A SURVEY ON THE EFFECT OF TRANSIENT BEHAVIOUR OF CURRENT 888TRANSFORMERS ON HIGH SPEED DISTANCE RELAYS

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ABSTRACT

Current transformers and voltage transformers play an important part in the operation of modern power system. They provide the link over which information is derived from the main high voltage network for the purpose of measurement control, and protection. Measurements and control are generally concerned with the steady state conditions, while high speed protective relays are concerned with the transient conditions.The performance of current transformers and voltage transformers is therefore of considerable importance to protective gear particularly under power system fault conditions. The subject of the transient response of current transformers is therefore dealt with in the present study, with particular reference to its effect on high speed distance relays. The transient behaviour of the conventional iron cored current transformer and air-gaped current transformer has been considered. Moreover, the effect of current transformer saturation on the performance of high speed distance relays is presented. On the other hand, corrective measures have been considered to overcome the errors caused by the poor transient response of current transformers affecting the distance relay performance either external to and/or with the relay circuitry.

INTRODUCTION

The dynamic performance of high-speed protective relays depends to a large extent on the overall transient response of the associated measuring transformer. These, in turn, are affected by the nature and severity degree of the fault generated phenomenon in the primary power system.

It is therefore of utmost importance for system planners and protection engineers to make a safe assessment of the behaviour of protective relays and associated measuring transformers, in order to obtain the required power system reliability and availability under fault conditions.

Going by the principle of "worst case" analysis and piling up the most severe service and fault conditions results generally in heavy over-dimensioning and or extreme accuracy requirements on the instrument transformers and protective relays with the subsequent economical impact of the installation.

It is with this background that this study has been prepared and it is hoped that the work will promote a better understanding of the subject and help users as well as manufacturers to reach an optimum technical-economical compromise in the design and application of different protection schemes.

TRANSIENT PHENOMENA IN HV SYSTEMS

System faults or switching operations cause abrupt structural changes of HV power systems implying a redistribution of the electric and magnetic energies stored in the capacitive and reactive network elements. Due to the physical nature of these elements, the system has to pass through a transient state to reach its new steady state. This gives rise to current and voltage transients which can be classified as follows:

- Ultrafast transients involving essentially only the transmission lines. They are electromagnetic waves, travelling along the lines with almost the speed of light, giving rise to reflected waves at the line termination.

Application of travelling wave theories is necessary to analyse these phenomena.

- Fast transients featuring oscillations energized in resonant circuits formed by the L,R,C network elements in the respective combination, The frequencies of these oscillations reach from audio frequency in recovery voltage to subsynchronous oscillations and d.c. components in short-circuit currents. This type of transient can be analysed using lumped system parameters.
- Slow transients like electromechanical oscillations of synchronous machine rotors causing power swings. These transients cause torsional stresses on rotor shafts and endanger system stability. Concerning the transient behaviour of protective relays, the latter transients can be assumed as quasi-stationary and are, therefore, not considered further in this study.

In order to assess the amplitudes and the frequencies or time constants of the transients, it is necessary to consider structural changes of the HV power systems caused by fault inception, fault clearance and normal switching operations.

Fault inception

The transient process after fault inception can be divided into two different phenomena:

Discharge of the faulted phases (s) through a high frequency travelling wave oscillation.

The current and voltage, on a transmission line with distributed parameters, as a function of time shall be described by the following equations. The solution for the lossless line delivers the voltage and current state on the line as superposition of a forward (u_f,i_f) and a backward travelling wave (u_b,i_b).

$$u = u(x,t) = F_f(x-v.t) + F_b(x+v.t) = u_f + u_b$$

$$i = i(x,t) = \frac{1}{Z_c}\,[F_f(x-v.t)-F_b(x+v.t))] = \frac{1}{Z_c}\,(u_f-u_b)$$

where F_f and F_b are arbitrary functions in time which are defined by the boundary conditions, and

$v = \sqrt{(1/LC)}$ speed of propagation

$Z_c = \sqrt{(L/C)}$ characteristic line impedance

At the moment of fault inception, the voltage collapses at the fault point and travelling waves propagate in both directions along the line. The amplitudes of the step surge can be calculated from the above wave equations:

$$u_f = u_b = -\frac{Z_c}{2R_f+Z_c}\,U \sin\lambda \; ; \; i_f = -i_b = \frac{1}{2R_f+Z_c}\,U \sin\lambda$$

where U is the peak line voltage at the fault point, R_F= the fault resistance and λ the angle of fault inception.

