 8.7\frac{4.82}{9.30}$ $= 4.52$	
Select Tap	$T_H = 2.9.$	$T_I = 4.6$	
3. Determine Mismatch			
% Mismatch	$100\frac{(I_{RH}/I_{RI}) - (T_H/T_I)}{T_H/T_I} =$ $100\frac{(3.08/4.82) - (2.9/4.6)}{2.9/4.6} =$ $100\frac{0.640 - 0.630}{0.630} =$ 1.6%	$100\frac{(I_{RI}/I_{RL}) - (T_I/T_L)}{(I_{RI}/I_{RL})} =$ $100\frac{(4.82/9.30) - (4.6/8.7)}{4.82/9.30} =$ $100\frac{0.518 - 0.528}{0.518} =$ −1.9%	$100\frac{(I_{RL}/I_{RH}) - (T_L/T_H)}{T_L/T_H} =$ $100\frac{(9.3/3.08) - (8.7/2.9)}{8.7/2.9} =$ $100\frac{3.02 - 3.00}{3.00} =$ 0.67%
4. Check CT Performance			
$Z_T =$	$3.4\ R_L + \frac{0.45}{T} =$ $3.4 \times 0.5 + \frac{0.45}{2.9} =$ $1.70 + 0.16 =$ 1.86 ohms	$3.4\ R_L + \frac{0.45}{T} =$ $3.4 \times 0.5 + \frac{0.45}{4.6} =$ $1.70 + 0.10 =$ 1.80 ohms	$1.13\ R_L + \frac{0.15}{T} =$ $1.13 \times 0.5 + \frac{0.15}{8.7} =$ $0.565 + 0.02 =$ 0.58 ohms
$N_P = \frac{N}{N_T} =$	$\frac{80}{240} = 0.333$	$\frac{120}{120} = 1.0$	$\frac{200}{240} = 0.833$
$\frac{(N_P V_{CL})}{100} =$	$\frac{800 \times 0.333}{100} = 2.67$	$\frac{200 \times 1.0}{100} = 2.0$	$\frac{200 \times 0.833}{100} = 1.67$
$(N_P V_{CL}/100) > Z_T$	Yes	Yes	Yes



device number chart

43— — — trip cutoff switch
86— — — type WL auxiliary tripping relay
87— — — type HU or HU-1 differential relay
DU— — differential unit
O- operating coil
R- restraint coil
R_1, R_2, R_3 } through restraint transformers
HRU— — harmonic restraint unit
O- operating coil
R- restraint coil
ICS— — Indicating Contactor Switch
IIT — — Indicating Instantaneous Trip

407C536

fig. 62: Types HU, HU-1 relay external connections.

further information

HU, HU-1: product bulletin 41-330C3
instruction leaflet 41-347.1

HU-4: product bulletin 41-330C5
instruction leaflet L-639965

type CAM single phase, regulating transformer, current balance, inverse timing

Regulating power transformers change either the circuit voltage or the phase angle of the voltage in accord with load conditions.

In applying a differential protection scheme to such a transformer, it is the usual practice to apply a type CA transformer differential relay to the series winding and a type CAM current balance relay to the exciting winding. The CAM is more sensitive than the CA and, in addition, the adjustable time delay permits adjustment to override magnetizing inrush current without tripping.

A simplified diagram of external connections of the CAM relay is shown in figure 63. A more complete diagram is shown in figure 64.

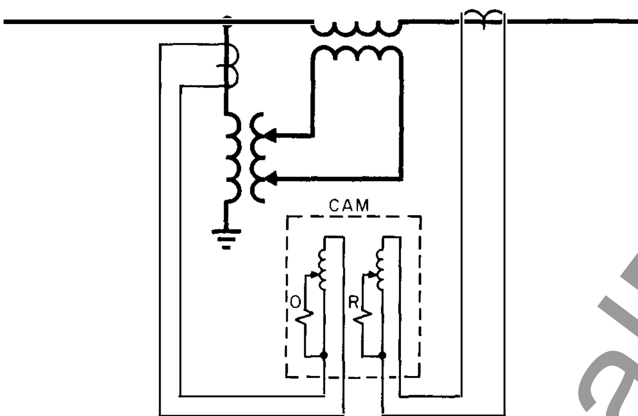


fig. 63: Type CAM relay basic external connections.

As shown in figures 63 and 64, the restraint circuit of the CAM relay is energized by the series winding, and the operating circuit by the exciting winding of the regulating transformer. The kva rating of the regulating transformer is usually approximately 10% of the primary circuit rating. Consequently, the magnitude of fault current in the exciting winding is limited as compared to faults in power transformers.

