International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463
Vol. 2 Issue 10, October-2013, pp: (72-77), Available online at: www.erpublications.com

Current Transformer Saturation and its Impact of DC offset on Protective System

Preet Khandelwal[1], Vijay Kumar Shukla[2],
[1]preet_27sep@yahoo.co.in

Abstract: Modern protective systems require a faithful reproduction of primary short circuit current. Often, specially in high power installations, an important part of the current, during a few cycles at least, is the D.C. component, which causes severe saturation conditions, if the current transformer is not correctly selected and employed. Prediction of the behaviour of these devices during the first 00-40 ms, when D.C. component is higher, becomes a must. Many models have been presented to simulate current transformers, but only some of them are well suited for transient conditions. This paper presents a comparison between predicted results, from accepted models, and real conditions ones, from high power laboratory tests.

Keywords: Current Transformer, Matlab Simulation, Relays, Saturation

I. INTRODUCTION

Current transformer saturation is associated with many protection problems encountered in power systems. CT (Current Transformer) saturation is a complex phenomenon and accurate modeling in a simulation environment is challenging. The magnetic characteristic of the CT is shown in Fig. 1 (hysteresis not shown). In the linear region, the CT will behave almost like an ideal ratio changer. That is, the CT secondary current is an identical but scaled down replica of the primary current. However, If the CT saturates, more current is required to magnetize the core and as a result the secondary current (I_S) available as inputs to the relay may not be an identical scaled down replica of the actual primary current(I_P). This can lead to protection issues and should be given due consideration. CT saturation can be explained using the simplified equivalent circuit shown in Fig. 2. In the linear region of operation, magnetizing current (I_{M1}) is very small and hence $I_P – I_M$ is approximately equal to IP. Thus I_S would be a scaled down version (by a factor of N). If the CT saturates, the magnetizing current increases (I_{M2}). As a result, only a part of I_P is available for transformation to the secondary.

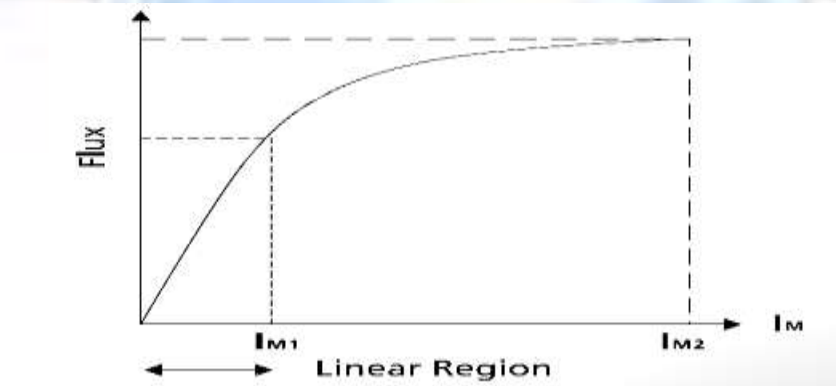

Fig. 1 Magnetic Characteristic of the CT

Current transformer (CT) saturation distorts the secondary current and in consequence leads to operating delay or malfunction of protection relays (e. g. under reaching of over current relays, overestimation of fault loop impedance in distance relays) [1]. Therefore an appropriate saturation detection method is necessary to maintain the protection system reliability. A method for detecting CT saturation onset based on the abrupt change in the current when CT saturates is suggested in [2]. This method can detect the saturation successfully only if the current collapses to zero after inception of saturation; however, it may operate incorrectly when the current does not change instantly when an anti-aliasing low-pass filter is used. In [3], an algorithm for calculating the core flux from the secondary current in order to compensate the saturation is proposed. This algorithm calculates the core flux and detects saturation based on given CT parameters. Another approach proposed in [4] is based on evaluating the mean of the error and the mean and variance of the current magnitude. The error is derived on the following assumption: If the current is a perfect sinusoid, the summation of the current and its second-order derivative is zero over time. In [5] an impedance-based CT saturation detection algorithm for bus-bar differential protection is suggested. Calculation of power system source impedance at the relay position is based on a first order differential equation. This method uses voltage and current signals of the bus-bar to detect CT saturation.

