The RAGEA, 100 % generator ground relay responds to the generator 3rd harmonic voltage which here-to-fore has been unused. The RARIO, generator negative sequence relay uses a sequence filter which is insensitive to frequency deviations and hence retains its calibration during system upsets. The RAGPC, loss-of-field relay responds directly to the parameters which jeopardize the generator during such operation and thus has minimum setting complexities.

The value of instantaneous high speed measurements was shown in the RADSS, RALDA and RAZFE. Oscillogram records of RADSS tests, confirmed by field experience, show that sensitive, secure relays can respond before ct saturation. The test oscillograms show that once false information due to saturation is injected into the system, integrating over a resonable period of time will not eliminate the errors and may aggravate these errors. Thus the new understanding is that:

> High speed, instantaneous, measurements, when properly made, are more reliable and secure than slower methods of fault determination.

This concept is not applicable to electro-mechanical relays where to get very high speed, over-sensitive relays are used. With static relays, high speed has no direct relationship to extreme sensitivity.

The RALDA extends this concept of high speed measurement to perhaps the ultimate in that the measurement is made in such a short time that the 60 Hz component of the fault current is not yet observable when the trip decision is made. In this relay the wave front and the polarity of the front of the fault wave is detected in less than one millisecond as it passes the relay location. Inherent in this relay is the rejection of all steady state or slowly changing values (as would occur during a system swinging out-of-step). Utilizing this concept a substantial reduction (1 cycle) in fault clearing time is realized compared to conventional techniques. Ultra high speed relays coupled with faster breakers than commonly used today will enable considerable economical advantages by increasing system loadability for some degree of stability and decrease system fault damage.

The concept of instantaneous measurements has been broadened in the RAZFE. In this relay the measurement is not only an instantaneous one, but the instant at which the measurement is made is controlled so as to provide the maximum of desired information.

All of the described relays are insensitive to variations in system frequency as would occur during a system upset and to distorted wave shapes as during arcing faults and transformer saturation. Setting calculations and testing procedures are all based on rms values and standard test equipment is used in all cases. Thus no new personal skills are required to profit from the use of these state-of-the art static relays.

Each relay has many years of experience which confirms the soundness of the described concepts and their practical execution. The newest and most unique of these relays, the travelling wave relay RALDA, has over 2 1/2 years of successful field experience.

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ABSTRACT

The static relay design engineer has many options not available to his electromechanical predecessor. The extent to which these result in better relays depends in large part to an understanding of both the protective needs of the system and the actual working environment in the secondary circuits of the instrument transformers. System protective needs have generally been expressed in terms of feasible electromechanical relay capabilities. When expressed in more fundamental terms, the potential value of well designed static relays becomes apparent. The significant feature of each of several relays is described to illustrate these new values.

INTRODUCTION

The relay application engineer is concerned with both the normal and abnormal states of the power system. The normal state includes all non-faulted conditions such as normal and emergency load flows and even the dynamic state following a fault removal where the stability limits of the network may be tested. These normal conditions provide limits beyond which one must not go in providing the needed system fault protection. Thus protective schemes which inherently suppress the normal conditions from affecting the relay are constantly sought. Differential relays fit this category. A new type of line relay based on a new differential principle is just now coming into use. This relay suppresses the through current by means of internal relay circuitry rather than by the conventional addition of the currents at the respective terminals. However, the most prevalent way of discriminating between normal and fault conditions on transmission systems is with distance relays. These may take many forms all of which inherently reach a trip decision based on the relative value of the phasor voltages and currents at the protected line terminal.

The majority of system calculations are made on an rms basis. Electromechanical relays tend to respond to rms values. Thus it is natural to evaluate new relays and relaying concepts in rms terms also. But what is the meaning of an rms value of a current wave of say a 1/2 or even 1/4 cycle duration? This question arises in coordinating instantaneous E-M relays with current limiting fuses where the let through current may last for less than 1/4 cycle. The empirical solution to this problem is certainly not acceptable as a general solution to all high speed relaying situations involving less than one cycle of elapsed time. Transmission relaying has more complex problems of defining the performance of ultra high speed relays. There is the need to also treat the asymmetrical component of the current as well. Additionally, when the relay contains 60 Hz filters or phase shifting circuits, the performance at other than 60 Hz must be considered to assure correct operation during system upsets. A simple statement of the rms value is thus not sufficient to fully define the desired relay performance, and other relay operating parameters may be useful when dealing with these modern relay applications.

