

# Primary Time Constant Calculation of Power System

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**Abstract**— *In this paper, a new technique is proposed for primary time constant calculation of power system using four samples of phase current signal following the fault occurrence. The proposed technique is able to accurately identify the actual primary time constant of power system under different fault resistances, inception angle, and loading levels. The suggested algorithm needs only three line-current measurements available at the protective relay location and can perform the primary time constant estimation task in about one-cycle period. Thus, the proposed technique is well suited for implementation in a digital protection system. The proposed algorithm is applied for El-kuriemat power station unit that produces 320 MVA. Alternative transient program (ATP) and MATLAB programs are used to implement the suggested technique.*

**Index Terms**—Circuit Faults, Protective Relay, CT Saturation, Primary Time Constant.

## I. INTRODUCTION

The primary fault current can be expressed as a combination of two components. The first component is a periodic and steady-state component determined by the source voltage and fault circuit impedance. The second component is a transient DC offset component produced at the fault instant against the sudden current changes. This DC-offset component will decay after a few cycles according to the non-defined  $L/R$  time constant of the power system network. The DC component may have any value from zero to the maximum fault current, depending on the instantaneous value of the voltage when the circuit is short-circuited, on the power factor of the circuit and the primary time constant [1]. Practically, the current and voltage waveforms that immediately follow power system faults are never pure sinusoids. This is particularly true for current waveforms, which often contain a relatively large and slowly decaying DC component. It follows that, in applying sinusoidal waveform-based algorithms, care must be taken in dealing with any DC offset components in the current signals, which in practice can be transferred in full to the digital processing stage. This is particularly so where the input circuit comprises an iron-cored transformer with resistive burden [1]. Flux in the current transformer (CT) is changed 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. There is difference between the non-offset and offset flux; in case of non-offset flux (i.e. non-offset primary current), The CT core does not go into the saturated region of operation so the secondary current is undistorted. Whereas in case of fully offset flux (i.e. offset primary current), the resulting secondary current is distorted. The increase in flux is not instantaneous, indicating that saturation does not occur instantaneously but takes time. This time is called the time-to-saturation [2]. Under ideal conditions, the secondary current developed by CT will be the primary current divided by the CT turns ratio. However, the CT secondary current will not be a sine wave when the flux in the CT core reaches into the saturated region. One important factor affecting this is asymmetry in the primary current (i.e. DC component). Actually, the DC component has far more influence in producing severe saturation than the AC fault current. Direct current saturation is particularly significant in differential relaying systems, where highly differing currents flow to an external fault through the current transformers of the various circuits. Dissimilar saturation in any differential scheme will produce operating current. Severe current transformer saturation will occur if the primary circuit DC time constant is sufficiently long and the DC component sufficiently high [2]. Many methods are used to avoid the CT saturation. The problem of CT saturation is eliminated by air-core CT's called "linear couplers". In fact, these CT's have a disadvantage that very little current can be drawn from the secondary, because so much of the primary magneto-motive force is consumed in magnetizing the core. Another method is used to increase the size of the CT core to obtain a higher saturation voltage than a calculated value [3]. Another one uses special core material to withstand large flux density [4]. These options present mechanical and economic difficulties. Recently, many software techniques are provided to solve these problems and each method has its advantage and disadvantage. Some techniques uses a DC component equal and opposite to that in the primary circuit generated by a circuit added to the secondary winding [5]. Other techniques used a magnetization curve and the equivalent circuit of a CT for compensating secondary current of CT during saturation. The second has practical difficulties, as it depends on CT parameters /characteristics and secondary burdens [6]. Also, the artificial neural networks (ANN) are used in this area. ANN attempts to learn the nonlinear characteristics of CT magnetization and restructures the waveform based on the learned