For a soild short-circuit and fault inception at the peak of the sinusoidal voltage we get the maximum step surges.

$$u_{f\,max} = u_{b\,max} = -U; \; i_{f\,max} = -\,i_{b\,max} = \frac{U}{Z_c}$$

After t=T=x/v seconds, the travelling wave arrives at a station and is reflected as it hits the network discontinuity there.

The reflection factor depends on the ratio of the discontinuity. If the surge impedance of the source (Z_{cs}) is small compared to the surge impedance of the line (Z_c), then the line can be considered as closed on both sides and the step wave has only to travel once to and from location. If Z_{cs} is high compared to Z_c, then the step wave has to travel four times along the line to complete one cycle.

The transient oscillation has one dominant frequency component with superimposed harmonics. The dominant frequency is inversely proportional to the line length (L') and increases with decreasing source impedance. It is in the range of

$$f = \frac{V}{4L'} \;\ldots\ldots\ldots\ldots\; \frac{V}{2L'} \qquad [5]$$

In the positive sequence system v is nearly speed-of-light ($c=3x10^5$ km/sec) while it is about 0.7 times speed-of-light in the zero sequence system. For practical line lengths the dominant frequency range is from about 150 Hz for very long lines to some ten kHz for short lines.

The value of the voltage oscillation can be as high as rated voltage and can therefore considerably exceed the quasi-stationary short-circuit voltage at weak infeed terminals.

Time constants have been calculated for the dominant frequency component of 50 to 100 msec with phase-to-phase faults and about 3 to 20 msec with phase-to-earth faults for line lengths of 50 to 300 km [18].

Series capacitors and line reactors have little influence on the travelling wave induced oscillation because they act as short-circuit and open circuit respectively for the high frequency wave. With increasing complexity of the network we get a larger number of branches for the travelling waves and a larger number of reflection points. In this case we can no more speak of only one dominant frequency. Frequencies in the range of 2-5 Hz have been found to be most significant [18].

Transient oscillations in the short-circuit loop

Neglecting the effects of shunt capacitance and conductance, the short-circuit loop consists normally of the line inductance and resistance (L_L, R_L) in series with the source inductance and resistance (L_s, R_s). In L, R circuits the transient is the well known exponentially decaying d.c. component. Assuming a sinusoidal electro-motive force, the short-circuit current and voltage are fully described by the following equations:

$$i(t) = \frac{E}{Z}\left[\sin(\omega t + \lambda - \varphi) - \sin(\lambda - \varphi)e^{-t/T}\right]$$

$$u(t) = \frac{E}{Z}\left[Z_L \sin(\omega t + \lambda + \varphi_L - \varphi) - L_L\left(\frac{1}{T} - \frac{1}{T_L}\right)\sin(\lambda - \varphi)e^{-t/T}\right]$$

where:

$$Z = Z_s + Z_L = (R_s + R_L) + j\omega(L_s + L_L) = R + j\omega L$$

$$T = \frac{L}{R},\ T_L = \frac{L_L}{R_L},\ \varphi = \text{arc tg}\,\frac{wL}{R}$$

$$\varphi_L = \text{arc tg}\,\frac{wL_L}{R_L}$$

λ = angle of fault inception

The d.c. component has its maximum, when $\lambda = \varphi \pm \pi/2$ which for mainly inductive circuits corresponds to a fault occurring near the voltage zero-crossing, a condition normally referred to as fully offset short circuit current. The d.c. transient disappears if $\lambda = \varphi$, i.e. when the fault occurs near the peak of the sinusoidal voltage.