The CAM relay will operate with a minimum of 1.0 ampere in the operating coil circuit with zero current in the restraining coil circuit. At 5.0 amperes restraining current, the operating current required to close the relay contacts is 5.75 amperes, or 15% unbalance. See figures 66 and 67.

Figure 68 illustrates the operating time characteristic using a #5 time lever setting, and with zero restraint current. Time of operation is approximately proportional to the time lever setting.

Connections for the relay auxiliary current transformers on the regulating transformer are determined by the method of grounding the exciting (shunt) winding, selected from (a) or (b) below.

(a) **ungrounded neutral:** Both sets of current transformers should be connected in wye, so that the CAM relay will operate on zero sequence current supplied from external ground for external ground faults.

(b) **grounded neutral:** Both sets of current transformers should be connected in delta to prevent zero sequence currents from operating the CAM relay for external ground faults. However, should external relays fail to operate, a prolonged flow of zero sequence current in the exciting windings can be prevented by the addition of a type CO-5 long time overcurrent relay. Such a scheme is shown in figure 65.

characteristics

single phase, 60 cycle, spst-cc contacts, FT-31 Flexitest case
operating time: see figure 68
one restraint circuit, one operating circuit
no ratio taps
unbalance, 15%—sensitivity, 115%
minimum trip: 1.0 ampere with restraining circuit de-energized
burden: see figure 69
relay settings: none required
performance curves: see figures 66 to 69

further information

product bulletin 41-330C4
instruction leaflet 41-207

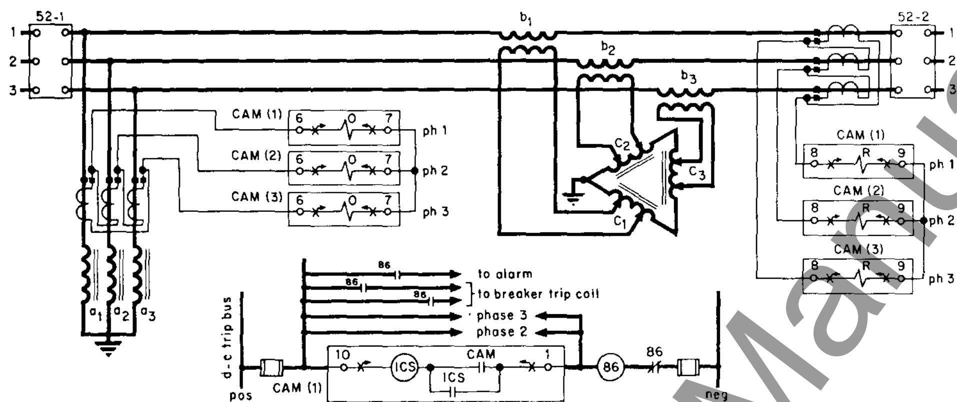


fig. 64: External wiring using CAM relay to protect exciting winding of regulating transformers.

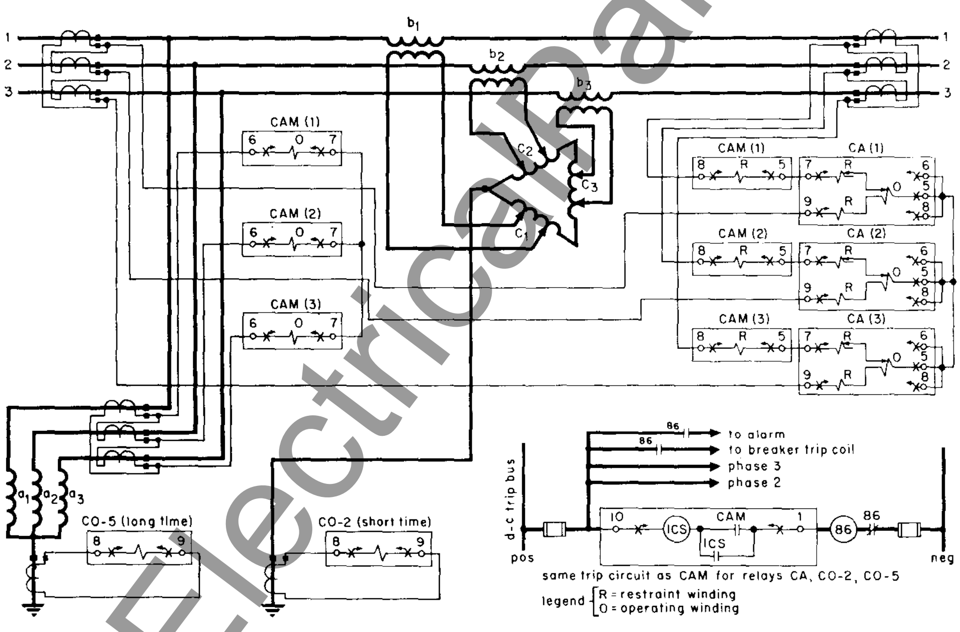


fig. 65: External wiring using CAM, CA, and CO relays to protect regulating transformers.

