PERFORMANCE OF CURRENT TRANSFORMERS UNDER POWER SYSTEM TRANSIENT CONDITIONS

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ABSTRACT

This paper presents a method for analysing of the transient performance of the iron-cored protective current transformer under power system fault conditions. The d.c component in the primary transient current has been considered. On the other hand, the secondary transient current including d.c aperiodic component conveyed to the secondary side of the current transformer has been evaluated. Moreover, the transient magnetizing current has been formulated as a function of the power system and current transformer secondary time constants using simplified equivalent circuit parameters for the current transformer. However, the protection system performance in the presence of d.c offset transient in fault current will be affected to a great deal, since the current is the usual measured quantity for most of high speed protective relays. Later, the cause of transient spilled currents and the knowledge acquired in that sense has lead to the eleboration of relays securing optional operation. The object of the present paper is to emphasize the principles of the transient error of current transformers, to discuss the effects of this phenomenon on ordinary relays and to extend it such as to cover the restraining element of relays.

INTRODUCTION

Protective relays are fed from the secondary side of the current transformers. Under transient conditions in power system due to switching operations and system faults, the secondary currents of the protective current transformers were found to differ in wave shape from that of the primary currents.

The performance of protective relays under such transient conditions would thus be dependent on the mode of transient transformation of the fault currents in the power network.

Therefore, the transient secondary current as well as the magnetizing current variation in the current transformer under transient conditions will be studied in the present paper.

TRANSIENT PHENOMENON OF PRIMARY CURRENT [8,4]

When an e.m.f. sinusoidal waveform is applied to an inductive circuit, the current in given by:

$$i = \frac{E}{\sqrt{R^2 + \omega^2 L^2}} \left[\sin(\omega t + \theta - \alpha) + \sin(\alpha - \theta)\exp. - \frac{R}{L} t\right] \tag{1}$$

where:
- E = peak value of the e.m.f. of the system
- R = primary resistance of the system.
- L = primary inductance of the system.
- θ = initial phase angle, (determined by the instant of switching in the system on)

$$\alpha = \tan^{-1} \frac{\omega L}{R}$$

The first term of equation (1) respresents the alternating current of the steady state whereas the second is a transient quantity due to asymmetry.

It is the last term that produce a transient error in the output current when a current flows through the primary winding of a current transformer.

REPRESENTATION OF A CURRENT TRANSFORMER [4,1]

The current transformer is represented by the equivalent circuit as shown in Figure (1). The analysis of such a system when a current i, given by equation (1) flows through it, leads to a complex expression, the evaluation of which requires certain boundary conditions.

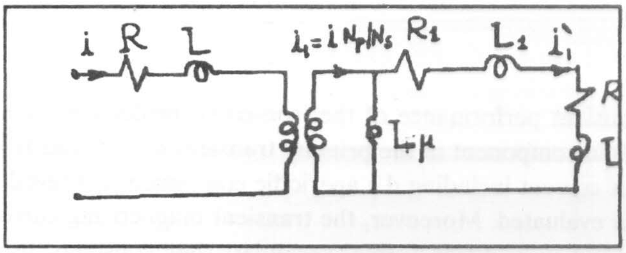

Figure 1. Equivalent circuit of the C.T. and its burden.

The solution is made easier in considering those conditions from the begining, these are:

1. The equivalent circuit corresponds to an ideal C.T., with a transformation ratio N_p/N_s, and supplying a secondary current i_1 given by:

$$i_1 = i\frac{N_p}{N_s} = \frac{E}{\sqrt{R^2 + \omega^2 L^2}} \frac{N_p}{N_s}$$

$$[\sin(\omega t + \theta - \alpha) + \sin(\alpha - \theta)\exp. - \frac{R}{L} t] \quad (2)$$

The current i_1 circulating in the secondary circuit comprising the shunt magnetizing admittance of the actual transformer, the the resistance and leakage inductance of the secondary winding R_1, L_1 and the resistance of inductance of the load R_2, L_2.

2. The maximal transient effect occurs when $\sin(\alpha - \theta) = 1$, this condition depends on the instant of closing the primary circuit and therefore no other condition has to be examined.

$$\frac{E}{\sqrt{R^2 + \omega^2 L^2}}$$

is the peak value of the primary steady state current

therefore equation (2) becomes;

$$i_1 = I_1 [\sin(\omega - \frac{\pi}{2}) + \exp. - \frac{R}{L} t] \quad (3)$$

3. In most C.Ts. used in the protection systems, the secondary leakage reactance ωL_1 is small (and even null in the case of ring type transformers having symmetrically distributed windings).