characteristics. This method could not be applied to different CT's due to the variations of CT's saturation characteristics and the secondary burdens [7]. Some other algorithms prevent relay operation during CT saturation. This may result in longer trip times. A method for compensating the secondary current of CT's is based on the ideal proportional transient secondary fault current. A portion of measured secondary current following the fault occurrence is described using regression analysis [8-9]. Another method utilizes four consequent samples during the unsaturated portion of each cycle for solving a set of equations to get the constants of the primary fault current equation for reconstructing the secondary current during the saturated part each cycle. This scheme supposes different values of primary time constant and chooses the value that gives the smallest error [10]. Through-out this work a simple technique for calculating the primary time constant of the power system is suggested. The technique is based on measuring the secondary current signal following the fault occurrence for detecting and defining the correct time constant. Thus the algorithm of the primary time constant is suitable for using in digital protection systems. The proposed algorithm uses a new equation deduced from the primary fault current equation of power grid. This constant is obtained by using four samples, of two successive cycles for phase current signal after fault occurrence, which are substituted in the produced equation. This technique takes into consideration the wide variations of operating conditions such as pre-fault power level, fault inception angle and fault resistance.

## II. PROPOSED TECHNIQUE

### A. Basic principles

A method for calculating a primary time constant of a power grid includes the following steps:

- (1) A power system model is simulated using Alternative Transient Program (ATP) package [11] according to the actual power grid parameters.
- (2) Locate a three phase-to-ground short circuit fault at one of two transmission lines to obtain fault data. Transient short circuit current, of the short circuit point, which occurs as a result of the fault is used as input signal to the proposed algorithm.
- (3) MATLAB package is used for processing the proposed algorithm for detecting the instant of fault inception and calculating the primary time constant of the power grid to avoid maloperation of the protection device by reasonably adjusting the preset value of the relay protection.

The primary time constant can be useful to obtain a non-periodic component attenuated with time (which is considered one component inserted in the transient short circuit current). So it is called also the attenuation time constant.

A primary time constant of a power grid directly influences the analyzing result of the transient characteristic of the current transformer. The primary time

constant in the power system which are located at different sites are different greatly. It has a value between 20 *mSec* to 30 *mSec* for transmission lines and it is larger than 200 *mSec* for a large generator-transformer. Consequently, the accurate calculation of the primary time constant at current transformer installation sites is an important premise and base of detecting the transient characteristic of the current transformer. The influence of primary time constant to a protective current transformer mainly includes the following items:

- 1- It is an important premise of analyzing the transient characteristic of the current transformer.
- 2- It determines the attenuation speed of a non-periodic component of the short circuit current.

As the main protection of various electric elements (a generator, a power transformer, a power transmission line, an electric motor etc.), the differential protection has been widely applied in the power system of various voltage levels. When a fault takes place outside of a differential protection area, the current transformers at the two sides can detect the difference between the transient attenuation current; and the difference between the primary time constants at the current transformer installation sites which is located at the two sides of the differential protection is large; the transient characteristics of the current transformers at the two sides will present different features. In this case, the current transformer with a larger primary time constant causes a differential current is generated in the differential protection. When the difference between the transient attenuation current exceeds a pre-set value of differential protection, a misoperation of the differential protection device will be caused. Thus it results in the expansion of the system fault. An accurate calculation of the primary time constant of the system can accurately determinate the transient characteristic of the current transformer and the misoperation of the protection device can be avoided by reasonably adjusting the preset value of the relay protection. Thus the primary time constant of the power grid is a very important parameter. It is required so as to improve the analysis and control ability of engineers on the power system. Therefore the method has a great technology and a high practicability. The object of our proposed technique is to provide an accurate method for calculating a primary time constant of a power grid, for accurately grasping a transient characteristic of the current transformer, so that a misoperation of a protection device can be avoided by reasonably adjusting a preset value of a relay operation. The technique is based on the delta algorithm and the pre-fault current signal for detecting the fault condition. The secondary current following the fault occurrence is accurately used for estimating the primary time constant of the power grid.

