Accurate Method of Excitation Current and Relay Current Prediction during an Offset Fault at the Terminals of Power Transformer and Derivation of Saturated Relay Current

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Abstract: *This article describes a method of accurately predicting CT excitation current and relay current from first principles during a terminal fault of a power transformer including AC and DC components which are required for over design values of CT flux as well as the knee point values of the CT depending on the relay applications desired. It is known that the CT secondary current is an accurate replica of the primary fault current but the relay current depends on the CT excitation current drawn. In case the relay current is to be analytically predicted the excitation current also has to be predicted accurately whose value has to be subtracted from the total secondary current. This excitation current depends on the CT saturation level and can form a considerable portion of the CT secondary current depending on the CT saturation level. Therefore an accurate method of analysis of CT excitation and relay currents becomes important. This article recommends a method of accurately deriving the excitation and relay current from first principles as a function of time taking into account both the AC and DC components for purposes of CT design and relay applications.*

Keywords: Power Transformer, Excitation current, Relay current, CT saturation, CT Over design factor, Offset fault Current

Abbreviations

L – Inductance of CT excitation circuit
RCT – CT secondary resistance
RL – CT secondary lead resistance
Rb – Relay burden
Xm- Reactance of excitation circuit =ωL
R =(Rct + RL + Rb)
L/R = Time constant in seconds of CT secondary
L1/R1 – Fault circuit time constant (seconds) of network
Cos(phi) = (R1/.ωL1) of network
Phi = Acos(phi)
ω(Rad/sec)– Assumed as 314.159 (2x Phi X 50)
Isec – CT secondary current

1. Introduction

It is the purpose of this article to first split the total secondary time response current into its components, i.e, the excitation current and relay current before attempting to predict the relay response. It is necessary because the relay current depends on the saturation level of the CT. Assuming no CT saturation (ideal condition) the relay current will be an exact replica of the total secondary current because the excitation amps can be considered negligible under this condition. But assuming that the CT is fully saturated the relay current will be negligible and the CT excitation current will fully reflect the total secondary current. When the CT is partially saturated then the secondary total current will be shared between the excitation circuit and relay circuit depending on the level of saturation. Therefore the necessity arises to derive the exact level of both the currents from correct network equations before predicting the time response of relay depending on the applications. The following sections describe how to analytically first split the two components of current whether there is saturation or not from a knowledge of the fact that the total secondary current is an exact replica of the primary current.

Derivation of network equations

Figure 1 shows the CT circuit with its components of excitation current **(i(t))** and relay current **[I(t) – i(t)]** and total CT current **I(t)**

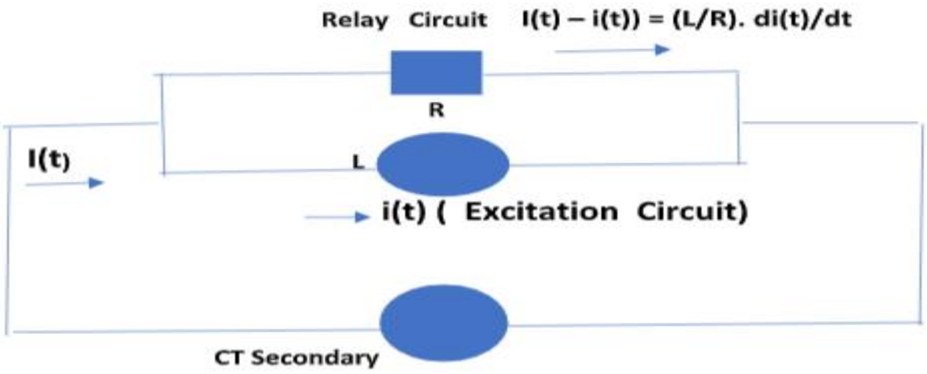

Figure 1

CT secondary amps as a function of time can be given as

$$\boldsymbol{I(t) = Isec\,peak.[(Sin(\omega t - phi) + Sin(\,phi).Exp(-(\tfrac{R1}{L1}).t)] \;----Ref\;(1)}$$

$$\boldsymbol{Now\;L.di(t)/dt \;=\; [\,I(t) - \;i(t)].R -\;(a)}$$

$$\boldsymbol{Hence\;I(t).R \;=\; i(t).R \;+\; L.di(t)/dt \;--(b)}$$

$$\boldsymbol{or\;I(t) \;=\; i(t) \;+\; (L/R\,).di(t)/dt - (\,c\,)}$$

$$\boldsymbol{(\,dividing\;(a)\;by\;R)}$$

Now following equations can be written down for the excitation circuit

$\boldsymbol{i(t) \;+\; (L/R).di(t)/dt \;=\; I(t)}$ -- (1)

