WESTERN PROTECTIVE RELAY CONFERENCE

EFFECT OF TRANSIENTS ON EHV PROTECTION

by

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PRESENTED AT THE FOURTH ANNUAL CONFERENCE
OCTOBER 1977
SPOKANE, WASHINGTON

4th Annual

WESTERN PROTECTIVE RELAY CONFERENCE

October 18-20, 1977
Red Lion Motor Inn
Spokane, Washington

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SUMMARY

This paper is concerned with transients following sudden short circuits in high voltage transmission systems and the effects of these transients on the performance of fast acting protective relays designed to initiate prompt removal of the faulty section from the system.

Influencing factors governing the character of fault transients and modification of these transients by current and voltage transformers are discussed. Effect of current transformer saturation is examined and the performance of distance and instantaneous current relays described.

EFFECT OF TRANSIENTS ON E.H.V. PROTECTION

INTRODUCTION

Protective relays are connected to the primary system via current and voltage devices which usually contain iron cores and are therefore liable to saturate when subjected to fault transients. The secondary circuit burden connected to these current and voltage transducers, together with the transducer parameters, constitute a circuit which itself has a transient response to the imposed condition. The primary system transient can be materially modified, depending upon the nature of the circuit and the degree of saturation that takes place. Thus the signal applied finally to the relay can be fundamentally different in character to that present in the primary system.

The effects of transients on protective relays may be either to speed them up or slow them down and, depending upon the type of relay and the quantities being compared, there is the ever-present danger that discrimination may be lost and the relay operate when it should in fact remain stable.

From the foregoing remarks it is evident that at least a qualitative understanding of fault transients and their effect on the various devices associated with protective relays including the relays themselves, is necessary if the protection is to be properly designed and applied to meet its fundamental requirements – discrimination combined with high speed.

PRIMARY TRANSIENTS

Energy balance during steady-state operation must, by definition, be such that energy distribution is fixed and the rates of transfer either constant or uniformly cyclic. When a sudden change is imposed on a circuit as occurs during a fault, the new condition results in a re-distribution of energy and new rates of transfer. Neither can be instantly accommodated, hence, in order to attain the new steady-state level, the circuit must pass through a transient-state.

When making a fault study a power system can be represented by a simple equivalent circuit comprising a series loop of resistance and inductance parameters, as shown in Fig. 1(a). Point P in the diagram is defined as the relaying point, and is the point where the current and voltage quantities due to a fault at F will be applied to a relay via current and voltage transformers.

The source parameters R_S and L_S are determined from a knowledge of the source MVA behind the relaying point, the source impedance $Z_s\underline{/\phi_s} = R_s + j\omega L_s$ being inversely proportional to the source MVA. The line parameters R_L and L_L are dependent on the impedance $Z_L\underline{/\phi_L} = R_L + j\omega L_L$ between the relaying point and the fault.

The energy equation for the simple series loop is given by:

$$iL\,di/dt + iRi = ei \qquad (1)$$

where, $R=R_S+R_L$ and $L=L_S+L_L$.

The resistive parameter accepts and dissipates energy at a rate $i^2R=ei$, while the inductive parameter stores energy of value $1/2Li^2$ and accepts it at a rate ei. When these rates are constant or uniformly cyclic the circuit operates under steady-state conditions and the fault current is said to have attained its steady-state value. Before this value is reached the circuit passes through a transient-state since the circuit change imposed by the fault cannot be instantly accommodated as this would imply infinite rates of energy transfer.

Solving the differential equation, eq. 1, for i gives:

$$i=E[\sin(\omega t+\epsilon-\phi)-\exp(-\tau t)\sin(\epsilon-\phi)]/Z \qquad (2)$$

when $e=E\sin(\omega t+\epsilon)$, where

ϵ=angle of voltage waveform at t=0,

$\phi=\tan^{-1}X/R$, $\tau=\omega R/X$, $X=\omega(L_S+L_R)$,

$R=R_S+R_L$, $Z=Z_S+Z_L$.

The form of this expression is shown in Fig. 1(b).

The final steady-state value of current is given by the first term in the above expression, but during the transient period this term is compounded with the second term to give the transient current. It can be seen that the transient current exponentially decays to its final steady-state value in a time dependent on the X/R ratio of the circuit, and has an initial value which is dependent on the offset angle $\delta=(\epsilon-\phi)$.

