Pakistan Journal of applied sciences 2(4): 502-517, 2002

Modelling of Power System Protection Signalling

[1]Mehmet Tümay, [1]İlyas Eker, [1]Vedat Kaslı Ergun Erçelebi and [2]M.Uğur Ünver
[1]EEE Department, University of Gaziantep, 27310 Gaziantep, Turkey
[2]EEE Department, University of Sakarya, 54040 Sakarya, Turkey

Abstract: In order to specify appropriate protection equipment and switchgear and to evaluate winding stresses and shaft torques subsequent to unsymmetrical operation full three-phase dynamic analytical techniques are necessary. In this paper a methodology of machine interconnection is presented which uses a combination of nodal analysis and current summation. In the combined method, a synchronous generator is treated not only as current source but also as a voltage source. Thus in the procedure adopted it is not only the current flow which is of interest but also the voltage characteristics of the machine. When conducting simulation studies for accurate protection of the power system network, transducers (Current Transformer (CT) and Capacitor Voltage Transformer (CVT)) should be represented very accurately. The present work also describes the integration of the transducers into a small power system network for protection signalling. The transducers are represented including magnetic non-linearity and hysteresis effects. The practical application of the analysis under abnormal operation is presented and the responses of the transducers are examined.

Keywords: Current Transformer, Capacitor Voltage Transformer, Power System Protection

Introduction

Methods of the transient analysis of the electrical machines have, in the past, been based on simple models derived using pragmatic assumptions that were justified in practice for simplified transient stability analysis. The generators were represented by a voltage source and simple reactance, the value of which depend upon whether steady state or transient solution were sought. Loads were either neglected or represented by static impedance absorbing constant active and reactive powers. Practical solutions using these simple models were often very difficult and in some cases were not feasible. To overcome some of the difficulties, in late 1920's, Park introduced a new approach to electrical machine analysis (Park, 1929 and 1930). He replaced the variables (voltage, current, and flux linkage) associated with the stator winding of a synchronous machine with variables associated with fictitious windings rotating with the rotor, in the other words, the stator variables were transformed to a frame of reference fixed in the rotor. Since then, this transformation was known as the Park transformation.

The d-q axes frame of reference model provides an accurate study for machine performance under balanced operation. Other advantages of the d-q representation relate to the number of the equations required and the integration step-length that is necessary for the solution. However, the d-q axes models are not easily capable of simulating conditions, such as unbalanced load conditions, unsymmetrical faults, and sequential-pole operation of circuit breakers. With the advent of modern computers, numerical methods can be employed efficiently for solving non-linear differential equations. In such a case, the direct three-phase model can be used for a more exact study of an electrical machine performance. With direct three-phase representation, various faults conditions, such as symmetric, unsymmetrical and sequential conditions, can be simulated with ease. The accurate representation of asymmetrical system operating conditions, due to the use of the direct three-phase machine models, has enhanced the viability and quality of various system studies and greatly extended the range of practical studies currently undertaken. For the best protection signalling, the primary power system should be modelled very accurate.

A high-speed distance relay is defined as a relay which, when supplied with signals which accurately represent line voltages and currents, will operate within approximately one cycle of power system frequency over the majority of its range. Many commercially available relays now fall into this category, and an increasing number of power supply authorities request this level of performance.

Capacitor Voltage Transformers (CVT) are very popular for measurement of voltages of 100kV and above because of their economic advantage, and for many years site experience with relays has been satisfactory (Cigre Study Committee, 1969 and AIEE Committee Report, 1951). It is widely appreciated that CVT's cannot respond quickly to changes in primary voltage. The behaviour of a CVT during transient conditions and the influence of various parameters on its response, have been extensively reported (Sweetana, 1971).

The large number of technical papers about performance of current transformers subjected to initially offset fault currents has hardly been of adequate help to relay engineers in solving their practical problems. Marshall and Langguth (1929) described how a current transformer reproduces a current, which is initially fully offset. Since then a number of papers have been written which are effectively summarized in the IEEE report.