Equation (1) can be rewritten as below

$\boldsymbol{di(t)/dt \;+\; (\,R/L).i(t) \;=\; R/L\,.I(t)}$ ----- (2)

OR in the differential operator form given by –[$\boldsymbol{D \;+\; (\,R/L)(i(t)] \;=\; R/L\,.I(t)}$

The solution of the above for **i(t)** for excitation current is given by

$\boldsymbol{i(t) = \left(\frac{R}{L}\right).Exp\left(-\left(\frac{R}{L}\right).t\right).\int Exp\left(\left(\frac{R}{L}\right).t\right).I(t).dt}$ -- (3)

Substituting for **I(t)** the solution for above equation (2) becomes

$$\boldsymbol{i(t) \;= (R/L).Exp(-(\tfrac{R}{L}).t).\int\; Exp(R/L.t).\left[Isec\,peak.\left(\left(Sin(\omega t - phi) + \right.\right.\right.}$$

$\boldsymbol{Sinphi.Exp{-}R1L1.t.dt}$ ---(4)

$$\boldsymbol{=\;(\,R/L)\,.Isec\,peak.[(1/\omega).(\,Cos(phi) - \;Cos\;(\omega t - phi)) + \;(\,Cos(phi)/\omega)\,.(\,Exp\,(\,(-\frac{R}{L})\,.t - 1)\,)\;+}$$

$$\boldsymbol{(R/(\omega^2.L).Sin(\omega t - \;phi)}$$

$$\boldsymbol{+\;(R/(\omega^2L).Sin(phi)\,.Exp\,(\,(-\frac{R}{L})\,.t)]\,/[1 + \;(R/\omega L)\,^2]}$$

$$\boldsymbol{+\;R/L\,.Isec\,peak\,.Sin(phi).\,[Exp\,(\,-\frac{R}{L})\,.t) - \;Exp\,(\,(-\frac{R1}{L1})\,.t)]/[R/L \;-\; R1/L1] \;----\;\;(5)}$$

Now the relay current as a function of time can be expressed as

Relay current =$[\boldsymbol{I(t)} \;-\; \boldsymbol{i(t)}]$--- (6)]

It must be remembered that the above are exact solutions and not an approximation of the solution.

Application example:

(Data for application example is taken is taken from an actual case from TEBODIN&PARTNERS LLC, MUSCAT, OMAN)

A fault is considered at the secondary of a 2000 Kva 11 Kv/433V power transformer with an RMS AC fault current value of 53336 amps. (Xt = 0.05 PU)

The other data are as below
CTR = 3200 /1A
RCT =9.9 ohms
RL = 0.2 Ohms
Rb = 0.2 ohms
R (Total CT secondary) = (9.9 + 0.2 + 0.2) = 10.3 ohmsXm(CT) =24000 ohms(Unsaturated) – assumed

X1/R1 of network = 7
R1/X1 of network = 1/7 = 0.1429 = Cos(phi)
Phi = ACos(phi)=ACos(0.1429) =1.4274 radians
Sin(phi) =0.9897
R1/L1 of network = 0.1429 x 314.159 = 44.88
Peak fault current of network = 53336 x2 x√0.5 =75428 amps
Isec peak = 75428 / CTR = 75428/3200 = 23.571 amps
X/R (CT unsaturated) = 24000 /10.3 = 2330.1
L/R (CT unsaturated) = 2330.1/314.159 = 7.4169 seconds
R/L (CT unsaturated) = 1/7.4169 = 0.13482

2. Results

The time response currents plotted in the following sections are derived usingthe formulas derived in equations 5 and 6 above

A) Unsaturated Condition of CT

Fig 2 represents the CT secondary total instantaneous plot of fault current which gives the AC component, DC offset current and total current when CT is unsaturated