Another CT saturation detection algorithm based on the third difference of the secondary current is proposed in [6]. The effects of remanence flux in the core and a low-pass filter on the saturation are included in this method. A method based on symmetrical components is suggested in [7]. The zero-sequence differential current gradient with respect to a bias current is utilized to detect saturation in a numerical current differential feeder protection relay. Another approach for detecting CT saturation is the use of artificial intelligence (AI) techniques such as artificial neural networks (ANNs) (e.g., [8]). In [9], it is proved that considerable improvement of the operation and quite simple achievement of adaptive features for protection function may be obtained by utilizing various AI techniques [1]. Neural computing methodologies have some advantages over conventional methods. However there are no general rules for choosing the type of ANN structure and its further parameters (such as number of layers and neurons, neuron activation function, and input signals) which depend on designer experiences with ANN usage. To overcome this drawback, in [1] an optimization approach based on the genetic algorithm is proposed.

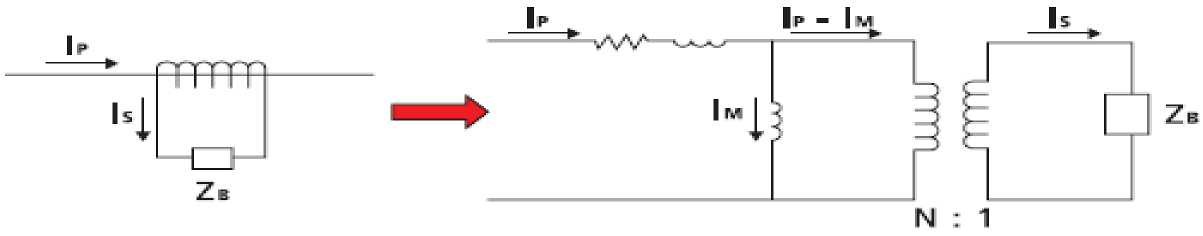

Fig. 2 Schematic Representation of CT (left) and the simplified Equivalent Circuit (right)

II. DC OFFSET CURRENT

Fault current consists of Symmetrical AC component, and DC offset current.
If *Rline* + *j*ω*Lline* models the line impedance, then for a fault at $t = t_0$, the fault current will be,

$$i(t) = \frac{V_m \sin(\omega t + \phi - \theta)}{|Z_{line}|} + I_0 e^{\left(\frac{t - t_0}{\tau}\right)}$$

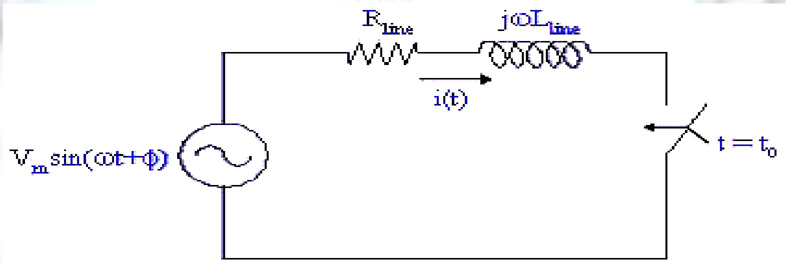

Fig. 3 Circuit Model to Simulate Model

Peak Value of DC Offset Current

The peak value of DC offset current is obtained by setting the current at t_0 to zero. It is given by,

$$I_0 = \frac{V_m}{|Z_{line}|} \sin(\omega t_0 + \phi - \theta)$$

The peak value of DC offset current depends upon the following parameters:

Time at which fault strikes; Phase angle ϕ of AC voltage; |*Zline*| and θ of transmission line.

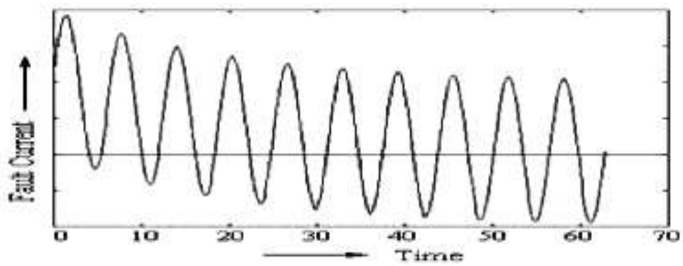

Fig. 4 Typical Wave Form of Fault Current

The severity of DC offset current is maximum when,

$\phi = \theta$ and $\omega t_0 = \pm 90$

It can be also concluded that,

Peak value of DC offset current can be as high as the symmetrical AC peak. DC offset current can be positive or negative. If $\phi = \theta$ and $t_0 = 0$, DC offset current may be totally absent. It has adverse impact on CT performance.