Present work describes the integration of the transducers to the small power system for protection signalling. The dynamic current summation method is the first approach to the development of the small capacity isolated power system.

Modelling of the Primary Power System: Dynamic modelling of the generator, power transformer, and line are developed. The dynamic current summation method (Smith and Chen, 1993) is used in the methodology of machine interconnection. Fig. 1 shows the simple power system network.

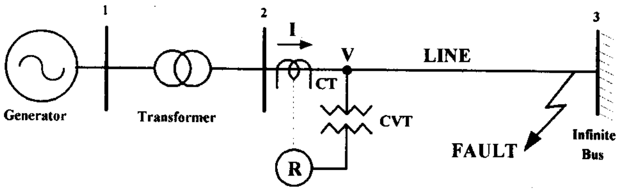


Fig. 1: Simple Power System Network

Development of Mathematical Models: The detailed models of various power system components have been described in the reference (Smith and Chen, 1993) are not repeated here, but it is appropriate that voltage equations, in matrix form, are represented in the following sections.

(a) Synchronous Generator: Because the nodal voltage in the study (Kew, 1990; Shackshaft *et al.*, 1977 and Shackshaft, 1963) the voltage equation for the synchronous generator can be expressed as,

$$[V_{sg}]=[R_{sg}][-I_{sg}]+[L_{ssg}]p[-I_{sg}]+[L_{srg}]p[I_{rg}] \quad (1)$$
$$+\omega_{rg}[G_{ssg}][-I_{sg}]+\omega_{rg}[G_{srg}][I_{rg}]$$

$$[V_{rg}]=[R_{rg}][-I_{rg}]+[L_{rsg}]p[-I_{sg}]+[L_{rrg}]p[I_{rg}] \quad (2)$$
$$+\omega_{rg}[G_{rsg}][-I_{sg}]+\omega_{rg}[G_{rrg}][I_{rg}]$$

The negative sign associated with stator currents in the equations indicates that the current is flowing out of the machine, i.e. flowing into the generator bus.

(b) Induction Motor: The voltage equation for the induction motors can be expressed as,

$$[V_{sm}]=[R_{sm}][I_{sm}]+[L_{ssm}]p[I_{sm}]+[L_{srm}]p[I_{rm}] \quad (3)$$
$$+\omega_{rm}[G_{ssm}][I_{sm}]+\omega_{rm}[G_{srm}][I_{rm}]$$

$$[V_{rm}]=[R_{rm}][I_{rm}]+[L_{rsm}]p[I_{sm}]+[L_{rrm}]p[I_{rm}] \quad (4)$$
$$+\omega_{rm}[G_{rsm}][I_{sm}]+\omega_{rm}[G_{rrm}][I_{rm}]$$

The direction of the current flowing into the machine, i.e. flowing out of the connected bus, is defined as positive.

(c) Power Transformer and Auto-transformer: The components of the power system concerned with system interconnection include transmission lines, power transformers, and auto-transformers. In the small power systems where the actual physical distances are negligible the transmission lines are considered to possess low impedances and the connection between the including generators or induction motors are facilitated by including resistances and reactances of the transmission lines into the machine models. The mathematical models of the power and auto-transformer have been studied without including magnetic non-linearity and hysteresis effects in digital test bed. The voltage equations for the power transformer and auto-transformer can be expressed as,

$$[V_{1t}]=[R_{1t}][I_{1t}]+[L_{11t}]p[I_{1t}]+[L_{12t}]p[I_{2t}] \quad (5)$$

$$[V_{2t}]=[R_{2t}][I_{2t}]+[L_{21t}]p[I_{1t}]+[L_{22t}]p[I_{2t}] \quad (6)$$

The direction of the current flowing into the transformer, i.e. flowing out of the connected bus, is defined as positive.

