Investigating Factors Affecting CT Saturation Using MATLAB

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***Abstract* – This paper focuses on a phenomenon known as "CT Saturation" which occurs when currents of too much amplitude passes through the CT. CT Saturation has a negative effect on the CT since it decreases its reliability.**
In addition, the paper will discuss factors that control the time at which saturation occurs including "Burden Impedance", "Transformer Ratio" and "Primary Impedance" as well as opening secondary winding of CT. These factors will be examined using MATLAB software. The results shows that the saturation of CT is affecting by Asymmetry Current ,Burden resistor ,turn ratio and (X/R) ratio on the CT saturation

***Index Terms*— Transformer; Saturation; Power system Current Transformers; protection element ; Protective relay.**

I. Introduction

Current transformer is important equipment for the power system protection component. Current transformers are commonly used for current metering and providing protection in high voltage systems.. Their main function is transforming the high current into a low current (1 or 5 A) adequate to be processed in measuring and protection equipment (such as relays and recorders) .They also isolate the measuring equipment from the high voltage of the monitored circuit. Figure 1 shows the equivalent circuit of CT including load impedance.[1,2]

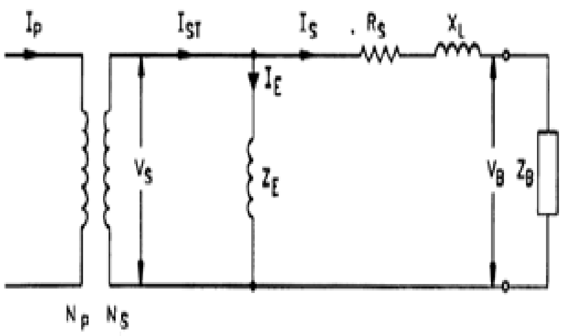


Figure 1Equavilent Circuit of CT

V_s : is the secondary exciting voltage .

V_B : is the CT terminal voltage across external burden.
I_P : is the primary current .
Z_E : is the exciting impedance .
I_{ST} : is the total secondary current .
R_S : is the secondary resistance.
I_S : is the secondary load current .
X_L : is the leakage reactance.
I_E : is the exciting current .
N_P: N_S is the CT turn ratio.
Z_B : is the burden impedance.

CT saturation describes the state in a CT when it is no longer able to reproduce an output current in proportion to its primary current or its ratio. The main cause of CT saturation is the property of the core that goes into magnetic saturation due to a number of reasons including large primary currents, high burden or an open circuit in the secondary [3] .

voltage Saturation: The saturation voltage (VX) is the symmetrical voltage across the secondary winding of the CT for which the peak induction just exceeds the saturation flux density where Vx is used to find the Saturation factor Ks which can be defined as the ratio of the saturation voltage to the excitation voltage and is an index of how close a CT is to saturation. It is used to calculate the time-to-saturate under transient conditions[3].

$$K_S = \frac{V_x}{V_s} \qquad (1)$$

II. Dynamic Characteristics

A. Nature of Fault current

Fault current contains a symmetrical ac component and a dc offset current . To understand the concept of Dc offset current, study a transmission line unloaded exited by an equivalent voltage source. The fault attacks a time t=0 . This can be happen by closing the switch at $t=t_1$ figure 2 shows that .

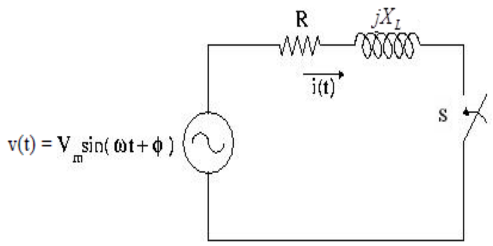


Figure 2 Transmission Line with Voltage Source

For the system of Figure (2) let the voltage source is given by $V(t) = V_m \mathrm{Sin}(\omega t + \emptyset)$

And $R + j\omega L$ or $Z < \theta$ is the line impedance. For simplicity assume that fault happened at $t = 0$. The instantaneous fault current value in the line at $t \geq 0$ is expressed by :

$$i(t) = \frac{V_m}{|Z|}\sin(\omega t + \theta - \emptyset) - \frac{V_m}{|Z|}\sin(\theta - \emptyset)e^{-(\frac{t}{\tau})} \quad (2)$$

where θ is the impedance angle of transmission line [4]. Figure 3 illustrates the wave form of fault current .