### B. Fault detection

Initially for fault detection, a transition is detected if  $\Delta i_i$

$> 20\% I_n$ , where  $I_n$  is the nominal current of the protected power system element. The delta algorithm is considered additional one processed in our technique for fault confirmation. This is processed by calculation of predicted and superimposed values for each phase current signal  $i_s(x)$  as follows:

$$i_{sp}(x) = 2i_s(x - N_s) - i_s(x - 2N_s)$$

$$\Delta i_s(x) = i_s(x) - i_{sp}(x) = i_s(x) - 2i_s(x - N_s) + i_s(x - 2N_s)$$

Where,

$i_{sp}(x)$  : predicted value of current signal  $i_{sp}$  at sample  $x$ .

$\Delta i_s(x)$ : the change of measured current signal  $i_s(x)$  at sample  $x$  with respect to the predicted value  $i_{sp}(x)$  at the same sample  $x$ .

$i_s(x - 2N_s)$  : measured current signal ( $i_s$ ) at sample two cycles prior to  $x$ .

$i_s(x - N_s)$  : measured current signal ( $i_s$ ) at sample one cycle prior to  $x$ .

$i_s(x)$  : measured current signal ( $i_s$ ) at sample  $x$ .

$N_s$ : the number of samples per cycle used in the simulation.

### C. Primary time constant calculation

The proposed technique is based on the ideal transient secondary fault current. The following equation represents the primary fault current [5].

$$i_p(t) = I_{max} [\cos(\omega t + \theta - \alpha) - e^{-t/\tau_p} \cos(\theta - \alpha)] \quad (1)$$

Where,  $I_{max}$ ,  $\theta$ ,  $\alpha$  and  $\tau_p$  are parameters related to the power system condition during the fault. The primary fault current  $i_p(t)$  can be expressed as a combination of two components. The first component is a periodic and steady-state component and the second component is a transient DC offset component (non-periodic component) produced at the fault instant against the sudden current changes. The current transformer secondary current ( $i_s(t)$ ) is an image of primary current divided by  $N_T$ , where  $N_T$  is the current transformer turn's ratio. The current transformer secondary current  $i_s(t)$  is presented as in equation (2).

$$i_s(t) = I_{smax} [\cos(\omega t + \theta - \alpha) - e^{-t/\tau_p} \cos(\theta - \alpha)] \quad (2)$$

The above equation is used to obtain the parameter  $\tau_p$  from the actual secondary current during the interval that follows directly the fault occurrence. This constant is used in the transient equation for DC components calculation and it

can be used for reconstructing the distorted secondary current due to CT saturation.

Equation (2) can be rewritten in a discrete form as:

$$i_s(x) = I_{smax} [\cos(\omega h x + \theta - \alpha) - e^{-h x / \tau_p} \cos(\theta - \alpha)] \quad (3)$$

Where,  $i_s(x)$  is the secondary current at the sample  $x$ , and  $h$  is the time interval between each two successive samples ( $t = xh$ ).  $I_{smax}$  is the peak value of the sinusoidal steady state secondary current during the fault,  $\tau_p$  is the time constant of the primary system ( $\tau_p = X_L / \omega R$ ).  $X_L$  and  $R$  are the reactance and resistance of the primary system to the point of the fault, respectively.  $\theta$  and  $\alpha$  are the fault-incidence angle and the power system angle of the primary system, respectively.  $\omega$  is the angular velocity of the power system ( $\omega = 2\pi f$ ).

An accurate and simple method for estimating the equivalent ( $\tau_p$ ) is presented. The algorithm estimates the DC time constant by using four samples of secondary current waveform  $i_s(x)$ ,  $i_s(x + N_s)$ ,  $i_s(x + m)$  and  $i_s(x + m + N_s)$  through the period after fault inception directly;  $N_s$  is the number of samples per cycle and  $m$  is the selected shift number of samples. This method relies on Equation (16) deduced as follows:

$$i_s(x) = i_s(x)Ac + i_s(x)Dc \quad (4)$$

$$i_s(x) = I_{smax} [\cos(\omega h x + \theta - \alpha) - e^{-h x / \tau_p} \cos(\theta - \alpha)] \quad (5)$$

$$i_s(x + N_s) = i_s(x + N_s)Ac + i_s(x + N_s)Dc \quad (6)$$

$$i_s(x + N_s) = I_{smax} [\cos(\omega h (x + N_s) + \theta - \alpha) - e^{-h(x + N_s) / \tau_p} \cos(\theta - \alpha)] \quad (7)$$