Figure 3 gives the excitation component of current , AC Component, DC component and total component when CT is unsaturated. It can be seen that the excitation current and hence the flux(total) increases with time .Since the CT secondary flux is directly proportional to the current when CT is unsaturated, it has an AC component and a DC component as well during steady state. Hence its peak value during steady state is the maximum design value if the CT is to be maintained in an unsaturated condition. It can be expressed as a fraction of the peak AC flux as an over design value for unsaturated condition of CT. In the present example it works out to 8 as seen in the graph. It can be shown that this overdesign factor is equal to (1+X1/R1) of network as used in various references given at the end (Ref 3,6,7,8,9,10)

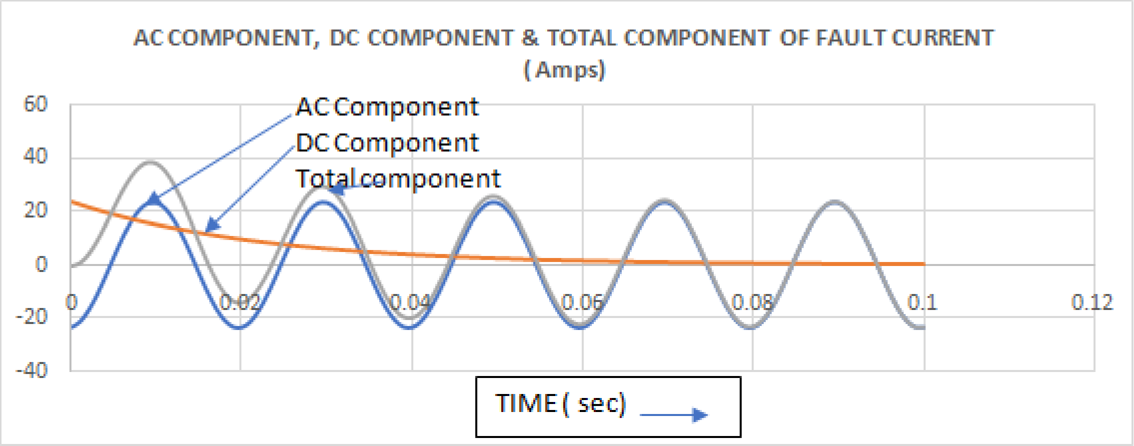

Figure 2: CT secondary fault currents un saturated

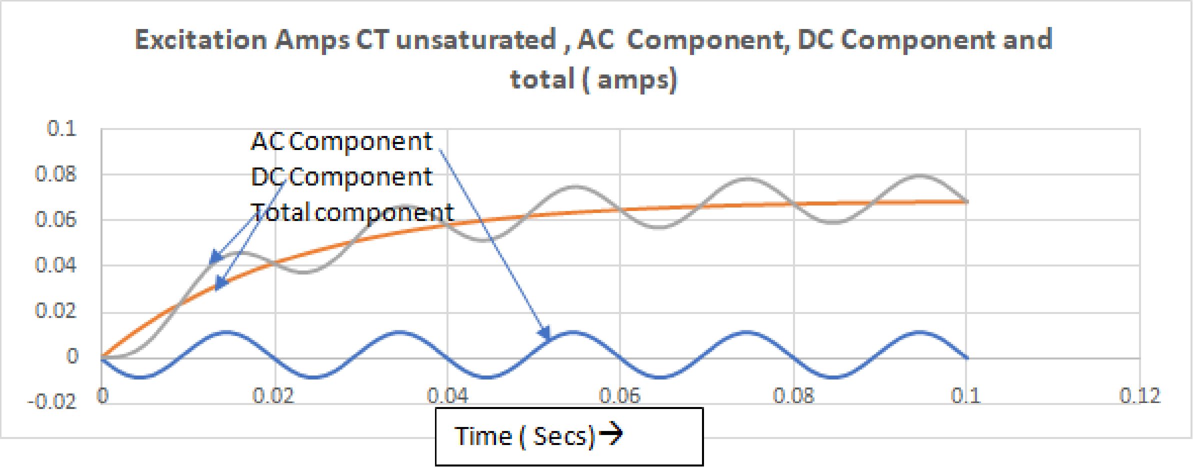

Figure 3

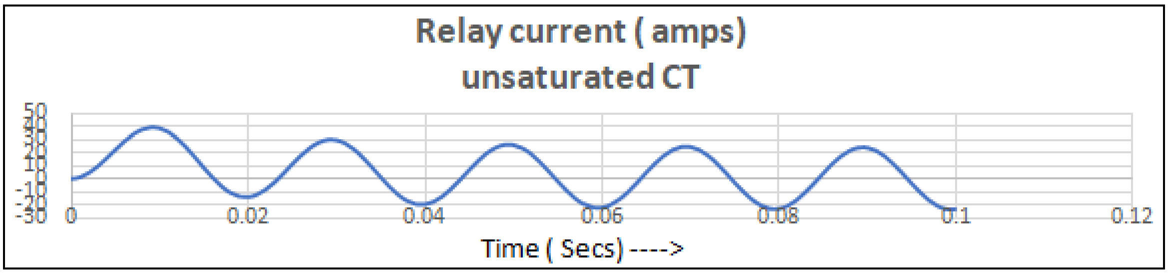

Figure 4

Observations when CT is unsaturated

A) Figure 4 gives the relay component of current when CT is unsaturated. It can be seen from above plots 3 and 4 that the excitation component of current is quite small when compared to the relay current when CT is unsaturated and almost the total secondary current passes through the relay.

How to Simulate Saturated Condition of CT

In the unsaturated condition of CT the excitation curve of CT is linear and the slope does not vary, which means that L/R (i.e., Xm) value of excitation circuit does not change. In the saturated region of excitation the excitation curve becomes more flat. Hence more the flatness more will be the saturation level. Therefore to simulate the saturation level as desired the Xm value of excitation circuit needs to be reduced accordingly to simulate the saturation level. This is the method which is adopted in this article in the following sections to study the relay current and response under saturated conditions of CT

B) Fully Saturated Condition of CT

Let us assume that the CT is designed only for the flux level demanded by the AC peak value and not overdesigned considering the DC component. It will then exhibit saturation and will accordingly get reflected in the excitation current and relay components of current. When more is the saturation level more will be the excitation component and less will be the relay component. If it is assumed that the CT is completely saturated all the secondary current will pass through the CT excitation circuit alone.