Finally, the actual magnitude of current E/Z is dependent for a given applied voltage on the impedance of the fault loop $Z=Z_s+Z_L$.

The voltage appearing at point P due to a fault at F is given by:

$$V=R_L i+L_L(di/dt). \qquad (3)$$

Solving this differential equation gives

$$V=EZ_L[\sin(\omega t+\epsilon-\phi+\phi_L)-\cos\phi_L\sin(\epsilon-\phi)(1-\tau/\tau_L)\exp(-\tau t)]/Z \qquad (4)$$

where $Z_L=R_L+j\omega L_L$, $\phi_L=\tan^{-1}\omega L_L/R_L$

$\tau_L=R_L/L_L$.

A transient voltage therefore appears which is similar in form to the transient current but with two important differences.

First, the magnitude of the transient component is dependent upon the amount of resistance in the line impedance. Secondly, the magnitude of the transient component is further influenced by the system and line X/R ratios. When these are equal there is no voltage transient, even though there may be a transient current producing the voltage.

Examining the transient current and voltage expressions given above, eqns. 2 and 4, a number of common observations can be made:

(i) Both the initial and final magnitudes are dependent upon the source and line impedances Z_S and Z_L.

(ii) The transient term decays exponentially depending on the system X/R ratio. A circuit with a high X/R ratio will retain its transient longer than one with a low X/R ratio.

(iii) The offset angle $\delta=(\epsilon-\phi)$ regulates the inital magnitude and polarity of the transient term. When $\delta=0$ there is no transient while maximum transient response occurs when $\delta=\pi/2$.

INFLUENCE OF SYSTEM Z_S/Z_L RATIO

The initial and final values of current and voltage at point P in a system may be determined from a knowledge of the source/line impedance ratio Z_S/Z_L and the actual value of the line impedance Z_L. Furthermore, the system X/R ratio determines the rate of decay of the transient component and is itself dependent upon the source and line parameters.

It follows that examination and interpretation of primary current and voltage transients at a relaying point are best made using families of curves based on the system Z_S/Z_L and X/R variables.

Relay Current and Voltage in terms of Z_S/Z_L. The peak symmetrical magnitudes of current and voltage are given from eqns. 2 and 4 as:

$I_R=E/Z$ and $V_R=EZ_L/Z$.

Since $Z=Z_S+Z_L$ both the above quantities can be rewritten as:

$$I_R=I/(Z_S/Z_L+1).$$

$$V_R=E/(Z_S/Z_L+1) \quad \ldots\ldots \quad (5)$$

where $I=E/Z_L$.

The relay current and voltage expressions given by eqn. 5 are plotted in Fig. 2. It should be noted that E is the source voltage behind the source impedance and is therefore the generator open-circuit voltage. While I is the current that would flow if an infinite busbar source was assumed. It is therefore the maximum current that can flow for any given value of Z_L.

System X/R ratio in terms of Z_S/Z_L. Using the system source and line impedance parameters $Z_S\angle\phi_S$ and $Z_L\angle\phi_L$ an expression for the system X/R ratio in terms of Z_S/Z_L can be derived.

$$\text{System X/R ratio} = \frac{Z_S\sin\phi_S + Z_L\sin\phi_L}{Z_S\cos\phi_S + Z_L\cos\phi_L}$$

dividing by $Z_L\sin\phi_S$ and writing,

$$\sin\phi_S/\cos\phi_S = X_S/R_S$$

$$\sin\phi_L/\cos\phi_L = X_L/R_L$$

$$\text{System X/R ratio} = \frac{X_S/R_S(Z_S/Z_L + \sin\phi_L/\sin\phi_S)}{Z_S/Z_L + (X_S/R_S)\sin\phi_L/(X_L/R_L)\sin\phi_S} \quad (6a)$$

For large angles,

$$\sin\phi_L/\sin\phi_S = 1.$$

Therefore,

$$\text{System X/R ratio} = \frac{X_S/R_S(Z_S/Z_L+1)}{Z_S/Z_L + (X_S/R_S)/(X_L/R_L)} \quad (6b)$$

The above expression can only be used with accuracy on bulk transmission systems where the source and line angles are greater than 70°.