In addition to these considerations as to the true nature of signals of less than one cycle duration, possible distortions created by arcing faults and ct's and vt's must also be factored in to all relay characteristics if accurate performance is expected. CT distortions generally consist of saturation effects. This gives rise to harmonic currents in the secondary circuit as well as a reduction in the fundamental value and a shift in the phase of the fundamental. Distortion in wound type voltage transformers is generally negligible except for possible 3rd harmonics in the residual voltage when used for ground relaying. The distortion in CCVT's will additionally include a subharmonic frequency which is most bothersome when there is a sudden and major change in the primary voltage.

Thus the evaluation of modern high speed, highly selective static relays requires considerations of more than the steady state fundamental frequency performance. Nevertheless, because of the practicalities of testing relays and the convenience of calculating system performance and relay settings on an rms bases, any relay to be acceptable must still be definable in rms terms. But this will not necessarily mean the relay responds to rms values. The situation is similar to many electronic instruments which are scaled in rms values, but which actually respond to the average or peak value of the applied signal.

BUS PROTECTION WITH DIFFERENTIAL RELAYS

A primary consideration in any bus differential scheme is ct saturation. This may occur on an external fault in which case a false residual current will appear in the relay. It may also occur during an internal fault in which case there may be insufficient current or current having a too high a harmonic frequency contact to cause relay operation. In both cases the result is that the relay receives distorted currents containing higher frequency components in addition to the dc component of any asymmetrical fault condition.

The RADHA relay is a 1/2-1 1/2 cycle high impedance relay which resolves these problems by utilizing an R-C circuit as shown in Fig. 1. This largely suppresses the dc component and at the same time enhances the relay sensitivity to the higher frequency components. The dc component is most troublesome during external faults. Thus its suppression can result in an improvement in the performance factor: ratio of maximum external fault to minimum internal fault. On the other hand, the worst wave distortion with the attendant high frequency components will occur during an internal fault. Thus the enhanced high frequency response of the DHA provides more sensitivity and setting margins for internal faults. To illustrate, a current transformer operating at its 10 % accuracy point, i.e., secondary current 10 % less than true ratio value, contains only a 92 % fundamental frequency component. This gives a total fundamental frequency ratio error of 18 % and not 10 % as implied by the Standard. Similarly at a 50 % ratio error, there is actually a 62 % error in the fundamental frequency component, the difference being contained in the harmonics. Fig. 2 shows the ct secondary current wave shapes for these saturated conditions.

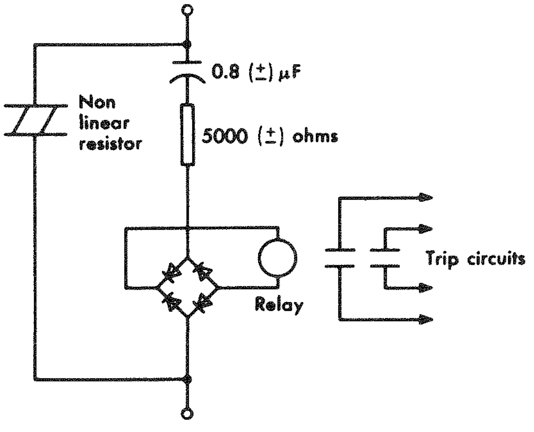


Fig. 1. Schematic of type RADHA high speed, high impedance relay.