CT Saturation due to DC Offset Current

When a CT core is saturated due to DC offset current, it cannot faithfully replicate the primary current waveform. The secondary current is given by,

$$i_2 = \frac{N_1 I_0}{N_2} e^{\frac{-t}{\tau}}$$

The voltage developed across CT secondary would be,

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

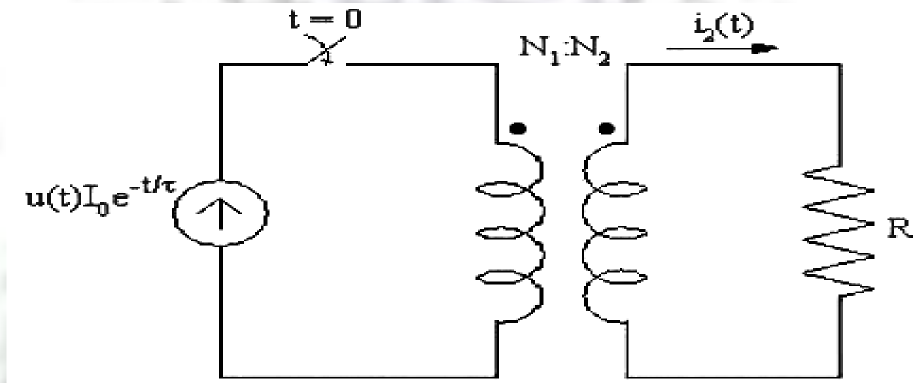

Fig. 5 Ideal CT Excited by DC offset Current, u(t) is Unit Step Function

Assume that initial flux in the transformer core at t = 0 is $\phi(0) = 0$.

Using Faraday's law,

$$v_2 = N_2 \frac{d\phi}{dt}$$

$$\phi(t) - \phi(0) = \frac{1}{N_2}\int_0^t v_2 dt = \frac{N_1 R I_0}{N_2^2}\tau(1 - e^{\frac{-t}{\tau}})$$

Since, maximum value of $I_0 = \frac{V_m}{|Z_{line}|}$,

$$\phi_{dc}^{max} = \frac{N_1 R V_m}{N_2^2 |Z_{line}|}\tau$$

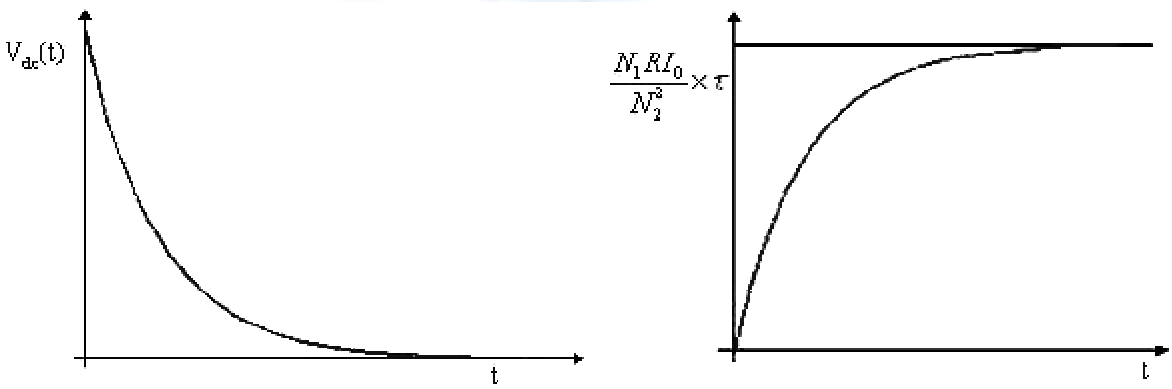

Fig. 6 Secondary voltage for Ideal CT with Resistive Burden and Exponentially Decaying Current Source (left) and Flux in the DC core for V_{DC} (Right)