The relationship given by eqn. 6(b) is plotted in Fig. 3 for various source and line X/R parameters. It should be noted that under maximum plant conditions, viz. when the fault current approaches the maximum possible value I, the system X/R ratio approaches that of the line. This is a pertinent fact when examining the requirements of protective current transformers.

MAXIMUM OFFSET TRANSIENTS

A re-examination of eqns. 2 and 4 shows that the current and voltage transients are initially a maximum when the offset angle $\delta = (\epsilon - \phi)$ is 90°, and when $\delta = 0$ no transient occurs. Accordingly, only the maximum offset conditions will be considered because it is the most severe. Writing $\delta = 90°$ in eqns. 2 and 4 and using the relations given above, the transient current and voltage expressions become,

$$i = \frac{I_R[\cos\omega t - \exp(-\tau t)]}{(Z_S/Z_L+1)} \quad (7)$$

$$V = \frac{E\cos(\omega t + \phi_L)}{(Z_S/Z_L+1)} - \frac{E[\cos\phi_L(1-\tau/\tau_L)\exp(-\tau t)]}{(Z_S/Z_L+1)} \quad (8)$$

Transient Decay time. The decay of the transient in each of the above expressions is dependent upon the system X/R ratio. Fig. 4 shows the decay time of the transient component for various system X/R ratios, 1 p.u. d.c. amplitude being the initial magnitude of the d.c. component at time t=0. The decay time constant is $1/\tau = X/\omega R$ and is the time for the transient to decay to 0.368 of its initial value.

It also represents the time it sould take for the transient to completely disappear, if the initial decay rate was maintained. Below 0.368 p.u. the decay rate becomes very slow and for practical calculations the transient period may be regarded as terminated.

Viewed in these terms the transient period may be regarded as persisting for a time

$$T = 2.65X/R \text{ m.secs. for a 60 Hz system.}$$

Thus, for a system X/R ratio of 15 (typical in 240 kV systems) the transient time is approximately 40 m.sec.—2.4 cycles at system frequency. During this period the protection is expected to have operated and the fault cleared.

Transient Voltage Ratio (TVR). At time t=0 the ratio of transient to steady-state terms in the voltage transient, eqn. 8, known as the transient voltage ratio, TVR is

$$TVR = (1 - \tau/\tau_L)$$

Since $\tau = R/L$ and $\tau_L = R_L/L_L$ this expression may be rewritten,

$$TVR = [1 - (X/R)_L/(X/R)].$$

Furthermore, by using the relationship between the system X/R ratio and the source/line impedance ratio Z_S/Z_L given by eqn. 6(b),

$$TVR = \frac{Z_S/Z_L}{(Z_S/Z_L+1)} \quad 1 - \frac{(X/R)_L}{(X/R)_S} \qquad (9)$$

Using eqn. 9, the transient voltage ratio has been plotted as a function of the source/line impedance ratio Z_S/Z_L for various values of source and line X/R parameters, in Fig. 5.

It should be noted that the ratio is entirely dependent upon the system Z_S/Z_L ratio when $(X_S/R_S) \gg (X_L/R_L)$ a condition that can apply when the fault occurs near a bulk generation point. However, the most important fact is that since the transient term is subtractive for positive offset angles, the voltage during the transient period may be depressed below its steady-state value.

This can seriously impair the performance of distance relays because there is a voltage limit below which the relay characteristic cannot be maintained. No compensation for this effect is possible.

SECONDARY TRANSIENTS

Secondary transients may be described as referred primary transients modified by the transfer functions of the transformer providing either the current or voltage link between primary and secondary.

The transformer is a non-linear device, its characteristic being the B-H curve. Approximations to linearity can be approached in practice when the working range for the c.t. or v.t. is confined to the straight line portion of the curve; above the ankle and below the knee. During fault conditions, abnormal voltages and currents exist and limits of linear working may be exceeded, the transformers entering saturation.

Current transformers are more severly affected than voltage transformers because steady-state fault currents alone may be many times full-load and the flux swing due to the d.c. decrement component is in the extreme case proportional to the X/R ratio of the primary circuit.

Voltage transformers are rarely subjected to voltages in excess of $\sqrt{3}$ times normal system voltage and in general the voltages are very much less than normal during fault conditions hence the problem of saturation does not usually arise. However, there is a secondary relaxation transient present which dies away with the time-constant of the secondary load and, in the case of capacitor voltage transformers ringing transients occur because the transformer contains elements of a bandpass filter.