(d) Static Load: The lumped static load can be modelled as a resistive load (R_k) and a reactive load (L_k). The voltage equation for the load can be expressed by

$$[V_{sk}]=[R_{sk}][I_{sk}]+[L_{sk}]p[I_{sk}] \quad (7)$$

Where,

$$[V_{sk}]=[V_{ak},V_{bk},V_{ck}]^T$$
$$[I_{sk}]=[I_{ak},I_{bk},I_{ck}]^T$$
$$[R_{sk}]=\text{Diag}[R_{ak},R_{bk},R_{ck}]^T$$
$$[L_{sk}]=\text{Diag}[L_{ak},L_{bk},L_{ck}]^T$$

(e) Transmission Lines: The transmission lines can be modelled as a resistive element (R_{TL}) and a reactive element (L_{TL}). The voltage equation for the transmission lines can be expressed by

$$[V_{TL}]=[R_{TL}][I_{TL}]+[L_{TL}]p[I_{TL}] \quad (8)$$

Where

$$[V_{TL}]=[V_{aL},V_{bL},V_{cL}]^T$$
$$[I_{TL}]=[I_{aL},I_{bL},I_{cL}]^T$$
$$[R_{TL}]=\text{Diag}[R_{aL},R_{bL},R_{cL}]^T$$
$$[L_{TL}]=\text{Diag}[L_{aL},L_{bL},L_{cL}]^T$$

Fault Simulations: In this section the formulations required for each symmetrical fault type are derived.

(a) Single-Line Earthed Fault: When a single-phase-earthed fault occurs at the generator bus, for example on phase A, effectively very small impedance is in parallel with the static load and machines. Moreover, the value of the parallel combination is very close to the fault impedance. Therefore, the simulation can be achieved by replacing the impedance of the static load at phase A by the fault impedance. That is

$$R_{ak}=R_f$$
$$L_{ak}=L_f$$

(b) Line-to-line Short Circuit Fault: This is the most complicated for all the fault conditions simulated. It is also an important fault in relation to the generator torsional shaft oscillations because it causes large negative sequence currents to flow which, in turn, may coincide with the blade natural frequency (Smith and Chen, 1993). Fig. 2 illustrates a simple configuration for line-line short-circuit analysis. When a line-line fault occurs, it may be represented by a fault impedance across phase A and phase B and as a consequence an additional differential equation is introduced:

$$V_{ak} - V_{bk} = R_f I_f + L_f pI_f \quad (9)$$

The current relationship between generator and load can be represented by,

$$I_{as} = -\sum_{i=1}^{n} I_{al} - I_f \quad (10)$$

$$I_{bs} = -\sum_{i=1}^{n} I_{bl} + I_f \quad (11)$$

$$I_{cs} = -\sum_{i=1}^{n} I_{cl} \quad (12)$$

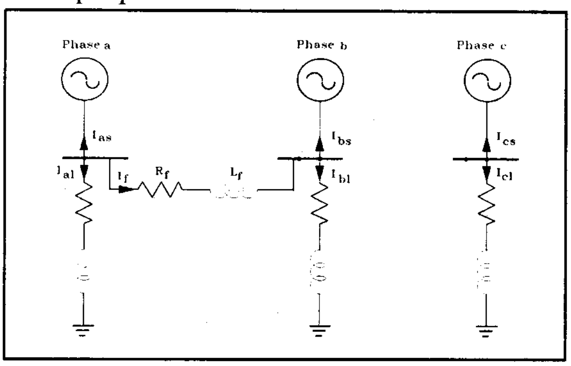


Fig. 2: Simplified Configuration for Line-line Fault Analysis

(c) Three-phase Balanced Fault: To complete the procedures for representing system faults the three-phase fault condition is considered here. In simulation of a balanced three-phase fault, only the static impedances are replaced by fault impedances. That is

$$R_{ak} = R_{bk} = R_{ck} = R_f$$
$$L_{ak} = L_{bk} = L_{ck} = L_f$$

Transducer Modelling: Dynamic modelling of the current transformer has been developed for the transient analysis of the equivalent circuit of the current transformer using the core model previously described (Tumay and Simpson, 1994). The developed routine is fully stable and is used to simulate the transient response of the current transformer, to asymmetrical fault currents.