In cases where the present phenomenon holds, the load inductance L_2 is generally small, the load is many cases constituted only by the connections.

On the other hand, if this inductance is not big, its effect on the transient flux is of second order. Inductances L_1 and L_2 will therefore be neglected.

The above considerations allow to simplify the equivalent circuit in the manner indicated on Figure (2).

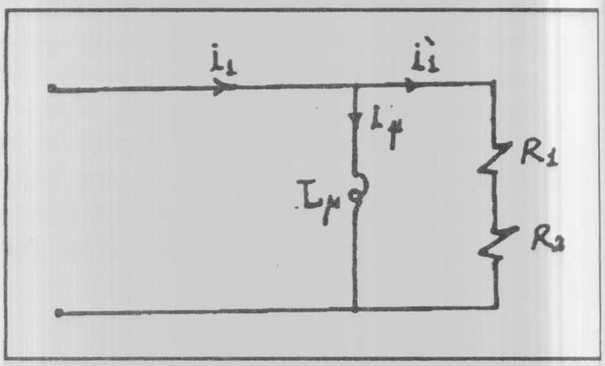

Figure 2. Simplified equivalent circuit of the C.T. and its burden.

In order to investigate the problem it is necessary to assume that the C.T. is completely linear, which is correct till the bend (Knee point) of the magnetising curve, but not further.

Anyway, in making this assumption, one can understand the problem in a way that allows observing the more general behaviour of the system.

The mathematical solution of the transient behaviour of a C.T. has been established by Warrington, Mathewes, and by Mason [15,8,7]. This thoey is exposed hereunder in order to give a useful context for evaluation of partial influences and repercussions or the relay's project.

SIMPLIFIED ANALYSIS [12]

Current transformer with infinite magnetizing inductance. We shall suppose, in the first place, that the C.T. does not absorb but a negligibile magnetizing current in comparison with the input i_1 in equation (3). Given that the circuit is completely, it is admissible to consider separately the two terms of the expression, the final results being superposed. The input current will be then divided into two components.

Stead state current $i_{1a} = I_1 \sin(\omega t - \frac{\pi}{2})$ (4)

Transient current $i_{1b} = I_1 \exp. - \frac{R}{L} t$ (5)

Given that the magnetising current is negligible, the currents i_{1a} and i_{lb} flow throgh the load resistance where $R' = R_1 + R_2$

The flux developed inside the C.T. to induce that current is given by:

$$\phi = \int_{t_1}^{t_2} \frac{R' i_1 10^8}{10^8 N_s} dt \quad \text{lines} \qquad (6)$$

Putting $k = \frac{10^8}{N_s}$, we obtain a flux corresponding to the symmetrical component of the current:

$$\phi_A = KR' I_1 \int_{t_1}^{t_2} \sin(\omega t - \frac{\pi}{2}) dt \qquad (7)$$

Integrating from $t_1 = \frac{\pi}{\omega}$ to $t_2 = \frac{3\pi}{2\omega}$, we obtain the peak flux:

$$\phi_A = - \frac{KR'I_1}{\omega} [\cos(\omega t - \frac{\pi}{2})]_{\pi/\omega}^{3\pi/2\omega} = \frac{KR'I_1}{\omega} \qquad (8)$$

Similarly for the transient component of the current we obtain:

$$\phi_B = KR' I_1 \int \exp. - \frac{R}{L} t \, dt \qquad (9)$$

Integrating from t = 0, , t = ∞, we obtain the maximum value of flux, assuming no remnant flux:

$$\phi_B = - \frac{KR'I_1L}{R} [\exp. - \frac{R}{L} t] = \frac{KR'I_1L}{R} \qquad (10)$$

Therefore the total maximum flux is $\phi = \phi_A + \phi_B$

$$\phi = \frac{KR'I_1}{\omega} + \frac{KR'I_1L}{R}$$

$$= \frac{KR'I_1}{\omega} (1 + \frac{\omega L}{R})$$

$$= \frac{KR'I_1}{\omega} (1 + \frac{X}{R}) \qquad (11)$$

The above result shows that the steady state flux $\frac{KR'I_1}{\omega}$ is multiplied by a factor $(1 + \frac{X}{R})$ during the transient period. This factor is therefore a criterion of seriousness of transient phenomena that could occur in C.Ts. connected to electrical power networks.