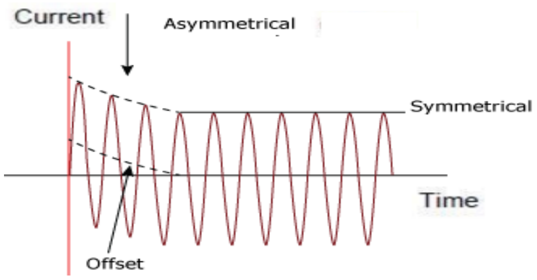


Figure 3 Fault Current with AC and DC Component Wave Form

B. *Effect of DC offset on CT saturation*

The DC offset can cause unacceptably high CT secondary currents which can saturate the CT core. To understand the effect of Dc offset consider an ideal CT excited by the dc offset current source as illustrated in Figure 4 . An ideal CT will faithfully replicate from primary current waveform on the secondary side.

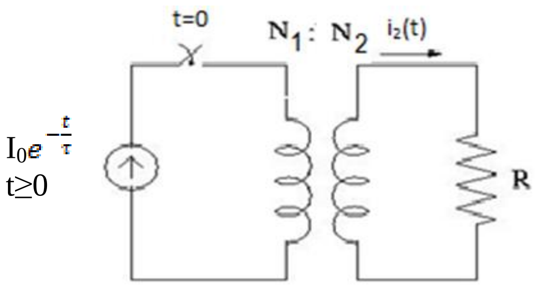


Figure 4 CT excited by The Dc Offset Current Source

Hence, the secondary current would be given by

$$i_2(t) = \frac{I_O}{N}e^{-\frac{t}{\tau}} \quad \text{where} \quad N = \frac{N1}{N2} \quad (3)$$

The voltage developed across CT secondary will be given by

$$v_2^{dc} = \frac{N_1 R I_0}{N_2}e^{\frac{-t}{\tau}} \quad (4)$$

Using faraday's law to compute the flux in the transformer core for simplicity assume the initial flux ϕ(0) in the transformer core at t=0 is zero.

$$v_2 = N_2\frac{d\emptyset}{dt} \quad (5)$$

Solving Equation 5 to find $\emptyset(t)$

$$\emptyset(t) - \emptyset(0) = \frac{1}{N_2}\int_0^t v_2\, dt$$

$$\emptyset(t) = \frac{N_1 R I_O}{{N_2}^2}\tau(1 - e^{-\frac{t}{\tau}}) \quad (6)$$

where. $\tau = \frac{L_{line}}{R_{line}}$ At $t \to \infty$ and $I_O = \frac{V_m}{Z_{line}}$

$$\emptyset_{dc}^{max}(t) = \frac{N_1 R V_m}{{N_2}^2|Z_{line}|}\tau \quad (7)$$

And the Dc flux waveform is shown in Figure (5)

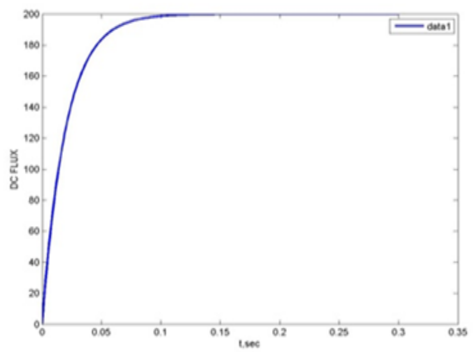


Figure 5 Dc Flux in the CT core

From equation (2) at the sinusoidal component The voltage developed across the CT secondary by the steady state is

$$V_2^{ac} = \frac{R V_m N_1}{|Z_{line}|N_2}\sin(\omega t + \theta - \emptyset) \quad (8)$$

The sinusoidal ac flux in the CT core can be obtained by substituting operator $\frac{d}{dt}$ by $j\dot{\omega}$ in equation (5). Hence:

$$\overline{\emptyset} = \frac{\overline{V_2}}{j\omega N_2}$$

$$\emptyset_{ac} = \frac{R V_m N_1}{\omega|Z_{line}|{N_2}^2}\sin(\omega t + \theta - \emptyset - \frac{\pi}{2}) \quad (9)$$