In general, the short-circuit voltage u(t) contains also a d.c. component. Only in the case of a homogeneous system where the source and line circuits have the same time constants, u(t) will be free of the transient for all fault incidence angles.

More than one exponentially decaying transient can appear in the short-circuit current when sources with different time constants feed into the short-circuit.

Network time constants can be as high as 200 to 300 msec in EHV systems, and in rare cases up to 400 msec near large power plants. However, the information received from the 23 member countries of CIGRE Committee 34 indicates that the majority of average values for the primary line constant for metallic faults lie in the range of 10-100 msec [12].

Further, field observations show that a fully offset short-circuit current has a quite low statistical probability and that a maximum figure of 50 percent offset would appear to be more realistic [12].

In networks with series capacitors the short-circuit loop consists of an L-C-R circuit. Therefore, instead of a d.c. component, the transient here is a subsynchronous damped oscillations which cause the characteristic slow build-up of the fault current amplitude. This component is present independent of the moment of fault inception [18].

In practice, the lowest frequency of the subsynchronous oscillations approximate 50 percent of system operating frequency with amplitudes of 100 percent and higher of the fundamental frequency. Values of 0.1 to 0.2 seconds have been reported for the time constant of the damped oscillation [18].

The short-circuit voltage may experience an abrupt phase shift by nearly 180 degrees and a voltage jump if the fault occurs behind the series capacitor and the protective gaps of the capacitors have not flashed over. When the gaps flash over, a few milliseconds after fault inception another phase and voltage jump appears. This results in heavily distorted voltage wave forms during the first 5 to 20 milliseconds after fault inception. The subsynchronous oscillations contained in the short-circuit current, if the gaps do not flash over, are integrated by the series capacitor and are therefore also contained in the short-circuit voltage.

Sequential flash-over of series capacitors' protective gaps causes phase unsymmetries which result in oscillations in the zero sequence system.

Fault Clearance

During the short-circuit the shunt capacities of the faulted phases are partly or completely discharged.

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When the faulted circuit is separated from the network, the shunt capacitances of the healthy part have to be recharged. As the breakers will interrupt the short-circuit current at its zero-crossing, the system voltage will be near the peak value, thus accentuating the recovery voltage transients. The peak voltage of the transient depends on the source parameters and on the distance to the fault; the frequency is in the order of some 100 Hz to some kHz. In complex networks there can be several resonant points so that the recovery voltage transients will contain also more than one frequency.

Overvoltage appearing after fault clearance can under certain conditions give rise to ferroresonant oscillations. Such oscillations can appear in network configurations where a non-linear reactance is in series or in parallel resonance with a capacitance. Non-linear reactances are power transformers, shunt reactors or potential transformers. These elements can interact with line shunt capacitances or series capacitors. Typical ferroresonance occurs between transformer magnetizing reactance and line shunt capacitance in isolated network parts.

The oscillation can be excited by an overvoltage or trapped voltage after fault clearance or can be continuously fed through the coupling capacity of a parallel line. Accordingly, the oscillation is damped or sustained. The frequencies can be harmonic or subharmonic, depending on the resonant circuit parameters.

Very high currents can flow and the voltage drop across the capacitive and reactive network elements can exceed the system driving voltage.

Normal Switching Operations

Switching operations in HV networks are normally controlled to avoid larger synchronizing power transients. However, voltage and current transients are induced when power transformers or lines are switched in or out.

The well-known inrush current appears when a power transformer is energized. This current contains a large d.c. component and a characteristic second harmonic. The harmonic content depends on the width of the base of the current wave, with typical values of 20 percent second harmonic and 8 percent third harmonic.

The amplitude of the power transformer inrush current is in the order of the short-circuit current and the attenuation time constant is in the range of seconds for large transformer banks.