TRANSIENT RESPONSE OF A CURRENT TRANSFORMER

Current transformers are divided into two broad classes, high-reactance and low-reactance types. The high-reactance type has a wound primary and there is usually considerable magnetic separation between it and the secondary resulting in appreciable internal secondary leakage reactance. The low-reactance type is toroidally wound and has a bar primary; thus the leakage reactance is very low. This latter type is the most common on power systems.

The complete subject of current transformer transient response is too large to give justice in this survey, therefore the transient response of a toroidal c.t. with a bar primary and a resistive load will be considered as it offers the simplest treatment while constituting the worst transient to which the c.t. and its burden can be subjected.

It can be shown that the secondary burden current for a maximum offset primary current with the c.t. unsaturated and operating over the linear portion of its characteristic, and unity turns ratio assumed is:

$$i_b=(E/Z)\ \cos\omega t+[a\exp(-at)-\tau\exp(-\tau t)]/(\tau-a) \quad \ldots\ldots\ldots\ldots \quad (10)$$

where τ is the reciprocal of the primary time constant and a the reciprocal of the secondary time constant. It should be further noted that $\epsilon=R_b/M$ where R_b is the burden resistance and M is the magnetising inductance of the c.t.

In the case of the ideal c.t. the magnetising inductance M is infinitely large and hence $a=0$. For this ideal case the primary transient is referred through the c.t. without modification. More generally, the ratio of the secondary and primary time constants is 3, viz. $\tau=3a$. For this case the primary transient term becomes a double exponential on being referred through the transformer. This latter condition is of most interest and is illustrated in Fig. 6.

SECONDARY CURRENT TRANSIENT

From Fig. 6 it can be seen that the transient component of secondary current is now a double exponential initially being due to the primary time constant, but persisting as a function of the secondary time constant. The transient changes polarity and the point at which the transient passes through zero is of particular importance as, at this interval of time, all of the referred primary transient current is used in exciting the core.

Thus, at this point the transient magnetising current is at a maximum and hence it is the point at which maximum transient flux density occurs if the c.t. remains unsaturated.

EFFECT OF SATURATION

The flux produced by the c.t. during the transient period is of particular importance because initially the rate of change of magnetising current is very high being the difference of the primary and secondary currents. The flux developed is $\phi = Mi_m$ and is therefore directly proportional to the magnetising current. Since in the extreme case the maximum flux swing is equal to X/R times the steady-state burden flux, the magnetic circuit must be very large in order to avoid saturation, and this in practice is often a prohibitive factor.

Accepting that to design c.t.'s with large magnetic circuits to withstand the highest flux swings is very often neither a practical proposition or necessarily desirable, because of the adverse effects of remanence, some degree of saturation under the highest fault conditions is inevitable.

The basic effect of saturation is that the magnetising reactance changes from a relatively high value to a low value. If the magnitude of magnetising reactance is regarded as the gradient of the B-H curve, then it can be appreciated that the modification is drastic after entry into saturation.

Quantitative analysis is difficult as with most non-linear systems, but by regarding the magnetising inductance as two-stage, some approximation to the truth can be obtained. In fact, the c.t. in saturation behaves in a similar manner to a linear coupler in so far as it gives a voltage output for a current input.

MODIFIED C.T. BEHAVIOUR

Fig. 7 shows for a resistive burden how the secondary current is modified by c.t. saturation. For clarity only the transient component of current is considered. Initially, the c.t. is not in saturation and the secondary current varies as illustrated in Fig. 6. This variation continues until the magnetising current reaches the value corresponding to saturation. At this instant the magnetising inductance becomes zero and the total primary current is expended in exciting the core, the secondary output disappearing.

This condition will last until the primary current has reduced to a value corresponding to the saturation point. From this point onwards the core comes out of saturation and the core flux decays in a transient largely determined by the secondary time constant. The secondary transient in this region is of negative polarity.

The most important aspect of the region of saturation can only be appreciated when both the steady-state a.c. component and d.c. transient component are considered together. This is shown in Fig. 8, the prospective values without saturation being shown dotted.