The peak value of ac flux is given by the following relationship:

$$\emptyset_{ac}{}^{max} = \frac{RV_m N_1}{\omega|Z_{line}|N_2{}^2} \qquad (10)$$

To find the instantaneous flux in the core Adding Equation (9),(10)

$$\emptyset_{ac}{}^{max} + \emptyset_{dc}{}^{max} = \frac{RV_m N_1}{\omega|Z_{line}|N_2{}^2} + \frac{N_1 R V_m}{N_2{}^2|Z_{line}|}\tau \qquad (11)$$

C. *CT over sizing Factor*

Typically, an efficient design of transformer would correspond to choosing the core cross section area such that $\emptyset_m^{ac}$ should be near the knee point of B - H curve. One obvious way of avoiding CT saturation on dc flux is by the summation of $(\emptyset_{ac}^{max} + \emptyset_{dc}^{max})$ to oversize the core, such that the corresponding B for the flux is below the knee-point[5].

Hence, the factor $\frac{\emptyset_{ac}^{max} + \emptyset_{dc}^{max}}{\emptyset_{dc}^{max}}$ is called Core-oversizing factor Which equal

$$1 + \frac{\emptyset_{dc}{}^{max}}{\emptyset_{ac}{}^{max}} = 1 + \frac{LI_O/N_2}{RI_O/\omega N_2} = 1 + \frac{\omega L}{R} = 1 + \frac{X}{R}$$

D. *Flux Change with Asymmetrical Primary Current*

The dc component of an asymmetrical current greatly increases the flux in the CT. When the dc offset is at a maximum, the CT flux can potentially increase to 1 + X/R times the flux resulting from the sinusoidal, or non-offset component, where X and R are the primary system reactance and resistance to the point of the fault.

E. *Effect Of Turn Ratio*

Turn ratio means the relation between the primary and the secondary of current transformer . The primary and secondary currents are stated as a ratio such as 200/5. With a 200/5 ratio CT, 200A flowing in the primary winding will outcome in 5A flowing in the secondary winding, delivered the correct rated burden is connected to the secondary winding. Increasing the turn’s ratio with the secondary will increase the accuracy and burden rating. However decreasing the turn’s ratio with the secondary will degrade the accuracy and burden rating.

F. *Time-to-saturation*

The time during which the secondary current is a faithful replica of the primary current [3].

$$T_S = -T_1 \ln\left(1 - \frac{V_x - I_S * R}{\omega T_1 (I_S * R)}\right) \qquad (12)$$

Where:

$R = R_S + R_B$

T_s : is the time-to-saturation

T_1 :is the primary system time constant

V_x: is the saturation

R_S :is the secondary winding resistance.

R_B :is the burden resistance[3,6].

G. *Minimizing the Effects of Current Transformer Saturation*

A general rule frequently used in relaying to minimize the CT saturation effects is to select a CT with AC voltage rating at least twice that required for the maximum steady-state symmetrical fault current.

Ways to avoid saturation :

- To avoid AC saturation, a CT should be capable of a secondary saturation voltage .$V_X > I_S * Z_S$ Where I_S is the primary current divided by the turns ratio, and Z_S is the total secondary burden $(R_S + X_L + Z_B)$ [7].
- To avoid saturation with a dc component in the primary wave and with pure resistive burden, the required (But ignoring effect of remanence saturation voltage is:

  $$V_X > I_S * Z_S(1 + \frac{X}{R}).$$

  Where X and R are the primary system reactance and resistance up to the point of fault.
- To avoid saturation under the worst case or scenario of pre magnetization (in the worst direction) which is the worst possible case, the required saturation voltage is :

$$V_X > \frac{I_S * Z_S(1 + \frac{X}{R} * \frac{R_S + R_B}{Z_S})}{1 - \text{remanence}(P.U)}$$

III. Simulation and Results

In order to investigate the factors that affecting CTs saturation, a network was designed in MATLAB/SIMULINK to simulate these parameters, and also to study the relationship between the flux, and the secondary current versus time to saturation, for several cases. The network under study is presented in Figure (6).