When a line or a cable is switched, a charging oscillation is induced. If the line is charged through a low source impedance, the frequency of the oscillation will correspond to the natural frequency of the line. The maximum amplitude of the oscillation appears when the line is switched in at the peak of the sinusoidal source voltage. Thus:

$$U_{max} = U_{source};\ i_{max} = \frac{U_{source}}{Z_c},\quad f = \frac{v}{2L}$$

If the line is charged through a high source impedance, the charging circuit consists of a resonance circuit built up by the source reactance and the line or cable shunt capacitance. The maximum values of the oscillation can therefore be calculated by the following formulae:

$$U_{max} = U_{source};\ i_{max} = \frac{U_{source}}{\sqrt{L/C}}$$

$$f = \frac{1}{2\pi\sqrt{L.C}}$$

where L = inductance of the source

C = lumped shunt capacitance of the line or cable

The frequencies are in the order of some hundred Hz to some kHz.

Considerable transient oscillations and ferroresonance can occur when resonant circuits are switched, e.g. a transformer connected to a cable or overhead line.

Of particular interest are transients in the zero sequence system, because sensitive earth-fault relays can be endangered. Such transients are induced due to unequal pole closing or opening times of the circuit breakers.

TRANSIENT RESPONSE OF INSTRUMENT TRANSFORMERS

The classical instrument transformers are normally designed to accomplish the correct transformation of the power frequency component between limits given by their accuracy class. Outside of this range, it is not possible from the indications found on their name plate to assume how they would behave under conditions accompanying a disturbance in the power system.

However, for Capacitor Voltage Transformer IEC standards impose additional requirements in case of a sudden change of primary voltage. Furthermore, standardization work is under way for Current Transformers, taking into account the exponential component existing in the short-circuit current [3].

Immediately after fault inception or suppression, currents and voltages in the power system are heavily perturbed. Besides the component at fundamental frequency, a number of terms with a non negligible amplitude are present, going from the so called d.c. component (in fact a combination of exponential terms) through harmonics of the fundamental frequency up to higher frequencies related to the line capacitance and inductances.

Computer calculation and some measurements have shown that the measuring errors of instrument transformers are relatively small in a frequency range of about [3]:

1 Hz to a few thousand Hz for current transformers.

1 Hz to several hundred Hz for inductive voltage transformers.

20 Hz to few hundred Hz for capacitor voltage transformers.

However, the values of the components and the design characteristics, especially the stray capacitances as well the losses in the circuit have large influence on the mentioned frequency range, because they determine mostly the frequency values for the maximum and minimum of the measuring errors as well as the amplitudes of those errors, that means the importance of the voltage or current errors and phase displacements.

Unfortunately, up to now it was not possible to perform measurements at high voltage, corresponding to those appearing under real service conditions and it was therefore not possible to determine the influence of the voltage, both on the inductance and on the iron losses of the components. On the other hand, variation of the inductance and loss values due to saturation of the iron cores was neglected because it is very unlikely that the frequency and amplitude of network transients may cause such saturation, except for current transformers.

Current Measurement

The design and the performance of current transformers are influenced by a number of factors, particularly the steady-state amplitude if the maximum symmetrical short-circuit current that, for a given burden, must be faithfully reproduced on the secondary side, while the major transient quantity of concern is the exponentially decaying d.c. component of the primary current. Its presence is well known to be one of the main factors influencing building-up of core flux, a phenomenon which is likely to cause errors. In the general case the flux is composed of an alternating part and of a unidirectional part caused by the primary fault current a.c. and d.c. components respectively. The relative magnitude of the flux components is a function of the primary and the secondary time constants, the time constant of the total burden and the relative value of magnetizing inductance as compared to the total burden inductance and resistance. However, the transient flux created by the d.c. component of the primary current can be quite large compared to the flux swing required by the a.c. component alone.

Because of its ferromagnetic character, a CT core may also retain unknown amount of flux. This remanent flux will either oppose or aid the build-up of core flux, depending on the relative polarities of the primary d.c. component and the remanent flux. Furthermore, after primary fault current interruption, because of stored magnetic energy, the CT produce unipolar decaying current and can have a high level of flux trapped in the core. This aspect must be considered when fast auto-reclose operations are foreseen.