The combined a.c. and d.c. flux curve will enter the saturation region at some point, and again, all the primary input is by-passed through the saturated shunt inductance. However, due to cyclic variation in the primary input, the core will come out of saturation for some period of each cycle. This can be appreciated by the fact that the negative loops of current require a negative flux change, i.e., reducing flux. The flux will reduce from saturation for the duration of the negative loop and again start to increase as the positive loop commences.

It is easily seen that there is a period of non-saturation on the positive loops as shown in Fig. 8, such that the area on the positive side is equal to the area of the negative loop. The secondary output will thus be distorted by loss of the output onthe positive loops during the period of saturation.

As the primary transient decays, the waveform becomes more symmetrical and less of the positive output is lost until eventually the core fails to saturate.

The effect of saturation on a protective relay is, in general, to reduce its speed of operation and cases where a comparison process if being carried out, to upset this process in such a manner that stability may be impaired.

A current transformer takes a finite time to saturate. In the example of Fig. 8 it is almost half a cycle. An approximation to the saturation time can be found, if remanence can be ignored, but using eqn. 11.

$$t_s = -(X/\omega R)\log_e(1-KR/X) \quad \ldots \quad (11)$$

Where X/R is the primary system X/R ratio and K is the ratio of c.t. kneepoint voltage to steady-state burden voltage. It can be seen that when K=X/R the c.t. will never saturate, hence it is the usual practice to match the c.t. characteristic and burden in this manner whenever possible. In cases where this matching rule cannot be applied, an attempt is made to avoid saturation until the relay has operated.

In large c.t.'s remanence can be a problem and, apart from the physical and economic factors involved is the principal reason for limiting the size of transformer cores. Ring-core, c.t.'s have hysteresis loop characteristics such that remanent flux densities of from 6,000 gauss (Stalloy type materials) to 8,000-9,000 gauss (cold rolled grain oriented steel) are easily obtained.

Such densities can exist following a fault which is cleared quickly as the flux due to the transient swing has reached a level whereby it cannot be destroyed by load cycling following supply restoration.

Remanence may therefore remain for an indefinite period and can be present when another fault occurs. The result would be that the effective flux change before entry into saturation is reduced. Saturation could therefore take place earlier and the effects be more pronounced.

A transient of opposite polarity would, of course benefit from remanence and the saturation effects be reduced, but this is small comfort to the protection engineer.

TRANSIENT RESPONSE OF VOLTAGE TRANSFORMERS

In general, the design requirements for normal steady-state accuracy are a low winding resistance and leakage resistance compared with connected burden. These, together with relatively low working flux densities, tend to minimise the problems of transient reproduction.

Transients which may have some effect on the working of a voltage transformer are:

(a) Transients due to switching.
(b) Sudden increase in system voltage.
(c) Sudden collapse of system voltage.
(d) Recovery voltage after fault clearance.
(e) Transient voltage during a fault.

Transients due to (a) are similar to those appearing in power transformers, the main transient appearing as an exponential magnetising current, with possible doubling of peak flux density at the start of the transient. There is little variation in the secondary output waveform provided the v.t. has a low working flux density. However, if the working flux density was similar to a power transformer then a similar distortion of the output waveform would result, due to cyclic saturation of the core.

A sudden increase in system voltage can be due to system earthing conditions. For example, if the system became isolated during a fault, the voltage on the healthy phases would rise to $\sqrt{3}$ times their normal value. If saturation of the v.t. occurs during these over-voltage conditions, resonance may be set up between the inductance of the transformer and the capacitance of the primary system. This danger is another reason for designing v.t.'s with low working flux densities.

A collapse of voltage, say, during a fault and subsequent restoration is similar to a switching transient. However, since the flux resulting from a fault dies away exponentially, rapid restoration of voltage may cause some increase in core flux due to the addition of transient and steady-state fluxes.

The condition of most interest is when a fault occurs in a non-homogeneous system and transient voltages appear across the transformer. Provided saturation does not occur, and this is unlikely because the voltage is depressed below normal, the transient is accurately reflected into the secondary burden circuit, but with the addition of a secondary relaxation transient. This relaxation transient is due to the fact that, unlike the current transformer case, the initial value of voltage across the burden before the fault is significant and cannot be ignored.