The transient factor $(1 + \frac{X}{R}) = (1 + 2\pi f \frac{L}{R})$

The term $\frac{L}{R}$ is known as the time constant of the primary transient state, and is designated by T. The transient factor is $1 + 2\pi fT$, with T in seconds, or $1 + 2\pi T'$ where, T' is the time constant in cycles of the primary e.m.f., this last form of the expression is useful for interpreting an oscillogram, the time constant being read directly in cycles, for instance, if the time constant of the system equal to three cycles corresponds to a transient 60 ms, then the transient factor = $(1 + 6\pi)$ = 19.85, i.e. the C.T. is asked to operate with a flux equal to approximately twenty times the maximal flux produced by the steady state current component, or when the d.c current component is zero.

The above theory is sufficient to give a general viewpoint on the problem.

In this simple conception, these has no inverse voltage (back e.m.f.) applied for demagnetising the transformer so that the flux will establish itself according to the curve of Fig. 3.

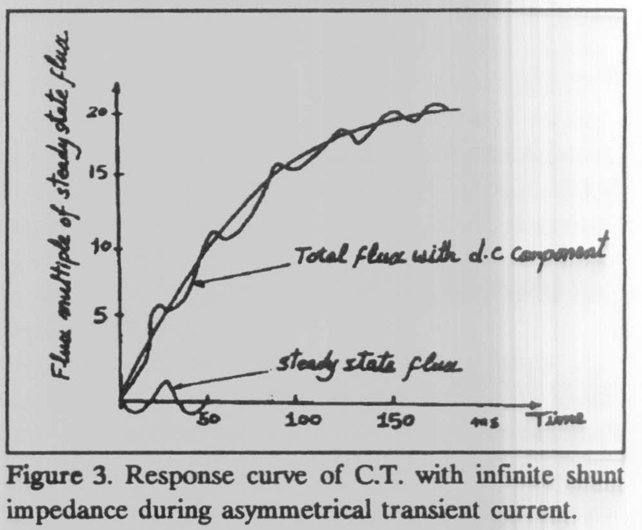

Figure 3. Response curve of C.T. with infinite shunt impedance during asymmetrical transient current.

Sinc a C.T. needs a finite magnetising current to maintain the flux, it will not remain magnetized for ever (neglecting hysterisis), and therefore a complete representation of the effects cannot be obtained unless we take into account the finite inductance of the transformer in our calculations.

TRANSIENT CURRENT APPLIED TO A C.T. OF FINITE INDUCTANCE

In the equivalent circuit of Fig. 2, we shall consider now that the magnetising inductance of the C.T.L_μ is finite, and that it is traversed by the component of current i_μ, let us suppose that the input secondary nominal current is i_1 as before, and that the output secondary current is i'. We have then:

$$i_1 = i_\mu + i'_1 \qquad (12)$$

In the same way:

$$L_\mu \frac{di_\mu}{dt} = R'i'_1 = R'(i_1 - i_\mu)$$

$$\text{therefore} \quad \frac{di_\mu}{dt} + \frac{R'i_\mu}{L_\mu} = \frac{R'i_1}{L_\mu} \qquad (13)$$

introducing for i_1 the steady state current of equation (2) we get:

$$\frac{di_{\mu a}}{dt} + \frac{Ri_{\mu a}}{L_\mu} = \frac{R'I_1}{L_\mu} \sin(\omega t + \theta - \alpha) \qquad (14)$$

from which

$$i_{\mu a} = \frac{I_1 R'}{\sqrt{R^2+\omega^2 L_\mu^{\,2}}} \left[\sin(\omega t+\theta-\alpha-\beta)+\sin(\alpha+\beta-\theta)\exp.-\frac{R}{'L_\mu}t\right] \qquad (15)$$

$$\text{where } \beta = \tan^{-1}\frac{\omega L_\mu}{R'}$$

Equation (15) is interesting, because it shows that there can be a transient component in $i_{\mu a}$ and hence in the flux which is proportinal to $i_{\mu a}$, even if there is no primary transient component, since it is only a symmetrical sine-wave that has been introduced for i_1.