A remanence factor (K_r) can be defined as the ratio between the remanent flux and the saturation flux.

Current transformers can be classified in three categories, depending on the transient performance requirements imposed on them, and their basic design.

The following categories are defined as follows:

Closed core current transformers (CCT)

This current transformer is able to reproduce both a.c. and d.c. components in the secondary circuit proportional to the primary fault current up to a limit, determined by the magnetization characteristics and defined by the knee-point voltage. Such CTs may have a relatively high remanence factor, for example $k_r = 0.8$.

When dimensioning a CCT, account must be taken to the unipolar part of the flux, if saturation is to be avoided, and a transient dimensioning factor can be defined as the ratio of total flux to a.c. flux. In other words, the CCT is an overdimensioned conventional CT.

For voltages above 100 KV, irrespective of system voltage, the majority of the values for the ratio between the primary symmetrical fault current (I_p) and the current transformer primary nominal rating (I_n) lie in the range 1 to 50.

The extreme values for the I_p/I_n ratio occur-as might be expected-under very close fault conditions and are 100 and 200 for the 380 -500 KV and 100 - 360 Kv respectively, indicating the possibility of a 2-4 times increase in the CT requirement, if extreme conditions are taken into account. The reported values for the highest primary time constant (T_p) at maximum I_p/I_n varied over a very wide range. To assess the results relative to CT specifications, the products $T_p x(I_p/I_n)$ and $(T_p)_{max} x\ I_p/I_n$ were computed and the results indicate that both products follow a similar pattern and the majority of values lie between limits of 0.5 and 5 seconds [15].

Independent of the field observation made on the probability of a fully offset fault current (see section 2.1.2), for CT specifications, 56 percent of the replies assumed a d.c. component value of 100 percent of the symmetrical a.c. fault current, while 22 percent assumed a value less than 100 percent. Little information was given on the reasons for the assumed d.c. levels.

It is clear that if the combined effects of the d.c. component of the fault current, the trapped flux at fast autoreclose and the remanent flux are to be taken into consideration, overdimensioning of the CT may become quite impractical in some cases, and saturation will therefore occur.

After saturation has been reached, the magnetizing current will increase rapidly and the secondary current will drop more or less rapidly.

The form of the distorted current depends very much on the design parameters of the CT and the total burden composition. Due to the complexity of the problem featuring the solution of non-linear equations, a simplified method assuming a resistive burden can be adopted in practice. It appears then that the secondary current after saturation consists merely of two terms: an exponential component decaying with the time constant of the saturated secondary circuit, and an almost periodic component, proportional to the first time derivative of the primary current.

Having entered the saturation region on one half-cycle, the core will come out of saturation during the following half-cycle, and will eventually re-enter the saturation region. This mechanism will be sustained until the unipolar flux component has decayed sufficiently to avoid saturation. The effects of the d.c. transient saturation on the closed core current transformer can be summed up to very substantial amplitude and phase errors. However, it should be observed that such a CT reproduces fairly accurately the primary current during short time intervals before it saturates.

Current Transformer With Anti-remanence Air Gap(AGCT)

This current transformer is able to reproduce within a specified accuracy, both the a.c. and d.c. component in the secondary circuit proportional to the instantaneous value of the primary fault current up to the accuracy limiting condition. Because a small air gap is introduced in the magnetic circuit, such a CT will have a low remanence factor (K_r not exceeding 0.1).

The general transient behaviour of this CT is similar to that of the closed core, CT, except for the fact that remanent flux has been considerably reduced, leading to a reduction in the total overdimensioning factor.

Air-gaped Current Transformer (ACT)

This current transformer is able to reproduce within a specified accuracy, the a.c. component in the secondary circuit proportional to the a.c. component of the primary fault current up to the accuracy limiting condition.

In other words, this is a CT that can be used in applications in which the accurate reproduction of the d.c. component of the primary fault current in the secondary circuit is of no interest.