It can be shown by a similar analysis to that carried out for a c.t. that the magnetising current transient component is,

$$i_m = (KE/R_p)[\beta/(\beta-\tau)][\exp(-\tau t)-\exp(-\beta t)] \quad \ldots\ldots \quad (12)$$

Where, R_p is primary winding resistance

$$\beta = R_p/M$$

$$K=[(Z_S/Z_L)/Z_S/Z_L+1)^2]\left\{\cos\phi_L[1-(X/R)_L/(X/R)_S]\right\}$$

If $B \ll \tau$ the usual case then the maximum value of transient magnetising current is equal to $K(X/R)$ times the peak steady-state magnetising current at normal voltage, I_m. In the limit when $(X/R)_S \gg (X/R)_L$ it becomes dependent entirely on the source/line impedance ratio, that is

$$i_m\,(\text{max.}) = \frac{Z_S/Z_L}{(Z_S/Z_L+1)}\, I_m \quad \ldots\ldots \quad (13)$$

From 13 it can be seen that when Z_S/Z_L is very large, the transient magnetising current approached the normal steady-state value, hence flux doubling is approached. However, since the v.t. normally has a low working flux density, well below the knee, this is not an embarrassment.

CAPACITOR V.T.

The capacitor voltage transformer is in essence a capacitance divider, the output of which is connected to a wound voltage transformer. This arrangement contains elements of a bandpass filter. The band width and cut-off frequencies depend on the design of the c.v.t. and an attempt is made to arrange for system frequency to coincide with mid-band.

Under impulse voltages accompanying switching or fault conditions, the device will ring at two frequencies: 8-16 c/s and 200-300 c/s. These ringing conditions are most significant on a sudden reduction of voltage, such as occurs on fault inception, and can seriously effect the performance of distance and directional relays. If the burden of the c.v.t is mainly resistive, the ringing transients are quickly damped, but during the damping period it is usual to delay the operation of distance and directional relays.

EFFECTS OF TRANSIENTS ON RELAYS

Fault transients of the types described in this article are troublesome only to relays of the high-speed class, that is, relays whose operating time under steady-state conditions would be less than 50 m.secs.

The effect of transients must be examined in relation to the type of relay and its application and whether or not transient saturation is only of relevance in relay current circuits.

Two classes of relays only will be considered: distance and instantaneous current. The former commonly employs induction cup and rectifier bridge movements, while the latter is often a simple, attracted armature type.

DISTANCE RELAYS

Distance relays compare current and voltage to measure impedance or some component of impedance. The impedance measured is usually positive sequence and the relay is calibrated on steady-state quantities.

Briefly, the effect of the current transient is to make the relay overreach, i.e. operate for a fault outside its nominal zone of operation. Voltage transients have little effect unless the transient depresses the applied voltage below the level at which the characteristic can be maintained. If this happens, the relay may underreach, i.e., its zone of operation is shortened. The presence of the current transients would usually cancel this effect, except when saturation occurs when it would become more pronounced.

Discrimination would be lost in either case until the transient disappeared. Delay in operation until the transient becomes innocuous may place undue stress on the system. However, this measure can be avoided by using replica circuits.

CURRENT AND VOLTAGE COMPARISON CIRCUITS

To obtain certain distance relay characteristics it is necessary to mix current and voltage signals before application to the relay. For example, $(V_R - I_F Z_L)$ is a typical input voltage signal, the circuit for which is shown in Fig. 9(a). Z_L is the secondary equivalent of the line impedance and is the setting of the relay. The corresponding current signal is $(V_R / Z_L - I_F)$ and the circuit for this is shown in Fig. 9(b).

Assuming ideal current and voltage transformation according to equations 7 and 8, then with a replica impedance $Z_L \angle \phi_L$ as shown iZ_L becomes equal to equation 7. In either case correct comparison is made, but it should be recognized that this only applies for faults at the reach point. For faults inside relay reach, provided the actual line angle has not changed, the scalar ratio is maintained as in the steady-state.

In practice the current contains a double exponential and the voltage a relaxation transient. Provided relay operation is within the primary time constant period and saturation has not taken place, the current signal will not be affected. The relaxation transient in the voltage signal is damped by resistance typically to 0.3 cycle, which is adequate for most relay speeds. However, this is at the expense of some sensitivity due to the increased voltage circuit burden.

EFFECTS OF TRANSIENTS ON COMPARATORS

Distance relays in common use are the induction cup and rectifier bridge comparators. The former is a phase comparator while the latter is an amplitude comparator.