transformer differential relays continued

type CAM single phase, regulating transformer, current balance, inverse timing

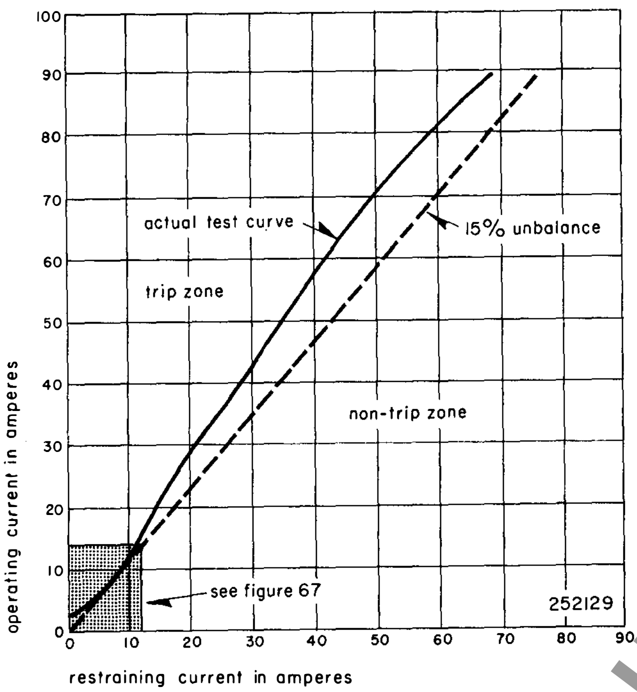


fig. 66: CAM relay operating curves.

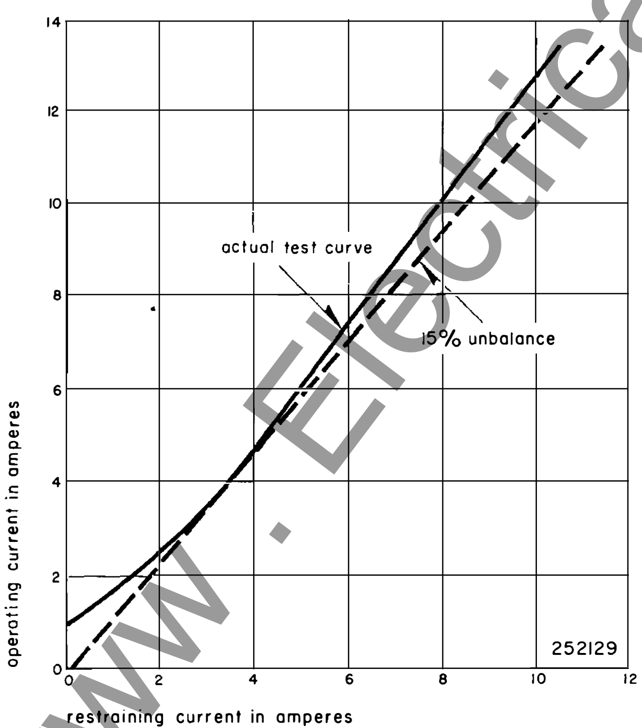


fig. 67: CAM relay typical operating curves.

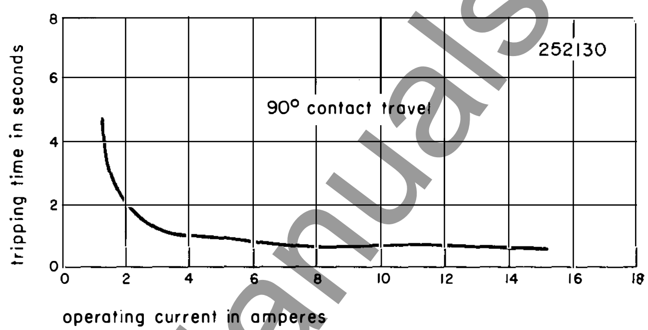


fig. 68: CAM relay typical time curves.