It can be seen that AC voltage induced flux is sinusoidal in nature and it has zero average value. DC offset induced flux is unidirectional and its average value is not zero. The peak value of instantaneous flux in the core is

$$\frac{RV_m}{\omega|Z_{line}|}\frac{N_1}{N_2^2}+\frac{N_1}{N_2^2}\frac{RV_{m}\tau}{|Z_{line}|}$$

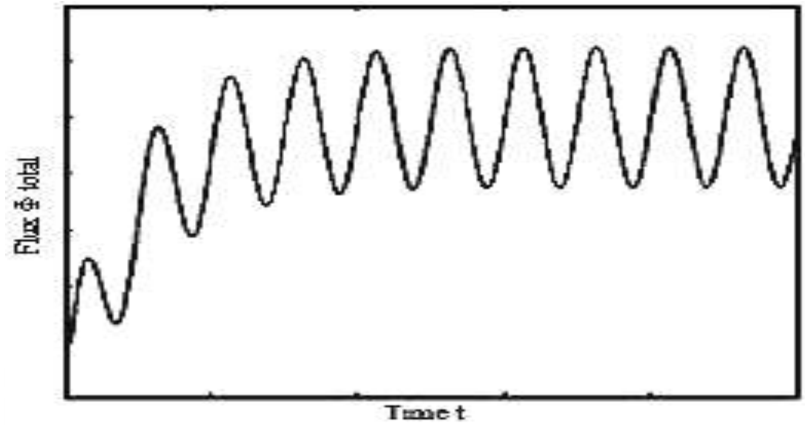

Fig. 7 Flux Value with time

Consequences of CT Saturation

- The secondary current will not faithfully replicate the primary current.
- Secondary current is clipped.
- This clipping of CT current leads to blinding of the relay.
- The relay should be fast enough to take decision before CT saturation.

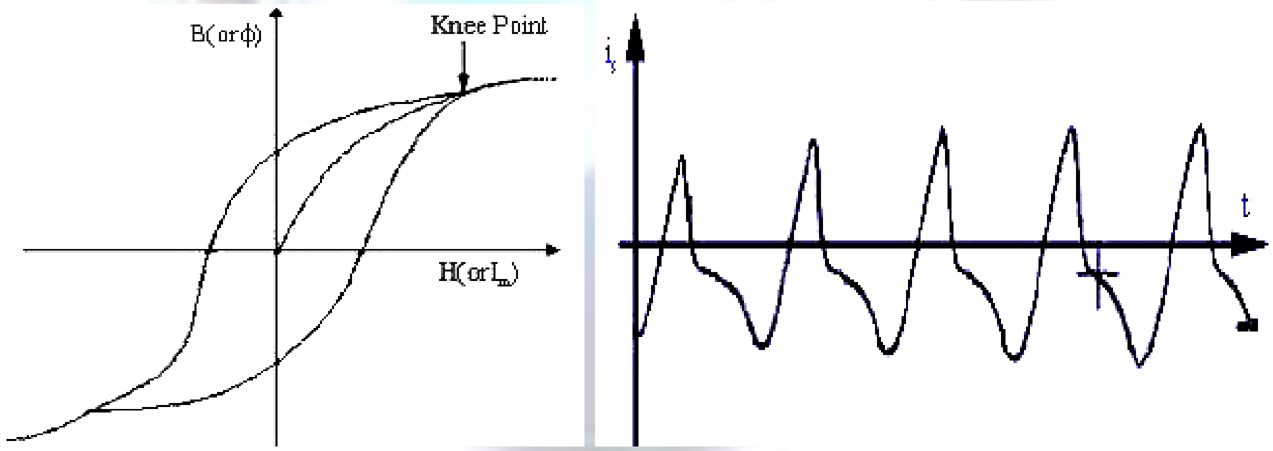

Fig. 8 B - H Curve and Experimentally Recorded CT secondary current under saturation.