The transient term is of maximum value when $\alpha + \beta - \theta = -\frac{\pi}{2}$, thus olmost doubling the amplitude at this value. In normal cases ωL_μ is much bigger than R', hence β is very nearly $\pi/2$ concluding that the doublage of flux occurs when $\alpha - \theta$ is approximately zero, and that this effect is small when $\alpha - \theta = \pi/2$.

The conditions are opposed to those controlling the transient component of the primary current, such that the maximum transient effect revealed by equation (15) never adds to the most serious primary transient effect.

When $\alpha\text{-}\theta = \pi/2$, the second term of equation (15) is of negligible value. Therefore substituting $\theta - \alpha = -\pi/2$ in equation (15) we obtain:

$$i_{\mu a} = \frac{R'I_1}{\sqrt{R^2+\omega^2 L_\mu^{\,2}}} \sin(\omega t - \frac{\pi}{2} - \beta) \qquad (16)$$

TRANSIENT TERM OF PRIMARY CURRENT: (d.c. Component)

Substituting for i_1, in equation (13), the transient component of equation (2), we get:

$$\frac{di_{\mu b}}{dt} + \frac{R'i_b}{L_\mu} = \frac{R'I_1}{L_\mu}\sin(\alpha\text{-}\theta)\exp.-\frac{R}{L}t$$

and putting $\alpha\text{-}\theta = \pi/2$ as supposed above we have:

$$\frac{di_{\mu b}}{dt} + \frac{Ri_{\mu b}}{L_\mu} = \frac{R'I_1}{L_\mu}\exp.-\frac{R}{L}t \qquad (17)$$

hence

$$i_{\mu b} = \frac{I_1 R'L\left(e^{-\frac{R'}{L_\mu}t} - e^{-\frac{R}{L}t}\right)}{RL_\mu - R'L} \qquad (18)$$

If $T = \frac{L}{R}$ is the time constant of the primary circuit

$T_1 = \dfrac{L_\mu}{R}$, is the time constant of the secondary ircuit

hen the equation (18) will become

$$i_{\mu b} = \frac{I_1 R'L\,[e^{-t/T_1} - e^{-t/T}]}{RL_\mu - R'L} \qquad (19)$$

s represented in Figure (4) for typical values of T and T_1. n order to determine the maximum value of the d.c omponent of the magnetizing current, differentiate quation (19) with respect to time and equate to zero.

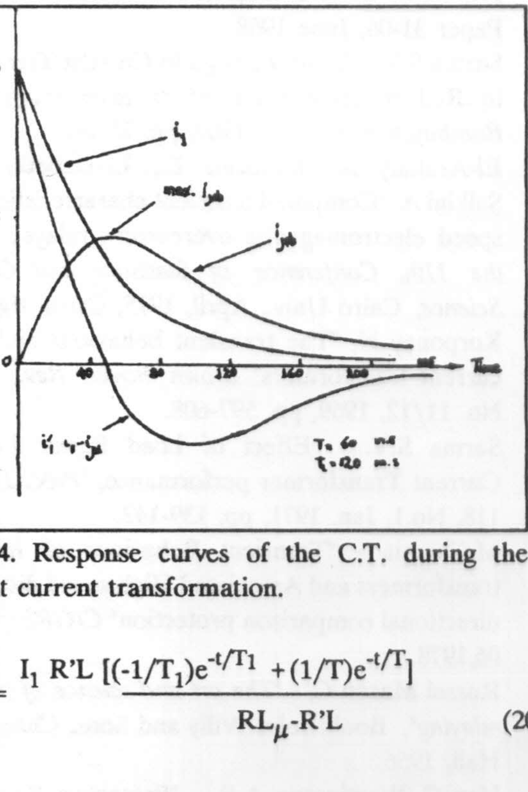

Figure 4. Response curves of the C.T. during the transient current transformation.

$$\frac{di_{\mu b}}{dt} = \frac{I_1 R'L\,[(-1/T_1)e^{-t/T_1} + (1/T)e^{-t/T}]}{RL_\mu - R'L} \qquad (20)$$

he time to reach this maximum value will be

$$t_{max} = \frac{T_1 T}{T_1 - T} \log_e \frac{T_1}{T} \qquad (21)$$

Substitute $t = t_{max}$ in equation (19) to get the maximum l.c component of the magnetizing current.