In our present example the L/R value of CT circuit is assumed to suddenly change from an unsaturated value of 7.417 seconds (Xm of CT circuit 24000 ohms) to a highly saturated value of 0.001545 seconds (5 ohms) suddenly for the purpose of simulation. (Actually speaking the L/R value of the CT secondary is a function of excitation current depending upon saturation level and not directly time dependent. When this modelling is used for saturation level into the general differential equation the time solutions for currents become very complicated and requires very involved numerical methods and not attempted in this report just for a simulation of saturation.

Figure 5 represents the response of excitation current in amps plotted in both the saturated condition and unsaturated condition of CT. It is clear that the excitation current in the CT saturated condition jumps to an almost full value of the CT secondary current as compared to the unsaturated condition when it is a negligible value. Therefore in the fully saturated condition the relay component of current will become a negligible value.

Figure 6displays the excitation amps under saturated condition (AC component, DC component and total value). It is seen that the DC component of excitation current becomes negligible as time advances since the CT secondary DC component also decays.

Figure 7 displays the relay current under both unsaturated and highly saturated conditions. It is clear that the relay current becomes a very low value under saturated condition of CT but the major component of CT secondary current forms part of excitation component as discussed under figure 5.

C) Partly saturated condition of CT (L/R value of 0.06108 sec, Xm1 value of 200 ohms)

Figure 8 depicts the relay Current response under this partly saturated condition when the AC component of relay current is returned just correctly matching with the unsaturated condition (both match).

Figure 9 depicts the excitation flux response under the partly saturated condition and it is found that the over sizing factor of CT to be considered is just about 5 which is much lower than the value of about 8 under the unsaturated condition . This becomes a more economical design of CT .