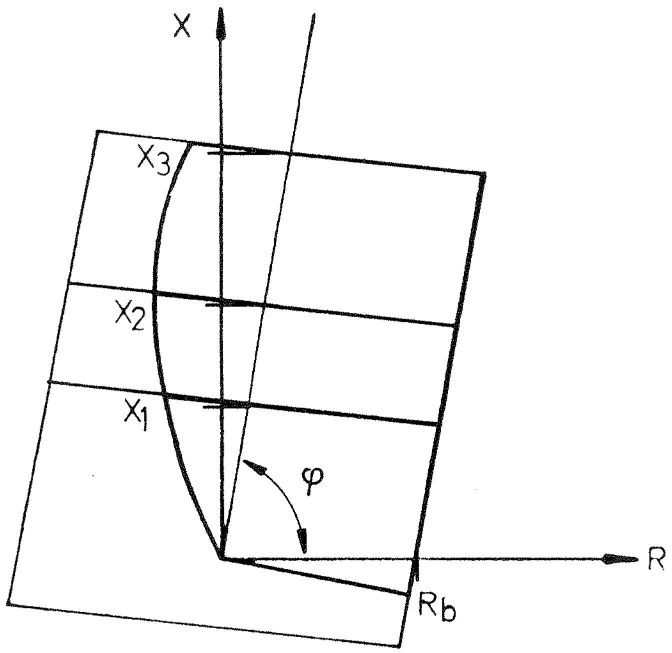


Fig. 14. Single phase and three phase fault characteristics for RAZFE.

External system considerations

Another system condition which must be treated in real life is the effect of phase shifts across the system. This can result in the fault current from one end being phase displaced from the other end. This will create a voltage drop across the common fault resistance which will appear to reduce the line reactance as seen from the leading end and to increase it from the lagging end. To eliminate any overreaching of the one relay, the reactance characteristic is built with a -6° ($\pm$ 2) slope. Thus will accommodate an apparent reactance error caused by the phase shift from 500 MW over 50 miles of 345 kV line with a 50 ohm fault.

Accurate measurement of high resistance faults must also treat the distorted nature of the fault currents and resulting voltages caused by the non-linear nature of both arc resistance and earth resistance. The ZFE responds properly to these distortions by virtue of the zero crossing, instantaneous, non-integrated method of measurement.

The blinders, sloped reactance line and method of measurement are thus seen to result in a relay characteristic which can accommodate conditions as they actually exist on the system external to the relay location.

CCVT and CT errors

There are two other conditions external to the ZFE which must also be recognized. These are possible vt errors and ct errors. Wound voltage transformers generally need no additional considerations. However, a ccvt will ring at a sub-harmonic frequency and this can cause overreaching and other incorrect relay operations if not compensated. In the ZFE, the extraneous signal generated in the ccvt is suppressed only when its severity is great enough to adversely affect the ZFE operation. This is determined by the relay voltage dropping to less than 15 % in the presence of fault current. As a consequence, for most faults the relay operating time is not affected, but for near in faults only a 10 ms delay is introduced by an active filter. This filtering is only applied to zone 1 units. It is not used for any other measurements.

Current transformer saturation effects must be considered in the application of any relay to a high capacity network. In the ZFE, ct saturation is generally not a problem. The very low burden of the relay minimizes the likelihood of saturation. When long (high resistance) ct leads are of concern one can use the 1 A or 2 A ZFE. The lead burden is reduced by the square of the reduced current level.

Should ct saturation occur, the directional measurement will remain secure and dependable, because it can allow a relatively large angular error between the measurands. For example, the directional measurement for the ground fault relay has a $\pm 90^\circ$ zero crossing error capability This is of course from all causes. With reasonable allowances for other causes CT saturation even within the first cycle will not cause misoperation.

The distance measurement will be slightly affected by ct saturation with a tendency to cause overreaching when the fault resistance is increased. This effect is somewhat contradicted by the fact that the probability of ct saturation due to the DC component of the current is strongly reduced when fault resistance is present since it effectively reduces the primary DC time constant. However, for a 100 % security in an underreaching setting of zone 1, the ct requirement should be not to saturate for faults close to the remote end of the line. For close in faults, where the likelihood of ct saturation is greater, ct saturation is allowed. The distance measurement is dependable under such conditions because during DC saturation one of the current zero crossings each cycle will be correct in both time phase and di/dt.

The ZFE measures phase-to-phase faults with a similar zero crossing technique. In the analog section, both the relay voltages and replica voltages are converted to phase-to-phase values and then subtracted.

$$E_{KAB} = (E_A - E_B) - Z_K(I_A - I_B)$$
$$E_{KBC} = (E_B - E_C) - Z_K(I_B - I_C)$$
$$E_{KCA} = (E_C - E_A) - Z_K(I_C - I_A)$$

where Z_K is the replica impedance and E_K the resultant subtraction of the replica voltage from relay voltage. The three resultant voltages are now compared for phase sequence. This again is a simple zero crossing comparison to establish that:

E_{KAB} lags E_{KBC}

E_{KBC} lags E_{KCA}

E_{KCA} lags E_{KAB}

For any Ø-Ø fault in the protected section all three of these relations will reverse and the lagging voltage becomes leading. A logic circuit confirms that at least two have in fact reversed sequence. This 2 out of 3 instead of just one indication enhances both the reliability and security of the system. The resultant characteristic on the (R, jX) diagram is a mho circle, as shown in Fig. 15. The effective reach of this Ø-Ø measurement is also independent of variations in system frequency by virtue of the zero crossing instantaneous measurement principle.