PRACTICAL CONDITIONS [3,4]

The preceding theory diverges from practice, taking into account the following:

1. We did not take into account the leakage inductance or the burden inductance. This inductance is generally small with respect to L_μ so that it exerts a negligible influence on the time constant of the secondary circuit and hence a small effect on the maximum transient flux.
2. We did not consider the iron losses. This results in reducing the secondary time constant, but unfortunately the value of the equivalent resistance is variable and depends at the same time on the sine-term and exponential term. Therefore we cannot include it in any linear theory and its expression is too complicated for enabling a satisfactory treatment.
3. The theory is based on the linear characteristic. This is true till the bend of the magnetizing curve but not at all beyond this point. A precise solution taking into consideration the non-linearity is not practicable, but the study of the linear theory allows as visualizing the problem for practical needs.
4. The effect of hysterisis, besides the losses discussed in paragraph 2, is not included in the theory. The hysterisis changes the inductance during the increasing and decreasing of the flux, such that the precise signification of the secondary time constant is a little obscure. However, the property pertaining to C.Ts. of having a residual magnetism, means that the value of ϕ_B developed in equation (10) must be considered as an addition of flux relative to any possible residual value, positive or negative.

The formula therefore is valid at the condition that the transient current applied does not produce saturation.

One can see that a precise calculation of the flux and magnetising current that could be established in each given case, is not realizable. The interest of this analysis resides only in the explanation of observed phenomena.

The asymmetrical (or continuous) component of current can be considered as a separate agent which establishes a mean value of flux, during a period of time corresponding to several cycles of the sinusoidal component, a period during which this last component produces an oscillation of flux about the variable mean level established by the asymmetrical component.

The asymmetric flux ceases to increase when the magnetising current is equal to the total asymmetric input currrent, since beyond that point, the output current, and therefore the voltage drop across the load resistance, are negative.

Due to saturation, the point at which the magnetising current equals the input current, corresponds to a level of flux lower than the one derived from the linear theory.

At the same time, the exponential component drives the transformer till saturation, the magnetising inductance becomes smaller and hence a big increase occurs in the sinusoidal magnetising current $i_{\mu a}$ Figure (5).

As mentioned above, the presence of residual flux makes the starting point of the excursion of the transient flux vary on the megnetising characteristic.

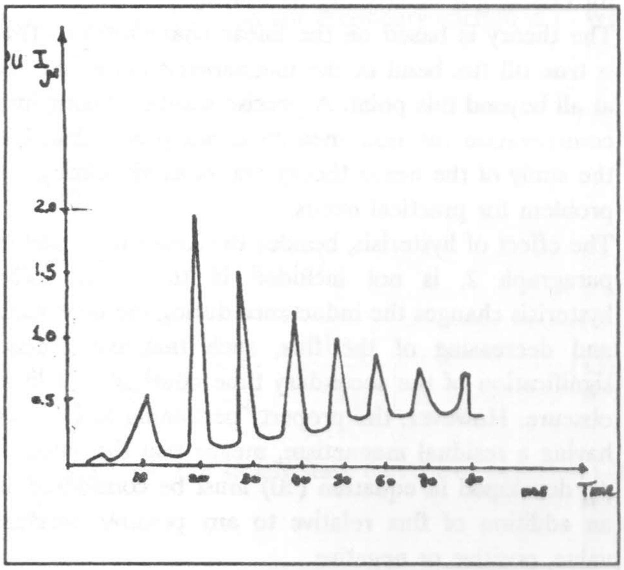

Figure 5. Typical curve of the magnetizing current of a C.T. with transient asymmetrical current.

The residual flux of same polarity of the transient flux shall reduce the value of the asymmetric current with given time constant (which can be transformed by the C.T.) without serious saturation, oppositely, the negative residual flux shall increase strongly the ability of the C.T. to transform the transient current.

CONCLUSION

From the given considerations in this study, it can be seen that they are of considerable importance in relation to high speed devices such as protective relays and instanteneous measuring instruments such as oscilloscopes.

The performance of current transformer subjected to transient conditions of faults on the primary system is therefore of considerable importance to protective gear, such as high speed electromagnetic, moving coil and static relays.

Since, the static protective relays are operating on the instanteneous values of the current and voltage, therefore the transient behaviour of the protective current transformers should be considered in case of designing and planning the protection of power system.

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