Because a substantial air gap is introduced in the magnetic circuit, the remanence factor will approach zero and the CT will have a relatively small value of rated secondary circuit time constant (60 msec at 50 Hz).

This CT is not affected by the remanence, and does not saturate in the same manner as CCT and AGCT. But because the d.c. component of the primary fault current is not faithfully reproduced on the secondary side, transient amplitude and phase errors will emerge when comparing the primary and secondary currents. Such transient errors will subside once the primary d.c. component has decayed. On the other hand, due to the comparatively small secondary time constant of the circuit, even during steady state symmetrical conditions, the amplitude and phase errors of a ACT will be larger than for CCT or AGCT.

PRINCIPLES OF OPERATION OF HIGH-SPEED DISTANCE PROTECTION

Distance and directional comparison relays operate according to several different measuring principles as will be shown below. Each system has its own merits and drawbacks in that some favour dependability (ability of the protection to operate when necessary) and some favour security (ability of the protection not to cause unnecessary operation), particularly when errors arise in the measuring quantities because of poor transient response of measuring transformers.

Only static (electronic) designs will be considered in this study since many electro-magnetic designs can today hardly be classified as high speed (1/4 to 2 cycles operating time) and also because information processing in electronic circuits is different in nature and can be easily refined to suit particular requirements. Although particular reference is made to distance protection, it is felt that the methods of analysis and the conclusions outlined in this study may be applicable to a certain extent to other types of protection.

Fundamental protection design aspects

The selectivity of the distance protection (when set in an underreach mode) is determined by two cut-off points on the line. The first cutoff point corresponds to the measuring point and required a directional measurement which is based on locally available quantities. The second cut-off corresponds to the set reach along the line and requires therefore a coordinate transformation of the local quantities, to quantities valid at the set balance point along the line. This transformation of local quantities to remote-end quantities is usually obtained by using a built-in model (Z_r) of the transmission line, to simulate the reactive and active voltage drops caused by the current flowing in the line, and thus compensate locally measured voltage ($U_c = U - IZ_r$).

Compensated voltage and local quantities are then compared to determine if the fault is in the protected zone of the distance relay.

The analog signals that are generated in the circuits of a distance relay take part in the measurement process either according to an amplitude criterion or a phase angle criterion. Whether the one or the other method is used depends on the way in which the appropriate signals are derived and the kind of circuit elements used in the design. A general tendency seems, however, to indicate a preference to phase angle criteria, essentially because of the advent of suitable semiconductor elements and the relative ease to handle information in modern digital circuits.

Signal filtering is normally used to limit the bandwidth of the relay to a few KHZ, thus avoiding measuring errors due to high frequency interference and/or low frequency transients. The bandwidth limitation degree is normally a function of the type of noise that is to be avoided, the transient and steady state response of the filter circuit and the required operation time of the relay.

The limitation in performance comes therefore from a compromise between the transient and steady state response of the filters used for noise rejection and the overall accuracy that can be maintained in the signals. One advantage with non-integrated systems is that the criteria of operation may be reached without delay even if CT saturation occurs and the measuring signals does not last or maintain its shape for more than a fraction of a cycle.

In order to minimize the effects of noise in the measuring signals, either due to poor transient response of the instrument transformers or due to errors generated in analog processing, some relay designs feature a dynamic alteration of the criteria of operation. Such systems show no difference in static characteristics compared to fixed criterion systems, but their transient response is greatly enhanced. For example, when conditions of marginal operation are detected, the operating criterion is automatically changed, and a new restrictive criterion must also be satisfied before operation is allowed, unless the original criterion is satisfied at two consecutive half cycles.

MEASURES TO IMPROVE OVERALL TRANSIENT PERFORMANCE

Poor transient response of instrument transformers leads to errors in the input signals to the relay. This may in turn affect the operation of the protection. In the following, the effects of CT saturation transients on the response of distance relays will be examined and some corrective measures outlined.