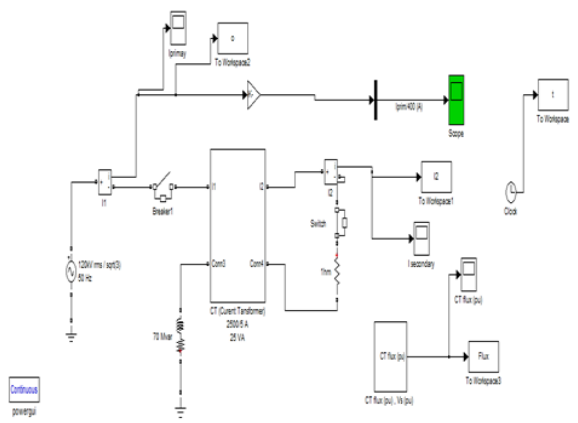


Figure 6 The Circuit Used In MATLAB Simulink of CT

A. *Effect of Burden*

In this test, the CT ratio is setting at 2500 : 5, the primary impedance is also setting at R =100 ohm and L = 1 H, while R load is setting to 4 and 14 ohm respectively.

Figure (7,8) Show the output of secondary current with different Burden resistances.

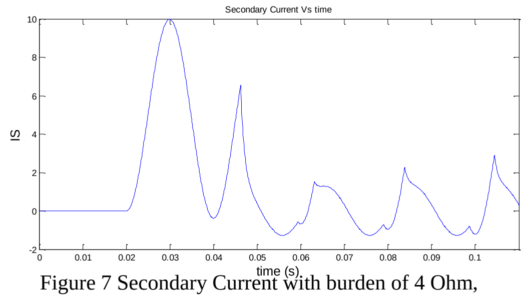


Figure 7 Secondary Current with burden of 4 Ohm,

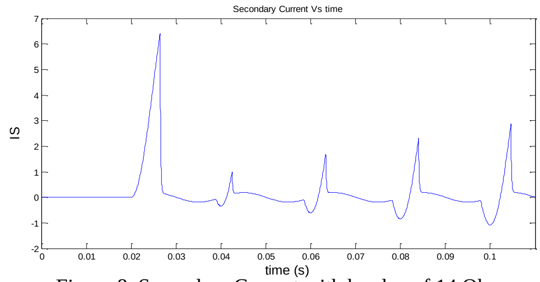
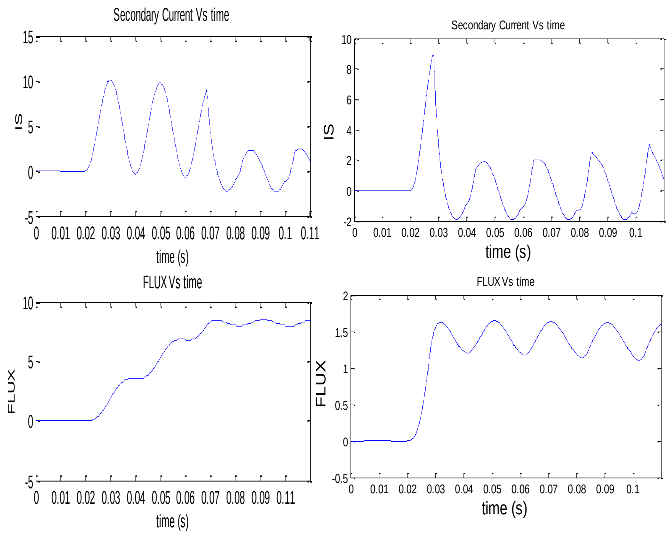


Figure 8 Secondary Current with burden of 14 Ohm

From the simulation results shown in Figure (7,8) It is clear that at 4 ohm burden resistance the time to saturation is approximately 0.04S. While at 14 ohm burden, the time to saturation decreases to approximately 0.022S .

B. Effect of Hysteresis (Remenant Flux)

In this case The breaker closing time is setting in order to close at a voltage zero crossing. t = 1/50 s is used. This switching instant will produce full current asymmetry in the shunt reactor . The parameters of this test are (Turn ration 2500:5),R burden 1 Ω ,frequency 50Hz, R primary 100 Ω &L primary 1H.Figure 9a Shows the Simulink Scope output For the flux and secondary current without the effect of the hysteresis. However Figure 9b shows the effect with the hysteresis .