III. CASE STUDY

A current transformer (CT) is used to measure current in a shunt inductor connected on a 132 kV network. The CT is rated 2000 A / 5 A, 5 VA. The primary winding which consists of a single turn passing through the CT toroidal core is connected in series with the shunt inductor rated 76.2 Mvar, 76.2 kV (132kV/sqrt(3)), 1 kA rms. The secondary winding consisting of 1*2000/5 = 400 turns is short circuited through a 1 ohm load resistance. A voltage sensor connected at the secondary reads a voltage which should be proportional to the primary current. In steady state, the current flowing in the secondary is 1000*5/2000 = 2.5 A (2.5 Vrms or 3.54 Vpeak read by the voltage measurement block V2). Open the CT dialog box and observe how the CT parameters are specified. The CT is assumed to saturate at 10 pu and a simple 2 segment saturation characteristic is used. The primary current reflected on the secondary and the voltage developed across the 1 ohm resistance are sent to trace 1 of the Scope block. The CT flux , measured by the Multimeter block is converted in PU and sent to trace 2. (1 pu flux = 0.0125 V *sqrt(2)/ (2*pi*50) = 5.63e-5 V.s). The switch connected in series with the CT secondary is normally closed. This switch will be used later to illustrate overvoltages produced when CT secondary is left open.

1. Normal operating condition

In this test, the breaker is closed at a peak of source voltage (t = 1.25 cycle). This switching produces no current asymmetry. Start the simulation and observe the CT primary current and secondary voltage (first trace of Scope block). As expected the CT current and voltage are sinusoidal and the measurement error due to CT resistance and leakage reactances is not significant. The flux contains a DC component but it stays lower than the 10 PU saturation value.

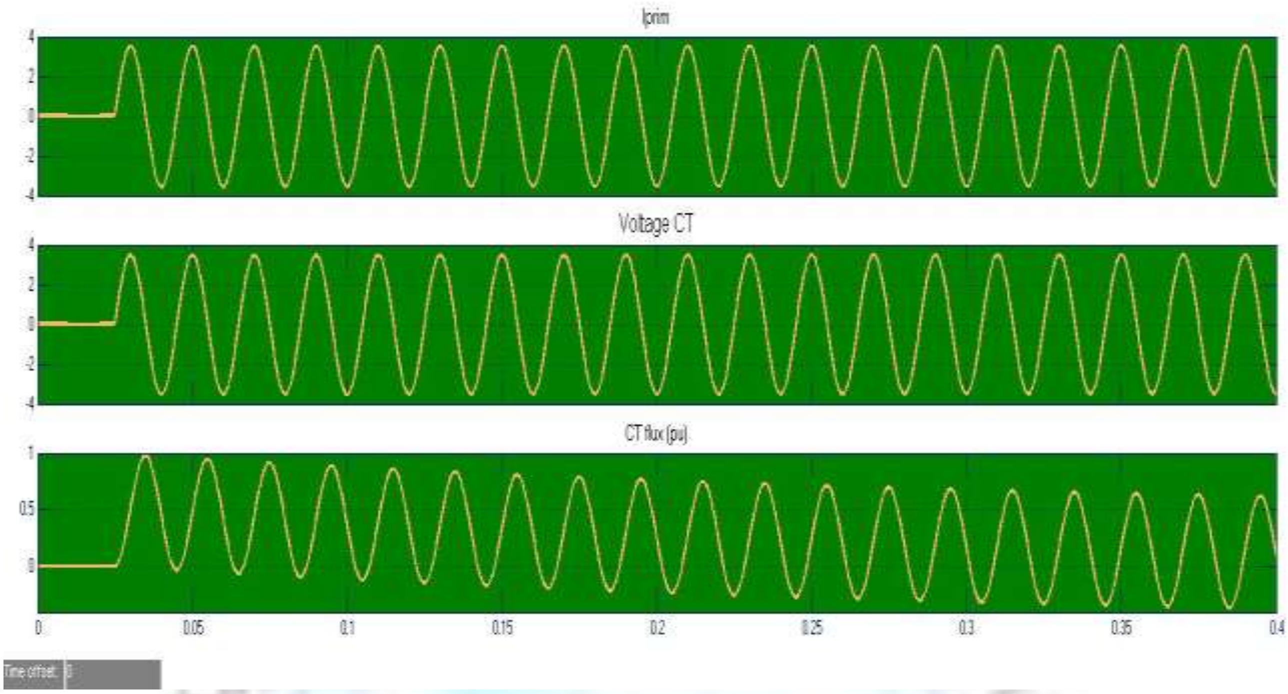

Fig. 9 Breaker is closed at a peak of source voltage (t = 1.25 cycle)