Where  $i_s(x)$  and  $i_s(x + N_s)$  are two samples of the measured secondary current at samples ( $x$ ) & ( $x + N_s$ ) respectively, which they have the same AC component. Where,  $N_s$  is the number of samples per cycle used in the simulation.

$$i_s(x)Ac = i_s(x + N_s)Ac \quad (8)$$

$$i_s(x) - i_s(x + N_s) = i_s(x)Dc - i_s(x + N_s)Dc \quad (9)$$

$$i_s(x) - i_s(x + N_s) = I_{smax} \cos(\theta - \alpha) \times [e^{-h(x + N_s) / \tau_p} - e^{-hx / \tau_p}] \quad (10)$$

$$i_s(x + m) - i_s(x + m + N_s) = i_s(x + m)Dc - i_s(x + m + N_s)Dc \quad (11)$$

$$i_s(x + m) - i_s(x + m + N_s) = I_{smax} \cos(\theta - \alpha) \times [e^{-h(x + m + N_s) / \tau_p} - e^{-h(x + m) / \tau_p}] \quad (12)$$

Where  $i_s(x + m)$  and  $i_s(x + m + N_s)$  are two samples of the measured secondary current at samples ( $x + m$ ) & ( $x + m + N_s$ ) respectively, which they have the same AC component.

By division (10)/(12), it produces the following equation:

$$\left[ \frac{i_s(x) - i_s(x + N_s)}{i_s(x+m) - i_s(x+m + N_s)} \right] = \left[ \frac{e^{-(x+N_s)h/\tau_p} - e^{-(x)h/\tau_p}}{e^{-(x+m+N_s)h/\tau_p} - e^{-(x+m)h/\tau_p}} \right] \quad (13)$$

$$\left[ \frac{i_s(x) - i_s(x + N_s)}{i_s(x+m) - i_s(x+m + N_s)} \right] = \left[ \frac{(e^{-(x+N_s)h/\tau_p} - e^{-(x)h/\tau_p})}{(e^{-m.h/\tau_p})(e^{-(x+N_s)h/\tau_p} - e^{-(x)h/\tau_p})} \right] \quad (14)$$

$$\left[ \frac{i_s(x) - i_s(x + N_s)}{i_s(x+m) - i_s(x+m + N_s)} \right] = e^{m.h/\tau_p} \quad (15)$$

$$\tau_p = \left[ \frac{m.h}{\ln\left(\frac{i_s(x) - i_s(x + N_s)}{i_s(x+m) - i_s(x+m + N_s)}\right)} \right] \quad (16)$$

Where,  $h = (1/f_s)$ ,  $f_s$  is the sampling frequency of the system ( $f_s$  is given and  $f_s = 2.5 \text{ kHz}$  used in our algorithm); and  $m < N_s$ , select  $N_s = 50$  samples per cycle and  $m$  is the selected shift number of samples ( $m$  is given and  $m = 5$  samples used in our algorithm). Equation (16) shows that the actual DC time constant ( $\tau_p$ ) can be determined by using four samples, measured after fault detection, for two successive cycles of current signals. Despite the apparent complexity of its form, the previous equation is in fact relatively easy to evaluate.