(a) (b)

Figure (9) Simulink Output a) Without Hysteresis. b) with Hysteresis For Secondary Current and Flux.

C. Effect of Hysteresis With Different Burden

In this case the burden are is changed from 1 ohm to be 9 ohm , and the parameters of this test are (Turn ration 2500:5), frequency 50Hz,Breaker Time (1/50), R primary 100 Ω &L primary 1H.Figure 10 Shows the Simulink Scope output For the flux and secondary current with the effect of the hysteresis.

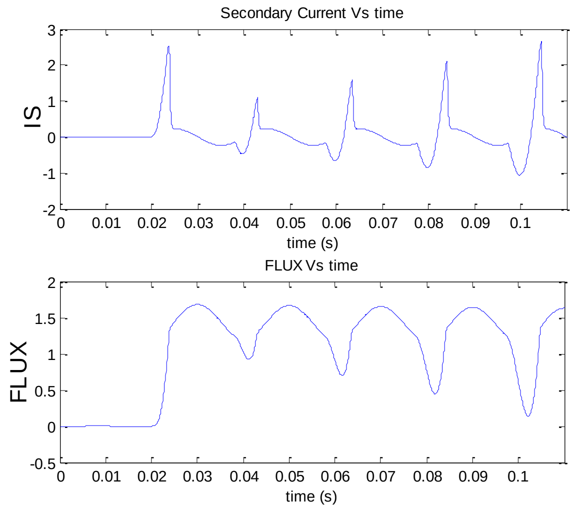


Figure (10) Simulink Output with Hysteresis For Secondary Current and Flux.

From the simulation results shown in Figure 9(a,b), It was found that the Time to saturation for secondary current without hysteresis is approximately 0.07S .However with hysteresis only is approximately 0.03S . And for Figure 10 the time to saturation is approximately 0.02s .

D. Effect of no Asymmetry Current

In this test, the breaker is closed at a peak of the source voltage (t = 1.25 cycle). This switching produces no current asymmetry .The parameters are (Turn ration 2500:5),R burden 2Ω ,frequency 50Hz, R primary 100 Ω &L primary 1H. Figure 11 Shows the Simulink Scope output For the flux , primary and secondary currents.

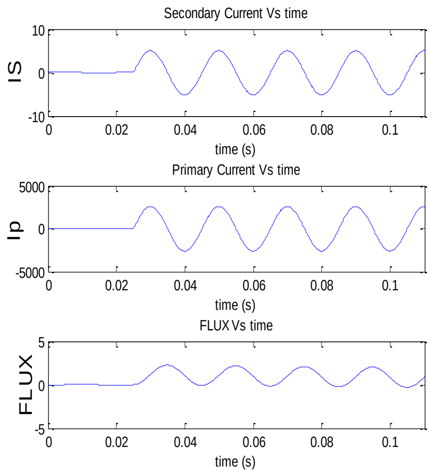


Figure 11 Simulink Output At No Asymmetry Current For Primary Current, Secondary Current and Flux .

E. Effect of Asymmetry Current

In this case The breaker closing time is changed in order to close at a voltage zero crossing. t = 1/50 s is used. This switching instant will produce full current asymmetry in the shunt reactor . The parameters of this test are (Turn ration 2500:5),R burden 2 Ω ,frequency 50Hz,Breaker Time (1/50), R primary 100 Ω &L primary 1H. Figure 12 Shows the Simulink Scope output For the flux , primary and secondary currents.

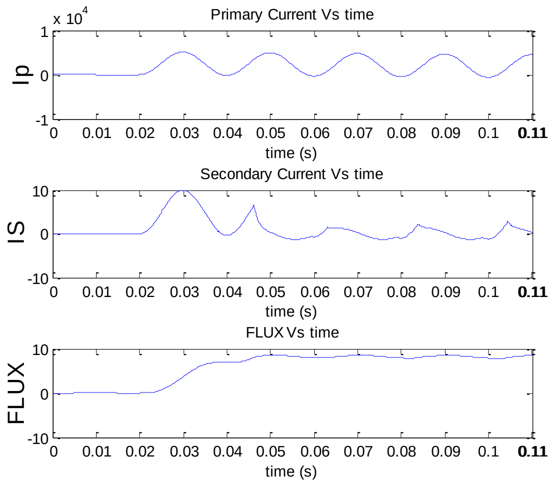


Figure 12 Simulink Output At Asymmetry Current Primary Current, Secondary Current and Flux.