2. CT saturation due to current asymmetry (DC offset)

Now, change the breaker closing time in order to close at a voltage zero crossing (Fault Conditions). Use t = 1/50 s. This switching instant will now produce full current asymmetry in the shunt reactor. Restart the simulation. Observe that for the first 3 cycles, the flux stays lower than the saturation knee point (10 pu). The CT voltage output V_2 then follows the primary current. However, after 3 cycles, the flux asymmetry produced by the primary current causes CT saturation, thus producing large distortion of CT secondary voltage.

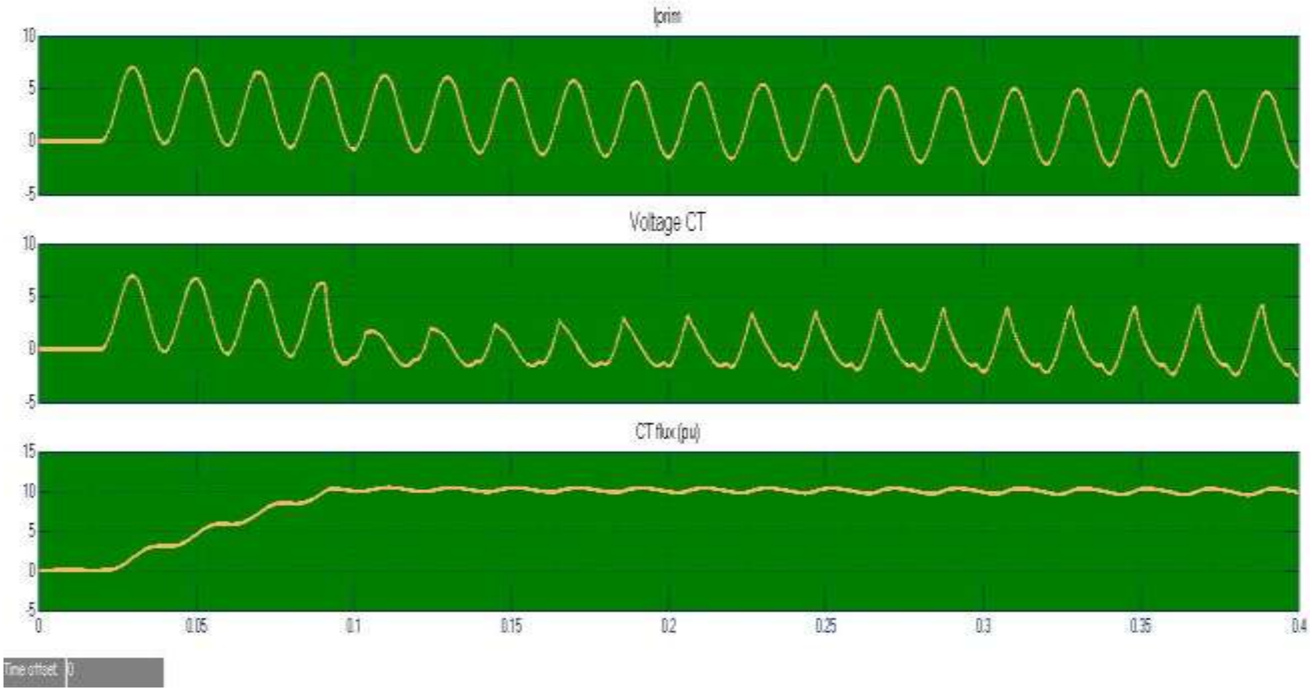

Fig. 10 Breaker is closed at a peak of source voltage (t = 1 cycle)