### III. POWER SYSTEM DESCRIPTIONS

The proposed technique is applied on the power system shown in Figure 1. The system parameters are obtained from one-generation unit in El-kuriemat power station that produces 320 MVA [12]. The parameters of the selected system are as follows:

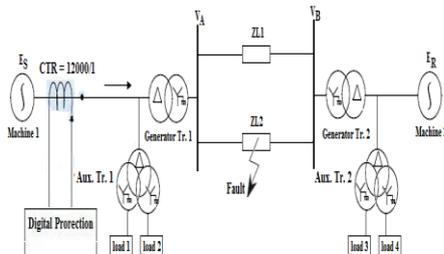


Fig 1 The Simulated Power System

#### Machine 1 (sending source):

Rated line voltage is 19 kV, volt-ampere rating is 320 MVA, frequency is 50 Hz, voltage phasor angle phase is  $20^\circ$  and number of poles is 2.

#### Machine 2 (receiving source):

Machine 2 has the same parameters of Machine 1 except the steady-state voltage phasor angle phase is  $0^\circ$ .

#### Main Transformers:

At each side there is a step up transformer 340 MVA, 19.57/500 kV (Delta/Star earthed neutral), its primary impedance is  $0.0027 + j0.184 \text{ ohm}$ , its secondary impedance is  $0.7708 + j 61.8 \text{ ohm}$ .

#### Aux. Transformers:

At each side there is an auxiliary transformer 32 MVA, 19.57/6.3/6.3 kV (Delta/Star/Star earthed neutral), its primary impedance is  $0.02978 + j0.4894 \text{ ohm}$ , its secondary impedance is  $0.0039 + j 0.0261 \text{ ohm}$ .

#### Transmission Lines

T.L. impedance is  $0.0217 + j0.302 \text{ ohm/Km}$  with 200 Km length for each circuit.

#### Loads

Each load is  $100.0 + j60.0 \text{ ohm}$

### IV. SIMULATION RESULTS

Three phase-to-ground faults were considered at the middle of one circuit of the two transmission lines assuming that short circuit is temporary and resistive. The developed technique was applied by calculating the DC time constant for one cycle period of current signal. The actual DC time constant ( $\tau_p$ ) of the primary power system can be determined for application in digital protection systems. To implement the present technique, the studied power system configuration was simulated by using ATP program and the calculations are done by MATLAB. The generated and measured three phase current signals are taken from the terminals of generator "1". An extensive simulation studies to examine the effects of fault resistance ( $R_f$ ) on the accuracy of the developed technique are presented. In each case study, the fault resistance ( $R_f$ ) is changed to check its effect on the value of primary time constant. The current signals generated at sampling rate of 50 samples per cycle that means sampling time of  $0.4 \text{ ms}$  (i.e.  $f_s = 2.5 \text{ kHz}$ ). The total simulation time is 2 Sec (i.e. the total number of samples is 5000). The fault inception time is 0.402 Sec and the fault clearing time is 0.502 Sec from the beginning of simulation time.

#### A. Primary time constant calculations in cases of different fault resistances ( $R_f$ )

This case shows the effect of the change of the fault resistances ( $R_f$ ) on the estimated primary time constant of power system. Figure 2 (a-c) present the instantaneous values of the three phase currents at operating power angle for generator "1" equals 20 degree and the fault resistance ( $R_f = 2 \text{ ohm}$ ). In this case, it is noticed that the three phase currents during the fault are higher than the pre-fault currents; their values are nearly ten times the pre-fault current. After fault clearing, the three phase currents oscillate and they are damped at the sample number 2700 from the beginning of the simulation time; this occurs due to power swing condition. From the simulation results obtained from processing of primary time constant algorithm, it is evident clear that the technique determined successfully the accurate primary time constant of power system. Their values are large in cases of low fault resistances (for example,  $R_f = 2 \text{ ohm}$ ) and they are small in cases of high fault resistances (for example,  $R_f = 400 \text{ ohm}$ ). Summary of the estimated primary time constant of power system for different cases (1-6) at different values of fault resistances ( $R_f$ ) are shown in Table 1. In case "1", the results show that the time constant is  $\tau_p = 1.863 \text{ Sec}$  at  $R_f = 2 \text{ ohm}$ . It is considered large value. The large value causes high DC components and increases the offset in the waveform of

the phases "A" and "B". But, in case "5", the time constant is  $\tau_p = 0.004$  Sec at  $R_f = 400$  ohm. It is considered small value. The small value causes low DC components and reduces the offset in the waveform.