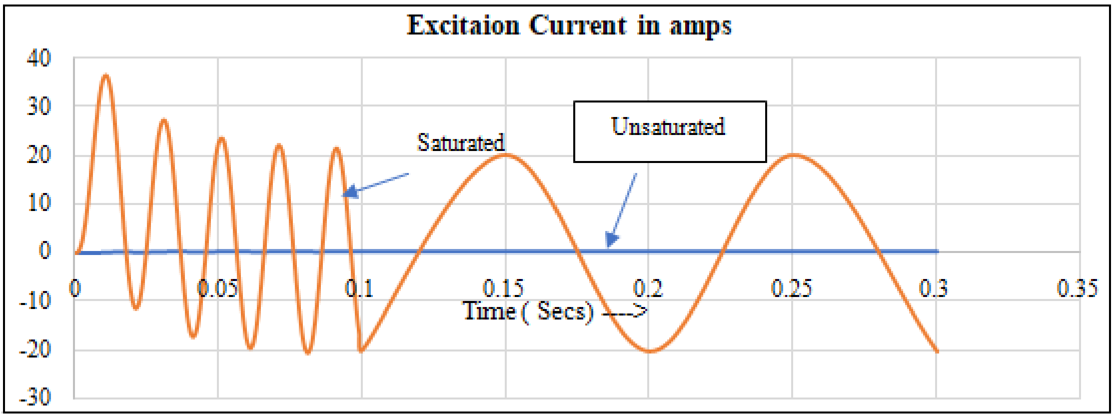

Figure 5

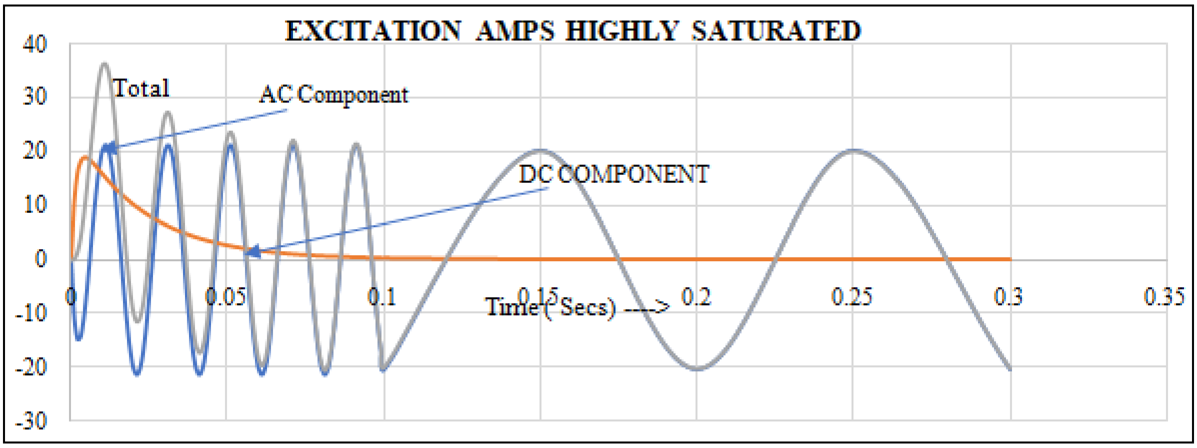

Figure 6

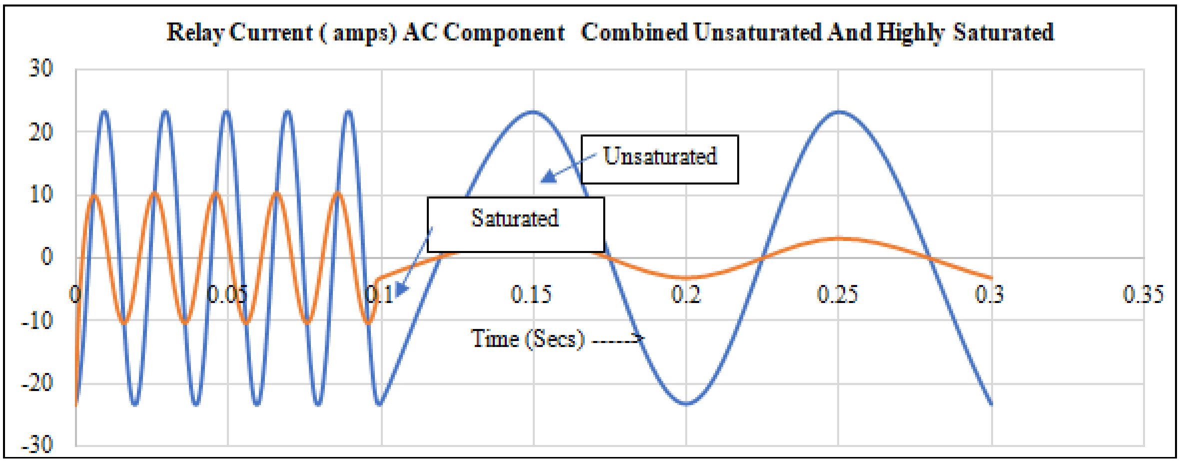

Figure 7

(Note: In the above simulation the Xm value is reduced suddenly just to simulate the saturated condition in this