3. Overvoltage due to CT secondary opening

Reprogram the primary breaker closing time at t = 1.25/50 s (no flux asymmetry) and change the secondary switch opening time to t = 0.1 s. Restart the simulation and observe the large overvoltage produced when the CT secondary is opened. The flux has a square waveshape chopped at +10 and -10 pu. Large dphi/dt produced at flux inversion generates high voltage spikes (250 V)

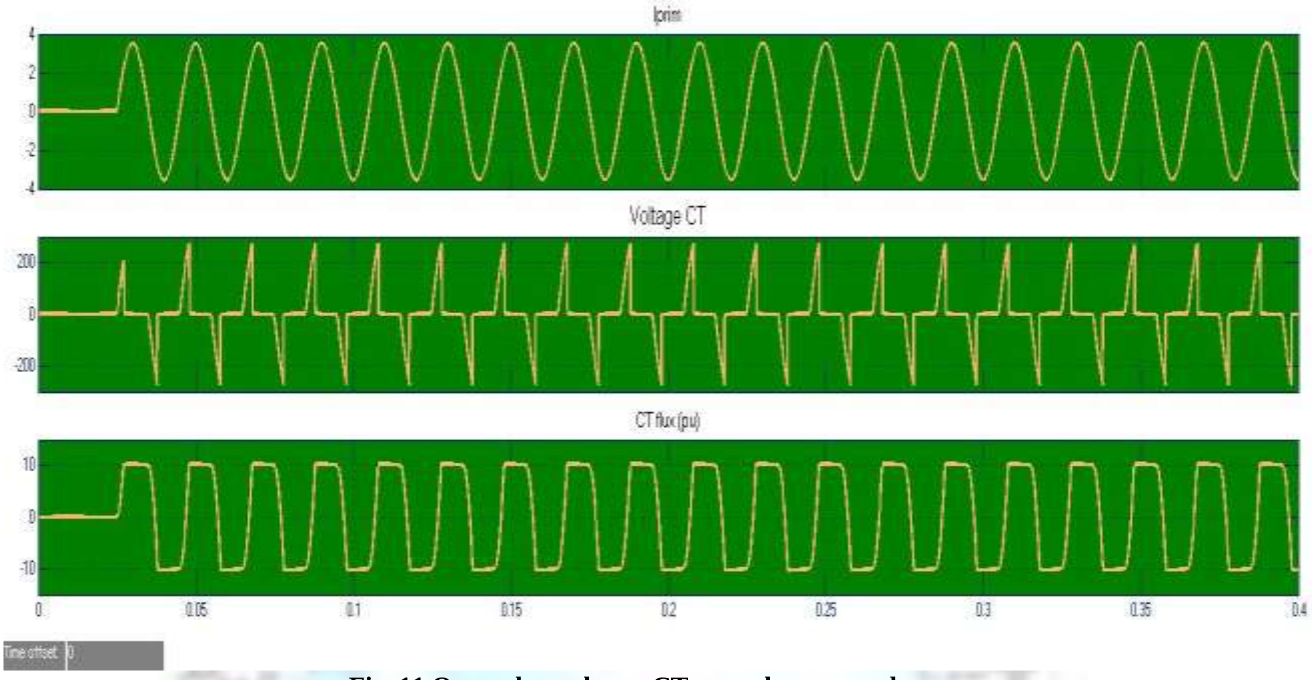

Fig. 11 Overvoltage due to CT secondary opened

CONCLUSION

An acceptable and precise current transformers model was implemented. The model is a very convenient way to test the transient behavior of the CT's as shown in Fig. 8. This model was validated and tested in the laboratory to ensure appropriate and accurate suitability. Impact of DC offset in the primary fault current. The point on the voltage wave form at the instant of the fault determines the level of the DC offset in the primary current. The maximum DC offset will occur when the fault is applied at a voltage, minimum. The results in Fig. 7, 8, 10 occur when the DC offset is significant. As can be seen, the DC offset causes the flux to be driven down and into saturation. The CT has saturated after about three cycles. The reduction of the secondary current is evident. The simulation results in Fig. 9 demonstrate a situation when there is no DC offset. As can be seen, the CT does not go into saturation and only a small amount of magnetizing current is required to magnetize the core. Therefore, the secondary current is an exact but scaled down replica of the primary current.

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