**Table 1 Primary Time Constant Calculations in Different Cases of Fault Resistance ( $R_f$ ).**

Fault Type	Case Number	Fault Resistance ( $R_f$ )	Primary Time Constant ( $\tau_p$ )
Three line-to-ground fault through fault resistance ( $R_f$ )	Case 1	2 ohm	1.863 Sec
	Case 2	20 ohm	0.121 Sec
	Case 3	100 ohm	0.02 Sec
	Case 4	200 ohm	0.01 Sec
	Case 5	400 ohm	0.004 Sec
	Case 6	500 ohm	0.003 Sec

## V. CONCLUSIONS

This paper presents a simple method for calculating the primary time constant of a power grid. The primary time constant is very important to determine the current transformer behavior. The proposed technique uses the secondary current signals after fault occurrence. ATP software is used to get reliable simulation results before and during different fault conditions. Three-phase current measurements, available at the relay location, are obtained and stored in a file; this data is in the discrete sampled form. Four current samples for each phase, after fault detection, are substituted in a deduced equation from the primary fault current equation. The produced equation processed in MATLAB to get an accurate primary time constant so as to improve the analysis and control ability of engineers on the power system. Therefore the method has a great technology and a high practicability. The obtained results show that the proposed technique does not need any of power system or current transformer parameters. Also, Results show that the suggested technique is able to offer very high accuracy and speed in primary time constant calculation. It can perform the time constant estimation task in about one-cycle period.

## REFERENCES

[1] "IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes", IEEE Std. C 37.110-1996.

[2] Zocholl, S.E.; Mooney, J.B. "High current low ratio", Industry Applications Magazine, IEEE, On page(s): 77 - 82 Volume: 11, Issue: 5, Sept.-Oct. 2005.

[3] Working group of the Relay Input Sources Subcommittee of the Power System Relaying Committee, "Transient response of current transformers", IEEE Transaction on power apparatus and systems, Vol. PAS-96, no. 6, November/December 1977.

[4] W.J. Smolinky, "Design Consideration in the Application of Current Transformers for Protective Relaying Purposes", IEEE Transactions on Power Apparatus and System, Vol. PAS-92, no.4, July/August 1973.

[5] D.A. Bradley, C.B.Gray, D.O'Kelly, "Transient compensation of current transformers", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, no.4, July/Aug 1978.

[6] Y.C. Kang, J.K.Park, S.H.Kang, A.T. Johns, R.K. Aggarawal, "An algorithm for compensating secondary currents of current transformers", IEEE Transactions on Power Delivery, Vol.12, no.1, January 1997.

[7] D.C.Yu,Z.Wang, J.C. Cummins,H.-J. Yoon, L.A.Kojovic, and D.Stone, "Neural network for current transformer saturation correction", in proc. IEEE Transm. Distrib. Conf., New Orleans, LA, Apr.1999.

[8] M.E. Masoud, E.H.Shehab-Eldin, M.M Eissa, and M.F.Elnagar, "A New Compensating secondary current technique for saturated current transformers", The 8<sup>th</sup>International Middle- East power system conference, "MEPECON 2001", PP549-555.

[9] Jiuping Pan, Khoi Vu, and Yi Hu, "An Efficient Compensation Algorithm for Current Transformer Saturation Effects", IEEE Transactions on Power delivery, Vol. 19, no.4, October, 2004, PP1623-1628.

[10] M.A. Salem, M.I. Gilany,Z. Osman and E. about Zahab, "A new algorithm for compensating the secondary current during current transformer saturation", The tenth International Middle- East power systems conference "MEPECON 2005" PP 427-433.

[11] ATP - version 3.5 for Windows 9x/NT/2000/XP - Users' Manual Preliminary Release No. 1.1 - October 2002.