article, hence the relay current also reduces right from t=0 instead of gradually)

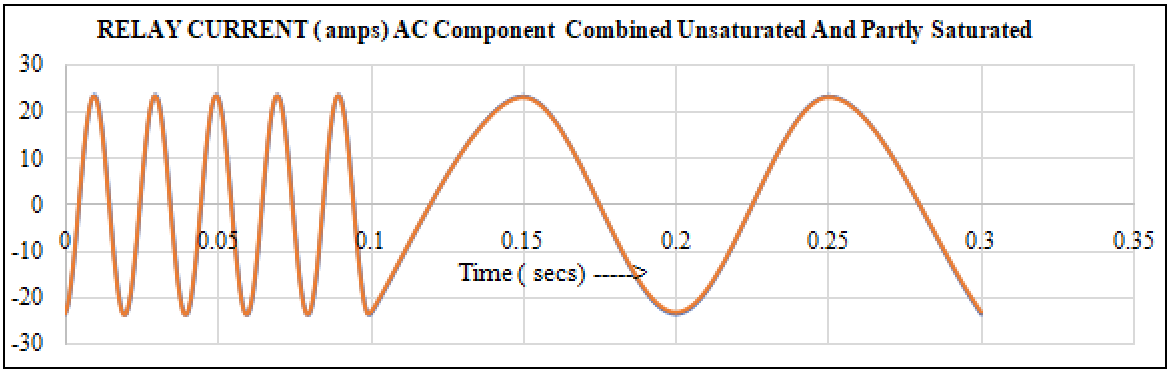

Figure 8

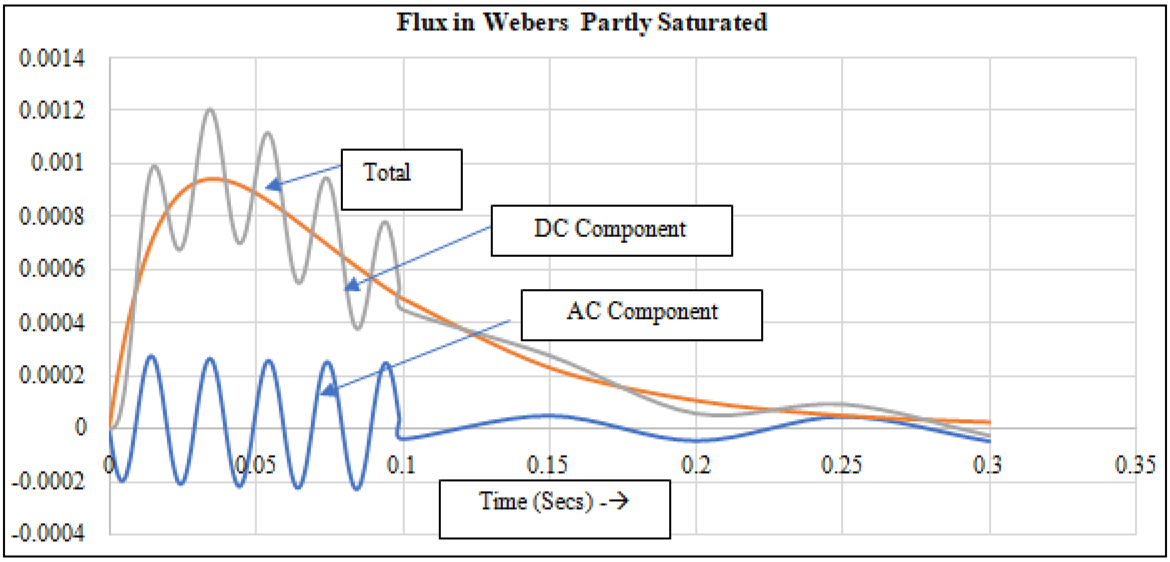

Figure 9

Considerations of relay response current and CT design for various relay applications