There is no limitation on the magnitude of an external fault. The allowable one ampere ct secondary circuit resistance may be over 1000 ohms, the exact value being a function of the relay restraint slope. Thus the relay application calculations are reduced to a simple test of the set slope of the relay being adequate for the ct secondary circuit resistances and that the minimum internal fault current is above the minimum pickup current of less than one ampere.

These two differential relays, the DHA and DSS both respond to the total current wave. They are both set on an rms sine wave basis. However, the DHA responds to the average wave, modified to accentuate the response to the higher frequencies while the DSS responds to instantaneous values of current.

The exciting current requirements of the parallel ct's limits the sensitivity of all high impedance differential relays. The DSS sensitivity to internal faults is not so limited in sensitivity because the ct paralleling occurs after diode rectification. See Figs. 4 and 5. The DSS speed of response and this method of paralleling ct's results in no reduction in sensitivity to internal faults due to idling ct's even under worst case ct saturation.

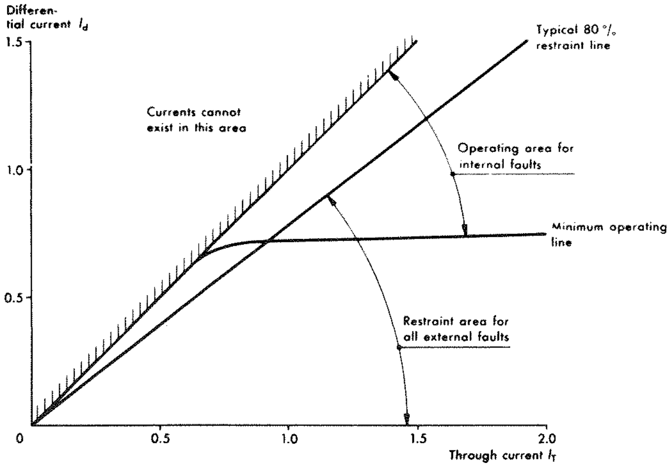


Fig. 4. Performance characteristic of the RADSS relay.

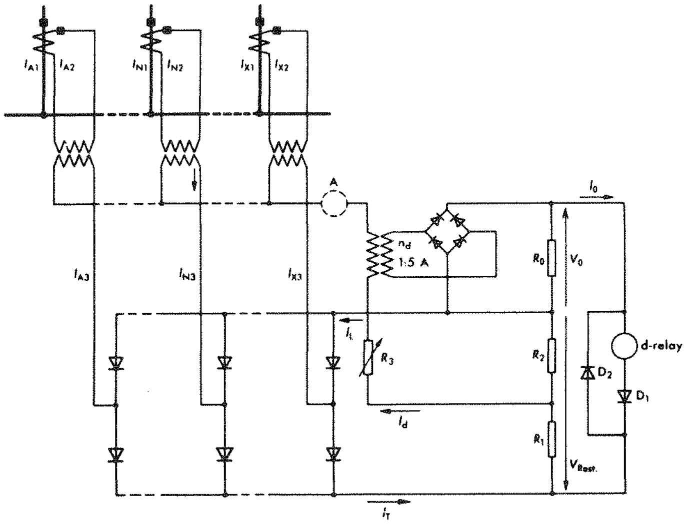


Fig. 5. Schematic of total RADSS bus differential protection.

TRANSFORMER PROTECTION WITH DIFFERENTIAL RELAYS

The primary consideration in transformer protection is to develop adequate sensitivity to minor internal faults while being fully secure against inrush currents and external faults. Since inrush currents always appear in the differential circuit of the relay, neither current magnitude, nor even percentage restraint current relays can fully distinguish between inrush and fault conditions.