F. Effect of Asymmetry Current with Hystersis and burden

In this case The breaker closing time is changed in order to close at a voltage zero crossing. t = 1/50 s is used. This switching instant will produce full current asymmetry in the shunt reactor . The parameters of this test are (Turn ration 2500:5),R burden 9 Ω , frequency 50Hz, R primary 100 Ω &L primary 1H. Figure 13 Shows the Simulink Scope output For the flux , primary and secondary currents.

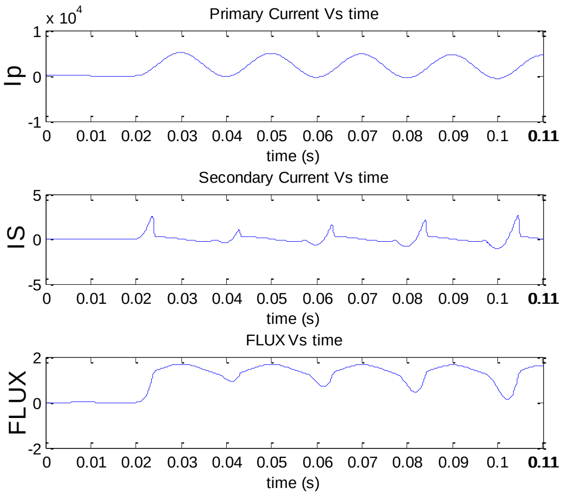


Figure13 Simulink Output At Asymmetry Current and Hysteresis with High Burden For Primary Current, Secondary Current and Flux .

From the simulation outputs shown in Figure 11,12 and 13 It is clear that time to saturation decrease when we have asymmetry current (Dc offset) .So it is important to include the effect of Dc offset when we Compute time to saturation.

G. *Effect of X\R Ratio*

In this case, the CT ratio is constant at 2500:5 and load resistance is 9 ohm, while the shunt impedance is variable with : R= 50 ohm, L=0.1H (X\R= 0.628) and R = 25 ohm and L= 0.7 H (X\R=8.79). Figure (14,15) Shows the output of secondary current with different (X/R) ratio .

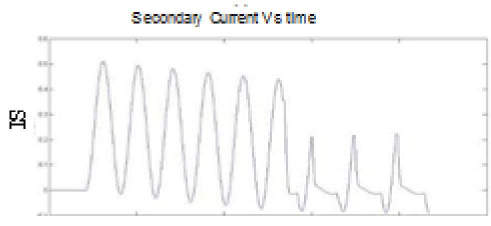


Fig 14 The Secondary Current when the X\R ratio = 0.628

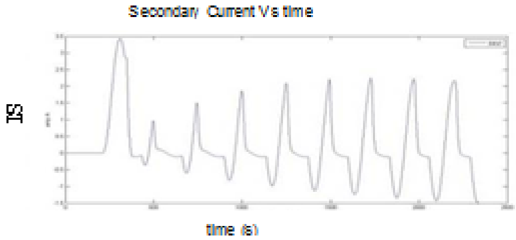


Fig 15 The Secondary Current When the X\R ratio = 8.79

It was Found From Figure 13(a,b) The Secondary Current when the X\R ratio = 0.628 and the time-to-saturation is approximately 0.138S . However The Secondary Current when the X\R ratio = 8.79 and the time-to-saturation is approximately 0.0379 S .

H. Effect of Turn Ratio

In this test, the load impedance is to 2 ohm and the primary impedance is set constant at R =100 ohm and L = 1 H, while the CT ratio is variable between 200:1 and 2500:5. Figure (16,17) Shows the output of secondary current with different turns ratio .