a) For IDMT applications

In the case of IDMT relays the relays have to respond after a certain time delay and hence the AC component has to be conveyed to the relay correctly without loss after that time to respond. It is therefore necessary for CTs to convey the replica of AC current only after this delay. If the CT returns a lower value of current at this time(as in fig7) the operating time of IDMT relay will get unduly higher which is not desirable. It can be said therefore that the L/R of the CT circuit can be reduced in such a way that a part CT saturation can be allowed and over sizing factor of the CT can be reduced to the extent that total unsaturation need not be made. This will allow economy in the selection of CT. It may be noted that the modern numerical relays automatically filter out the DC component and respond only to the AC component. Even otherwise during partial saturation the AC component can be conveyed even before the IDMT time delay is involved by suitably selecting the L/R value of the CT circuit. Hence the oversizing factor of CT is determined by the total excitation current as a function of the peak AC component of current at the time of IDMT response time with a suitable design margin after reducing the value of L/R of CT circuit. The application example will make this clear.

b) For instantaneous relay response applications

In the case of instantaneous relays the CTs have to deliver the proper AC value of current to the relay at and above the value of setting. In the case of transformer primary the relays normally are given a pick up setting is about 1.3 times the secondary reflected current. Hence at this value of setting the relays have to give an instantaneous response. The CTs feeding these relays at the HT side have to be so designed with a lower L/R value (and corresponding saturation value) so that the AC current is properly conveyed to the relays at the setting value. If due to over saturation the CTs return a lower than setting value of current to the relays the relays will fail to operate. In the case of transformer secondary relays the instantaneous pick up setting may be about 2 to 3 times the normal design current and hence the CT saturation has to be designed accordingly. It may be remembered that the over sizing factor is a function of total maximum flux and since the core flux is directly proportional to the excitation current, the excitation current derived by the exact formula above can be used as a factor for design.

c) Distance relay applications

In the case of CTs applied for distance relays the AC current has to be conveyed accurately for the first zone response instantaneously as well as at the delayed time for the 2nd zone. Since the measurement of V/I (impedance) is involved for relay response instantaneously in the first zone and with a time delay in the second zone the measurement of current is required(both magnitude and phase) accurately for these times. Normally the overdesign factor is specified by many relay manufacturers assuming no saturation for the CTs. Where the requirement of no saturation is specified the overdesign factor (1+X1/R1) (Ref 3, 6,7,8,9,10) may vary from a low value of 8 (transformer secondary relays) to a higher value of 20 or even higher for the distance relays. As can be seen from relay current response the AC current is conveyed correctly to the relay even when part saturation is considered in our example both in the first and normal second zone operating times and hence fully unsaturated condition of CTs is not required. In the present example of CT considered an over design factor of CT of about 4.5 is found acceptable corresponding to a part CT saturation (Xm value of 200) instead of a value of about 8 (i.e factor of (1+X1/R1)) corresponding to an unsaturated condition of CT. This overdesign factor of 4.5 is only about 0.56 times the value of 8 corresponding to the unsaturated condition. Alsthom (now GE) specifies an overdesign factor of only 0.6 corresponding to the fully unsaturated condition. Many manufacturers accept only an unsaturated value of overdesign factor (i.e., (1+X1/R1)) of CT for distance relay applications which may not be required. Hence the accurate CT excitation current response and relay current response helps evaluate these requirements for the specific applications instead of generalising the same.

In any case the Kpv value for any particular relay application varies with different manufacturers of the relays and must be followed and the procedure described in this paper illustrates only the general principles involvedin selecting the CTs for various applications.

3. Conclusions

This paper has described an exact method of analytically deriving the relationship for the CT excitation current and the relay current as a function of time from a knowledge of the fault current equation with maximum DC offset. An application example is chosen to plot a response of excitation current and relay current as a function of time. It is seen from the application example that the relay current goes from a maximum when the CT is unsaturated to a minimum when the CT is saturated almost fully. From knowledge of the relay current with the saturation behaviour of CTs the design criteria of CT can be arrived at for various relay applications.

4. Acknowledgement

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