The distinction between inrush and a true internal fault is the harmonic content in the inrush current. Harmonic restraint differential relays all use the 2nd harmonic of inrush current to restrain relay operation. However, the problem is compounded by the fact that ct saturation as may occur on a severe fault will create harmonic currents which can then restrain the relay from operating. In the RADSE relay this is resolved by separately controlling the restraining action of each harmonic frequency and by totalizing the harmonics in the three phases. The net effect is to provide a relay which:

1 Will not trip on inrush because of the restraint from the 2nd harmonics in all three phases. During worst case inrush, the current of the maximum inrush phase will contain very little 2nd harmonic current for restraint. But at least one of the other two phases will be rich in 2nd harmonics when this condition occurs.

2 Will not trip on overexcitation due to loss of load because of 5th harmonic restraint.

3 Will perform properly and trip for internal faults with saturated ct's because the restraining action of the resulting 5th harmonic distortion is largely cancelled by an operating voltage developed by the 3rd harmonic distortion component.

Note:

This 3rd harmonic effect on the relay is not applicable during overexcitation because the 3rd harmonic does not flow in the relay differential circuit because of the delta connected main transformer windings, or the ct secondary delta connection.

In addition to this selective use of the harmonics in the differential current, the level detector which makes the trip decision is in two stages. The effect is to require the instantaneous value of the signal to exceed the set level 41 % of the time of each half cycle with a minimum possible operating time of 3.4 ms. This leads to complete immunity to noise spikes regardless of magnitude and of equal importance provides maximum discrimination between trip and block signals in minimum time. Fig. 6 shows the effect of the three phase restraint during an inrush period and the value of the two stage detector. Note the rejection of about a 2 ms error signal at the initial energizing.

will react with the replica impedances, just as it does on the main transmission circuit. Thus an exact, proportionate recreation of the line drops are possible within the relay.

Instantaneous measurements

The second feature of the ZFE relay which enhances its accuracy is the instantaneous measuring technique. By making the measurements of the replica voltages always at the zero crossings of the current (or of some other replica signal) the time it takes to make the measurement is reduced. Additionally, this eliminates the need for integrating circuits or internal timing circuits which can affect the accuracy of the measurement.

The actual measurements are made as follows in the ZFE. First, the several replica voltages are subtracted from the system (secondary) voltages at the relay location. The resulting set of signals are now converted to square waves. All of the desired information is contained in the relative time of the zero crossings of a given pair of these resulting signals.

Zero crossings determine direction

To illustrate this zero crossing principle, consider a directional measurement. The torque equation for an E-M directional element is:

$$E_{max} \cos wt \times I_{max} \cos (\phi + a) + wt$$

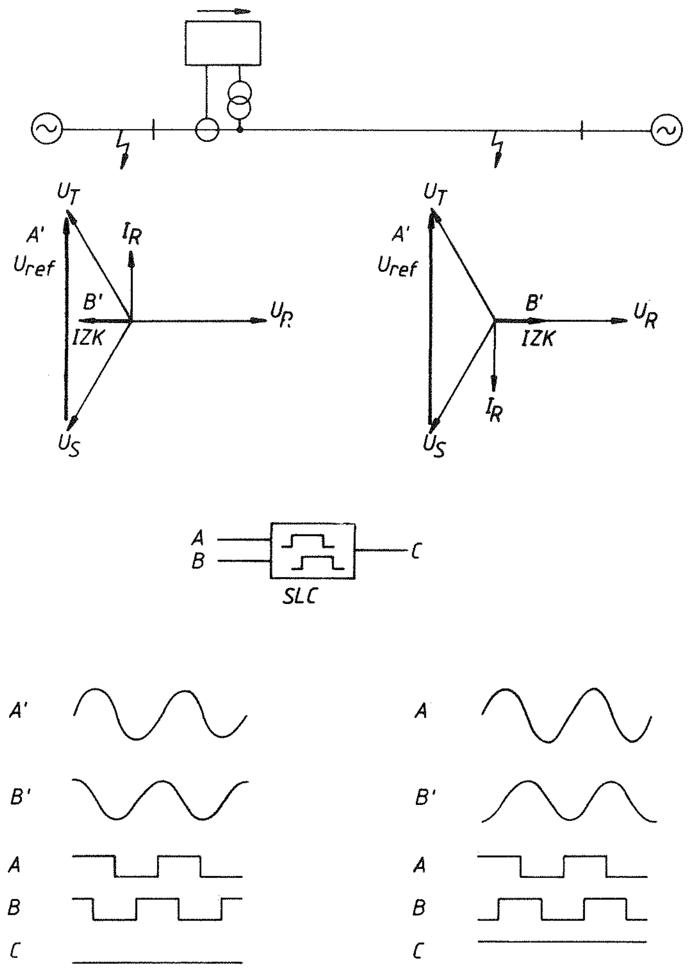
where ϕ is the angle between E and I and a is a design constant. When integrated over a full cycle the net torque is:

$$E \times I \cos (\phi + a)$$

It can be shown that an unambiguous directional determination cannot be made in less than 1/2 cycle. It is also apparent that the direction of an asymmetrical current will be properly measured since the torque equation has no dc term and hence the dc component will be ignored by the relay. In a static relay one could make the same type of measurement.

In the ZFE another method of directional measurement consisting of zero crossings is used. With this method the dc component is first removed from the current so that the zero crossings are the crossings of the ac component only. This is done by using the voltage developed across the replica impedance due to the line current flowing in it. This voltage is then compared to the unfaulted phase voltage, i.e., the replica voltage of Aϕ is compared to the sound B-C phase reference voltage.

With conventional polarities, with a ground fault in the tripping direction, the replica voltage will lag the reference voltage. If, when the reference crosses zero from negative to positive, the replica voltage is negative, the replica voltage must not yet have crossed zero from negative to positive, i.e., it is behind the reference and the fault is in the tripping direction. Thus by observing the sequence of the zero crossing of two signals one can derive the direction of the fault. This is shown in Fig. 11. It is obvious that a zero crossing will occur in the reference within one-half cycle or less and that this then becomes the maximum time needed to make an accurate, secure directional measurement.



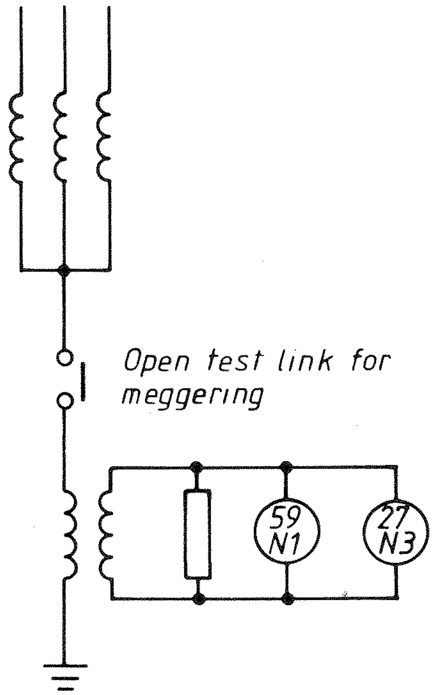
The SLC gives an output signal if A leads B

Fig. 11. Functioning of sequential logic circuit for a directional measurement.

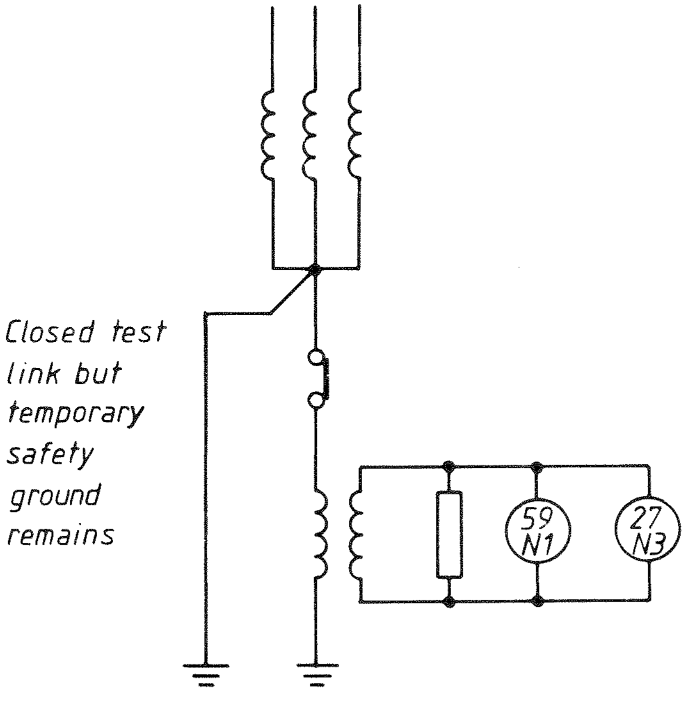
Zero crossings determine distance to fault