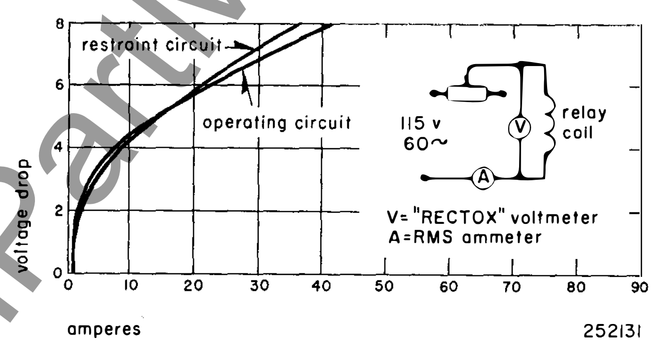


fig. 69: CAM relay typical burden curve.

type HRU harmonic restraint unit

This relay is an instantaneous overcurrent type with a second harmonic restraint unit to supervise the overcurrent unit contacts. It is used in various transformer differential schemes to provide high speed tripping on internal faults, and security against false tripping on transformer magnetizing inrush. It can be applied where magnetizing inrush is severe.

Where saturation of the current transformers occurs on asymmetrical and symmetrical faults external to the protected transformer, either the Westinghouse type HU or HU-1 relay should be applied, as they have separate restraining circuits and ratio tap adjustments for current transformer mismatch.

Magnetizing inrush current waves have various wave shapes. A typical wave appears as a rectified half wave with decaying peaks. In any case, the various wave shapes are high in harmonics, with the second harmonic predominant. Since the second harmonic is always present in magnetizing inrush waves and not in internal fault current waves, this second harmonic is used in the relay to restrain the unit on magnetizing inrush.

The relay uses two L-C filter circuits with a full wave rectifier at the output of each. The d-c output of the fundamental pass circuit is fed to the operating coil, and the d-c output of the second harmonic pass filter is fed to the restraining coil. The constants of these filter circuits are such that the harmonic unit will not close its contacts unless the second harmonic content is less than 15% of the fundamental component. Both the harmonic unit contacts and the instantaneous overcurrent contact must close to trip the breaker.

Basic HRU relay connections are shown in figure 70.

characteristics

single phase, 60 cycle, spst-cc contacts, FT-21 Flexitest case
one harmonic restraint unit, one instantaneous overcurrent unit
no ratio taps (2 relay ratings, 2.0 and 4.0 amperes)
minimum trip: 2.0 or 4.0 amperes
burden:
2.0 ampere relay—0.88 volt-amperes at 2.0 amperes
50.0 volt-amperes at 16.0 amperes
4.0 ampere relay—0.91 volt-amperes at 4.0 amperes
53.0 volt-amperes at 32.0 amperes
thermal rating: 300 amperes for 1 second
frequency response: see figure 71

further information

- product bulletin 41-330C6
- instruction leaflet L-639902

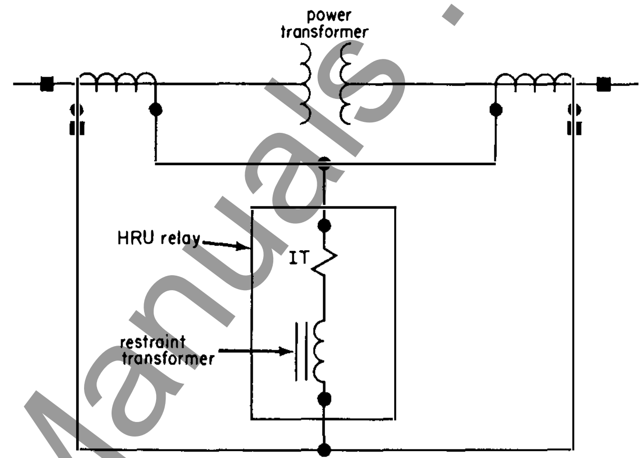


fig. 70: HRU relay basic external connections.

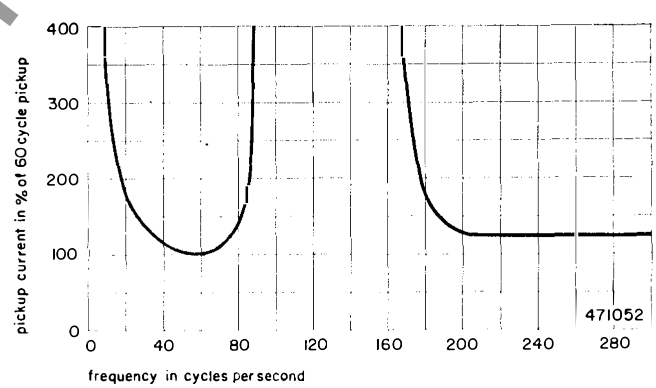


fig. 71: HRU relay frequency response curves.

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