Effect of CT Saturation [13]

Basically, CT saturation means that incorrect information is fed to the relay at least during parts of a cycle. If saturation is caused by the a.c. component of the primary current (steady state saturation), both half cycles will be affected. Saturation caused by the d.c. component of the primary current will affect the secondary current on half cycles of one polarity, leaving the half cycles of opposite polarity almost unaffected.

From a distance relaying point of view, CT saturation will affect several measurands: the current as well as any current derived quantity, and the compensated voltage $U_c = U - IZ_r$ that is necessary for the actual distance measurement. The effect of saturation on the shape of the current can be determined as a function of the primary current, CT parameters and secondary burden. An analysis of the shape of the compensated voltage U_c at CT saturation is much more complicated due to the presence of voltage U, and is also dependent on the relationship between the primary faulty loop impedance and the relay model impedance. Generally speaking, the net effect of CT saturation on the compensated voltage Ua_c will be a substaintial change in amplitude leading to irregular changes in polarity. Phase comparators fed with U_c as one input quantity will therefore sense false zero-crossings.

If the phase comparator is of integrating type, the false zero crossings in U_c may lead to a resultant signal not lasting for a sufficient time with respect to the integration time, thus delaying the operation of the protection for internal faults. If the phase comparator is of a pure non-integrating type, the fales zero crossings in U_c may lead to unnecessary operation for external fault beyond the set reach of the protection (assuming CT saturation would occur for remote and faults on short lines).

On the other hand, delays in operation for internal faults are less probable.

Corrective Measures

It is possible, to some degree, to offset the errors caused by the poor transient response of certain types of measuring transformers or the effect of power system transients by taking suitable corrective measures either external or within the relay circuitry.

Counteracting the Effect of CT saturation

Unfortunately, it is not possible by simple filtering techniques aiming at particular frequency components to restore the shape of the secondary current when saturation occurs. Advantage must therefore be taken of characteristic properties of the saturation phenomenon.

From a distance protection point of view, two approaches are possible:

a) The scheme may be designed such that it will refuse the incorrect information and wait for measurement until correct information is available. This approach implies that saturation must be detected somehow and that operation of the protection must be delayed. Depending on the nature of the operating criteria of the protection, the delay experienced may range from a half a cycle of power frequency for non-integrating systems to several cycles for integrating systems. In less sophisticated designs, the delay can be even longer and one may have to wait until saturation has subsided. Practical experience so far indicates that saturation detectors are seldom used in conjunction with relays.

b) The scheme may be designed such that it will accept all information (correct as well as incorrect) and use it for measurement. This approach implies that incorrect measurement may occur when incorrect information is presented to the relay. Two cases are possible: unnecessary operation for external fault (underreach) or missing operation on internal fault (overreach).

Depending on the nature of the operating criteria of the protection and the choice of measuring quantity, dependability or security will be favoured when saturation occurs. Practical experience so far indicates that this approach is more frequently taken by equipment designers.

Matching Relay Protection and Current Transformers

Although a protective scheme may, under indeal conditions, be quite secure and dependable, the transient response of the current transformers will ultimately affect either the security or the dependability of the system, or both. Relays of different operating principles may react in different manners when combined with a particular type of current transformer. It is therefore useful to introduce the concept of matching a relay protection having a particular principle, with a certain type of current transformer, in order to obtain a better overall technical performance during adverse transient conditions. In doing so, one may have to take into consideration the relevant power system parameters, the design characteristics of the current transformers and the protection, and decide whether security or dependability must be favoured if both cannot be obtained in the particular application.

Protective relaying experience shows that the concept of matching relays and current transformers has been practiced in several countries. Some utilities use CT's type CCT for busbar protection, type AGCT for transformer differential protection and ACT for distance protections which do not include an impedance replica, and prefer magnetic VT's for all applications.

CONCLUSIONS

The discussion illustrates clearly that exterme conditions can exist in terms of system parameters which, if imposed as design requirements, would have substantial economical impact on meassuring transformer designe. In the case of CT specification, a number of utilities appear to be accepting that saturation would occur under "worst case" conditions and are evenly divided between the result security and dependability aspects of the protection scheme. Others specify special relays and/or CT's to achieve the level of performamce required. Similar observation can be made relating to voltage transformers and protective relays.