The ground fault reach of the ZFE is also determined by the sequence in which two signals cross the zero axis. The one signal is the difference between the system voltage at the relay location and the replica impedance voltage within the relay. For faults beyond the set reach of the relay, the system voltage drop will be larger than the replica voltage and the resulting difference voltage will be in phase with the system voltage. For a fault within the set reach, the system voltage will be less than the replica voltage and the subtraction will result in a signal of opposite polarity. The fault current (including any dc component) zero crossing is used as a reference to establish this polarity. The same sequential zero crossing principle as in the directional measurement is utilized, i.e. if the fault is within the tripping zone, the resulting replica voltage subtraction from system voltage will be negative when the current goes through zero toward positive. This means this voltage must cross the zero line going toward positive after the current crossing. This sequence is recognized in the SLC (sequential logic circuit) and a trip output signal initiated. See Fig. 12. All of these measurements are made by two parallel systems of opposite polarity. Thus zero crossings going negative are also observed. This yields two measurements per cycle, not one. This distance measurement inherently measures the reactive component of the total line and fault impetion voltage, which is usually from 1-10 % of the machine voltage, is reduced to one-half or less. An undervoltage relay, with a fundamental frequency rejection filter can recognize this abnormality, trip and sound an alarm.

Fig. 7. Abnormal neutral conditions recognized by the RAGEA.



a) Neutral open to ground.



b) Neutral shorted to ground.

Thus the GEA utilizes all of the information in the residual voltage on a generator neutral bus, not just the rms value or just the value of the fundamental component. There is also an important philosophical aspect to the use of the GEA. This is the identification of a condition, which in itself may not be hazardous, but which can result in serious machine damage if a second "5-10 ampere minor fault" occurs before the first one is removed. Such a second fault can result in fault currents actually greater than those of a 3ϕ fault. If both faults are on one phase, slow clearing if at all detected by the normally used ground relay can result in complete destruction of the machine. The required sensitivity can only be attained with a sound theoretical as well as practical approach if incorrect nuisance trippings are to be avoided. The GEA includes filtering all higher frequencies from the 60 Hz signal so that there is no question that the fundamental frequency measurement is free of any extraneous unwanted information. The harmonic underfrequency measurement is also secure against noise since it is an under voltage measurement. Sporadic noise would thus only cause a brief delay in the operation of the relay and will not cause an incorrect tripout.

Unbalanced currents

Negative sequence current protection is essential on modern large generators. The RARIO provides the typical $I_2^2 t = k$ characteristic with excellent sensitivity for the most critical machines. In addition the negative sequence segregating network is insensitive to substantial changes in system frequency. This means that during system upsets, when large current unbalances are most likely to occur, the RIO relay will still be on calibration and provide full negative sequence protection.

Without this broad frequency response capability one of three undesirable conditions could result. Balanced three phase load currents could cause operation of the relay or minor unbalances might do likewise. Second, a harmful current unbalance may be out of phase with the relay internally created error and as a result the relay might not respond to a hazardous condition. Third, in order to minimize incorrect tripping if the frequency sensitivity of the relay is too severe, a frequency filter may have to be inserted between the sequence network and the level detector. This will prevent incorrect low (or high) frequency operation, but it may also block a desired operation during an off-frequency system upset condition.

The RARIO, by utilizing the proper phasor values of the applied signal regardless of frequency, is free of these hazards and thus maintains its calibration and security during system upsets.

Loss-of-field protection

Loss-of-field protection may take one of several forms. The RAGPC relay is directly responsive to that component of current which is hazardous to the machine. This is the leading reactive component. Thus the GPC main sensing unit is an overcurrent directional relay, with inverse time, type RXPE 4. This relay is unique in that it is sensitive to the phase angle of a reference voltage, but not the magnitude of this voltage. In this application it is set with a maximum sensitivity at 75°-80° leading. This gives a threshold operating line which coincides with the machine's leading power factor capability curve, a feature not available with the frequently used impedance relay. The RAGPC relay is easy to apply. Since the relay is directly measuring the machine damaging component of current, exhaustive system studies to establish the relay setting are not necessary. Such studies can be replaced with a simple matching of the relay threshold line to the machine capability line with full assurance that the machine is adequately protected. See Fig. 8.