[12] Instruction Manual for Generator Electrical Equipment, Upper Egypt Electricity Production Company, Elkureimat II 750 MW Combined Cycle Project, Steam Turbine Generator & Auxiliaries (Generator Electrical Equipment), Hitachi, Ltd., Tokyo Jaban,2006.

## PERSONAL PROFILE



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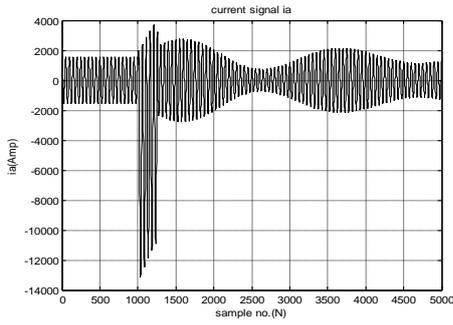


Fig 2 (a) The current  $i_a$  for case 1.

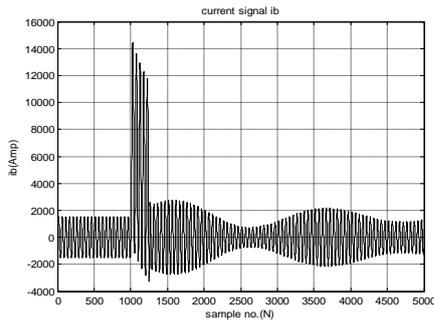


Fig 2 (b) The current  $i_b$  for case 1.

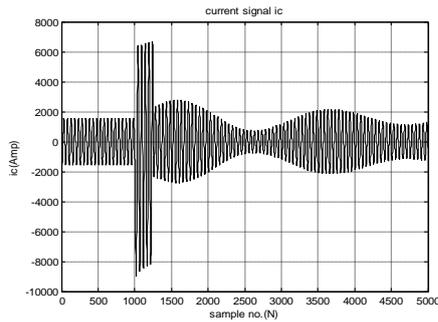


Fig 2 (c) The current  $i_c$  for case 1.

Fig2 (a-c) Three phase primary currents for case 1 ( $R_f = 2$  ohm).

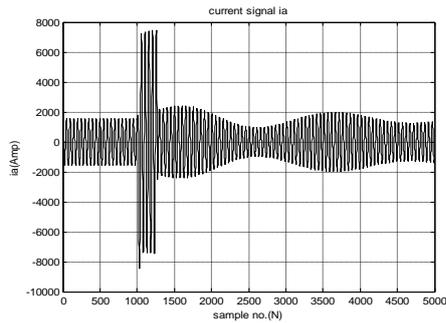


Fig3 (a) The current  $i_a$  for case 5.

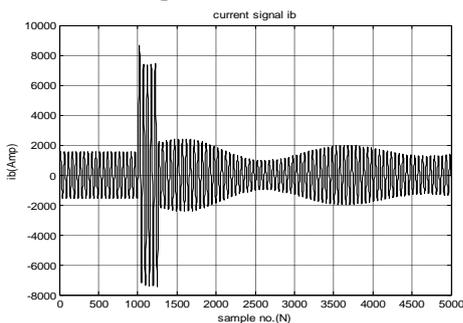


Fig 3 (b) The current  $i_b$  for case 5.

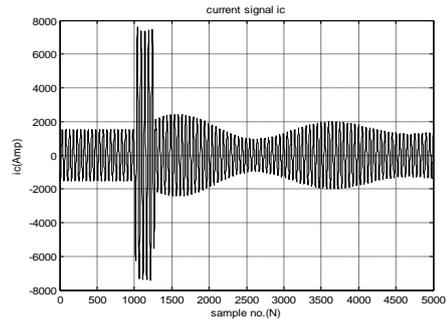


Fig 3 (c) The current  $i_c$  for case 5.

Fig 3 (a-c) Three phase primary currents for case 5 ( $R_f = 400$  ohm).