It is clear, however, that there are several different approaches used in practice concerning coordination of a variety of high-speed protection relays with the overall trasient response of associated current transformers. When assessing the service experience of such a variety of overall protective systems, only 12 incorrect operations out of a total number of 52582 correct operations for both electromechanical and static distance relays have been positively identified as being due to poor transient performance of current transformers [12]. By comparison, incorrect operations due to other unspecified known causes amounted to almost 100 times this figure. Very few utilities have statistics available.

The above mentioned facts suggest that present design and coordination practices are quite suitable. Furthermore, the advant of new relaying schemes will, as they gain application, ease many of the problems associated with poor transient response of instrument transformers.

Very few utilities have comprehensive fault recording systems. Many of the oscillographs used do not have the frequency response necessary for analysing highspeed protection performance. This warrants the increased prospective use of permanent installations of digital recorders to monitor network faults and produce recordings which could be made accessible to a broader public and perhaps lead in the future to a standard form of testing.

REFERENCES

[1] Hamilton, F. L, and Ellis, N. S: "Performance of distance Relays". Reyrolle Review, 1956, 166, P. 14.

[2] Mathews. P., and Nellist, B.D, : "Transients in distance protection Relays", Proc. IEE, 1963, 110, (2), pp. 407-418.

[3] Power system protection Reference Manual Reyrolle protection, Edited by Denis Robertson 1982.

[4] Non-conventional current and voltage transformers CIGRE, Paris., 1980 study committe. No. 34 for protection.

[5] H.Glavitsch, E. Ruoss: Transient voltages caused by the operation of circuit breakers in High voltage systems. CIGRE 1968, Report 13.05.

[6] E. Ruoss, P. Djurdjevic: Network analysers for studying transient phenomena in high-voltage networks. Brown Boveri Review. 55 1968 (12) pp. 734-739.

[7] H. T. Johns, R.K. Aggarwal: Digital Simulation of Faulted E.H.V transmission lines with particular reference to very high speed protections Proc. IEE. 123. 1976 (4) pp. 353-359.

[8] H.P. Herlein, A. Unlauf, Current transformers with linearized protection cores, IEEE. Paper. No. 71 cp 1980 PWR.

[9] S.V.N. Sarma, Effect of load power factor on current transformer performance. Proc. Inst. Elec. Eng. (GB) Journal paper,vol. 118, No. 1, Jan 1971, pp. 139-142.

[10] E.E. Conner, R.GG. Greb, E.C. Wntz, Control of Residual filux in current transformers. IEEE Trans. Power Appar. & Systems (USA) Journal paper, Vol. Pas. 92, No.4, July-Aug. 73, pp. 1223-1233.

[11] Zero flux current transformer for accurate measurement of direct and alternating current, Holepost (Netherlands) Journal paper, Apr. 1977, pp. 11-15.

[12] M. Chamia, "Transient Behaviour of Instrument transformers and associated high speed distance and directional comparison protection" CIGRE paper 34-06, 1978.

[13] El-Bastawisi B. M., "Transient Behaviour of protective current transformers and their influence on the performance of distance Relatys" Ph.D. Thesis,

CA., U.S.A, 1984.
[14] El-bastawisi B.M., "Performance of high speed protective relays under power system transient conditions", CIGRE paper 34-40, Sept. 1976.
[15] Protective current transformers and circuits by P. Mathews, Chapman,& Hall 1956.
[16] Power System Protection, Static Relays by M.Rao. Book, Tata McGraw Hill Publishing Co., New Delhi, 1979.
[17] C. Russell Mason, "The art and Science of Protective Relaying", Book, John Willy and Sons, Chapman and Hall, 1956.
[18] A.R. Van, C. Warrington, "Protective Relays, Their Theory and Practice", Vol. 2, 1969, London, Chapman and Hall.