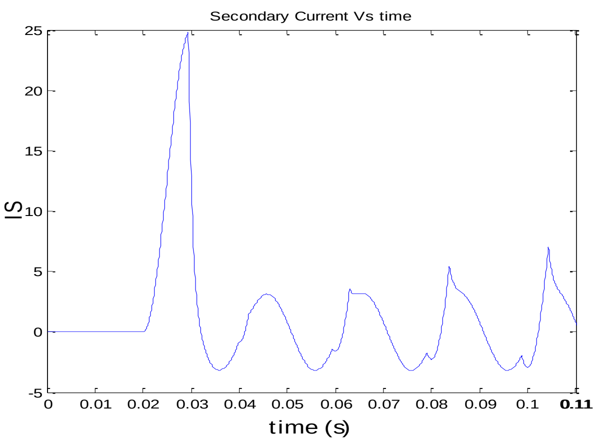


Fig 16 The Secondary Current When the .CT ratio 200:1

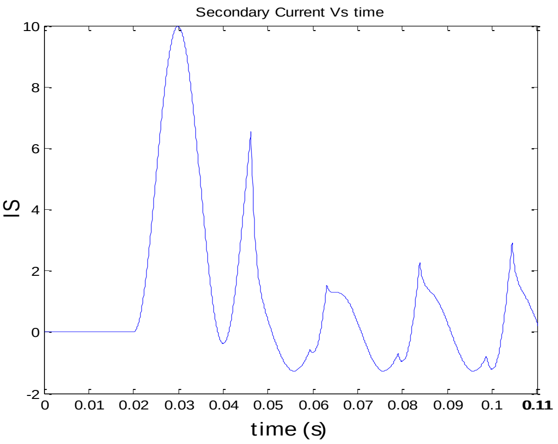


Fig 17 The Secondary Current When the CT ratio 2500:5

From the simulation outputs illustrated in Figure (16,17), It is clear that at 2500:5 turns ratio time to saturation is approximately 0.044S while at 200:1 turns ratio time to saturation decreases to approximately 0.029mS.

I. Effect of Over voltage

In the effect of over voltage , The primary breaker time sets at t=(1.25/50 S) and change the secondary switch opening time to t=0.2S. The overvoltage at this case produced when the secondary switch is open. Figure 18 Shows the output of primary , secondary current and the flux at this case .

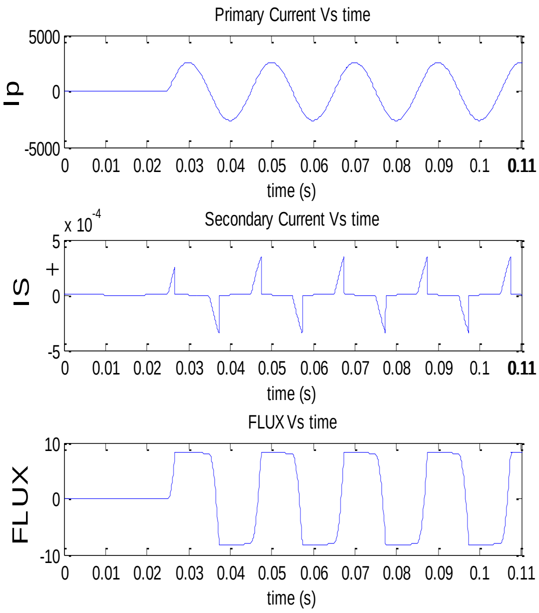


Figure 18 Simulink Output At Overvoltage for Primary Current, Secondary Current and Flux.

IV. Conclusion

- By investigate the effect of flux on the CT, where it was found that the increase of flux above a certain limit leads to saturation.
- The impact of X\R ratio was analyzed, and found that as the X\R ratio increase the time to saturation will be sorted.
- When the remnant flux is extremely high, the core will reach the saturation almost immediately, especial when the burden is high.
- CTs that have lowest ratio, they are the fastest to saturation.
- Simulation results show that the maximum dc component of a fault occurs when the instantaneous voltage is zero, which is make the primary current unsymmetrical, and then results shorter CTs saturation.
- The maximum dc component of a fault occurs when the instantaneous voltage is zero. Then the dc component starts decaying according to the time constant of the primary power system. The larger time constant will result in the longer decaying process, and then longer CT saturation period.
- The CTs have the lowest burden and Rct show the best performance and they have large time to saturation.
- The overvoltage on the secondary of the CT should be avoided by which (open circuit). in this case, the flux, which is corresponding to voltage, will increase and shorten the time to saturation

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