The standard torque equation for the induction cup is

$$T=K(i_1\,di_2/dt-i_2\,di_1/dt)$$

where i_1 and i_2 are the currents producing the fluxes acting on the cup.

Assuming that the two current signals are of the form

$$i_1=I_1\,[\mathrm{Sin}\,\omega t+A\exp(-\tau t)]$$

$$i_2=I_2\,[\sin(\omega t+\psi)+B\exp(\tau t)+C\exp(-\mu t)]\,.$$

Where ψ is the phase angle between the two signals, μ is the reciprocal of the voltage relaxation time constant, and A, B, C are constant coefficients, then the torque becomes:

$$T=I_1\,I_2\,\omega\,\Big\{[\sin\omega t+A\exp(-\tau t)]\,[\cos(\omega t+\psi)-\frac{B\exp(-\tau t)}{(X/R)}-\frac{C\exp(-\mu t)}{(X/R)_V}$$

$$-\sin(\omega t+\psi)+B\exp(-\tau t)+C\exp(-\mu t)]\,[\cos\omega t-\frac{A\exp(-\tau t)}{X/R}]\Big\}$$

where X/R is the system, X/R ratio and (X/R)v the X/R ratio of the voltage circuit burden.

The steady-state torque, from the above expression is $k\omega I_1 I_2 \sin\psi$ and there are damped 60 Hz terms due to the transient. Since, at balance point ψ=0, it follows that the damped 60 Hz torque associated with the primary time constant will vanish if A=-B, i.e. if transient inputs are balanced by the replica method. The damped 60 Hz terms due to the voltage relaxation transient can be reduced by proper choice of τ as explained earlier.

The transient unidirectional torque will disappear if either the forcing transient or the relaxation transient is eliminated, since it is due to the interaction between them.

Summarizing, to eliminate all transient effects it is desirable to have either A or C zero and a relay damped against 60 Hz operation, alternatively A=B=0.

BRIDGE COMPARATOR

The rectifier bridge comparator rectifies the two input signals and compares instantaneous values, giving an output equal to the instantaneous difference. The larger output thus controls the operation of the relay. The magnitude of the current in the relay is not proportional to the difference in the signals because of the self-limiting action of the rectifiers. It is, therefore, difficult to give a quantitative analysis for this comparator.

Fig. 10 shows the rectifier bridge circuit and Fig. 11 the outputs which can be expected and it will be noted that the effect of the transient is to increase the average value of its rectified signal. If the relay is properly matched by the replica method, the only unbalance will be due to the relaxation transient. Thus the relay will underreach until this disappears. It should be noted that the instantaneous differences may contain second harmonic components, hence the relay must respond to the average value only and not to the harmonics.

INSTANTANEOUS CURRENT RELAYS

The instantaneous current relay is commonly used in high set overcurrent protection schemes and in differential schemes. Electromagnetic types develop an operating torque proportioned to I^2 and may be of the d.c. or a.c. pattern. In the case of d.c. relays, operation is dependent on the average value of current while a.c. relays operate on the r.m.s. value.

Relay setting is based on the r.m.s. value of fault current and therefore if I is the steady-state r.m.s. value of fault current, the r.m.s. value of a fully offset wave is $\sqrt{3}I$. Hence, the relay will be operated for a fully offset fault current whose steady-state r.m.s. value is 58% of the relay setting. This is not of importance in balanced schemes, but in high-set, o/c schemes the protection overreaches and for example, could look through a transformer beyond the l.v. bus, causing the loss of the supply point for an l.v. system fault.

High-set overcurrent relays are used instead of distance relays in situations where the fault level is reasonably constant, provided these relays have low transient overreach. The following table illustrates the amount of feeder that can be instantaneously protected with relays having transient overreach factors of 5%, 25%, and 50%, respectively, without danger of the relays operating for fully offset faults on the low voltage side of a transformer. The figures have been calculated for various ratios of steady-state r.m.s. fault current levels for faults at the beginning and end of the feeder. In this the significant fact is shown that a wider variation in fault level at the high voltage busbars can be tolerated with low transient overreach relays.

The effect of filtering the offset components from the current waveform is bound to introduce some time delay. Therefore, these relays are about 20 m. sec. slower than the untuned relay.