Capacitive voltage transformer have been modelled by using equivalent circuit of the single phase CVT The core has been represented including magnetic nonlinearity and hysteresis effects (Tumay and Simpson, 1993).

Inclusion of Transducers Models: Fig. 1 shows the single line representation of a small power system model, which includes transducers for protection signalling. The main program (The digital test bed) composes of a main segment and 12 subroutines as follows.

Pspsdss: This is the main program. It reads the data for generators and load components, refers parameters to p.u. system, calculates initial values for the system variables, set up control flags.

Avrin, Icgov,Gviesc: These subroutines read the data, set up the initial values for the system variables, and calculate time increments of state variables for AVRs.

Govin, Icgov,Gviesc: These subroutines read the data, set up the initial values of the state variables, and calculate the increments of the state variables for gas-turbine prime movers.

RKG1: This is the integration subroutine

THPI: This subroutine calculates the rates of changes of system variables, calculate electro-mechanical torques, bus voltages, and etc.

Matrix: This subroutine sets up the [R],[L],[G] matrices for the system.

Gauss: This subroutine solves linear equations by Gaussian elimination.

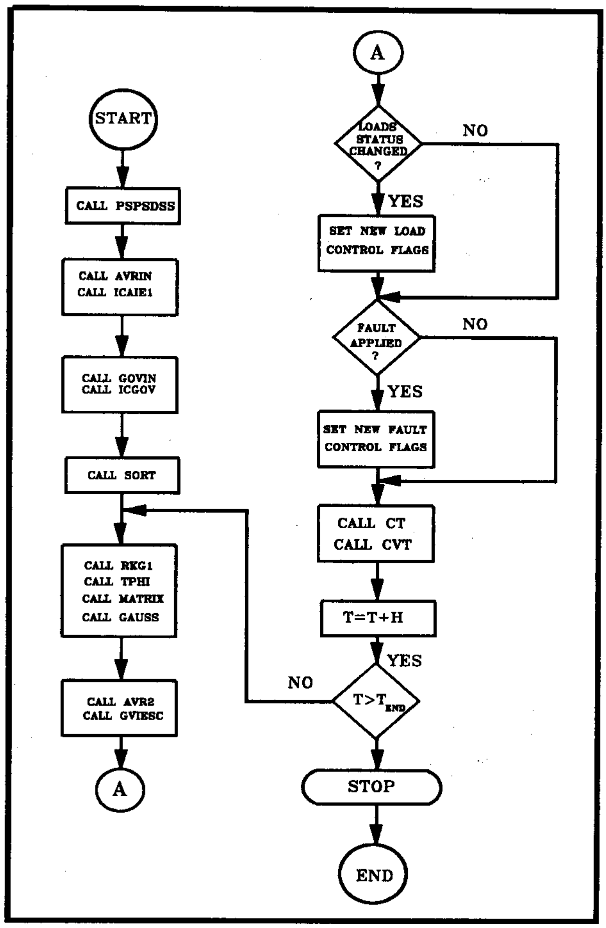
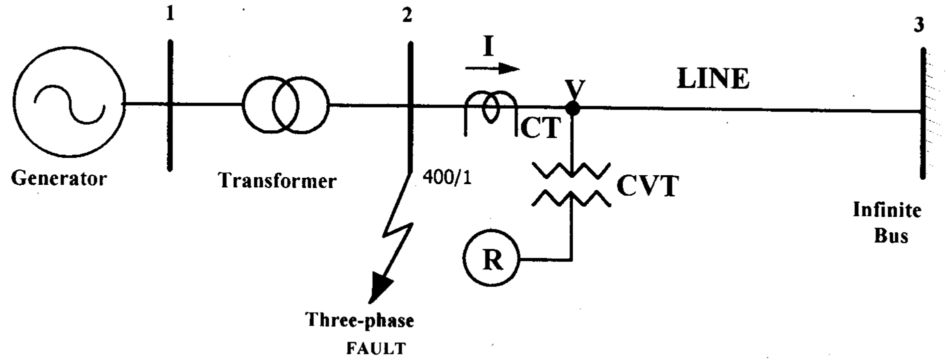
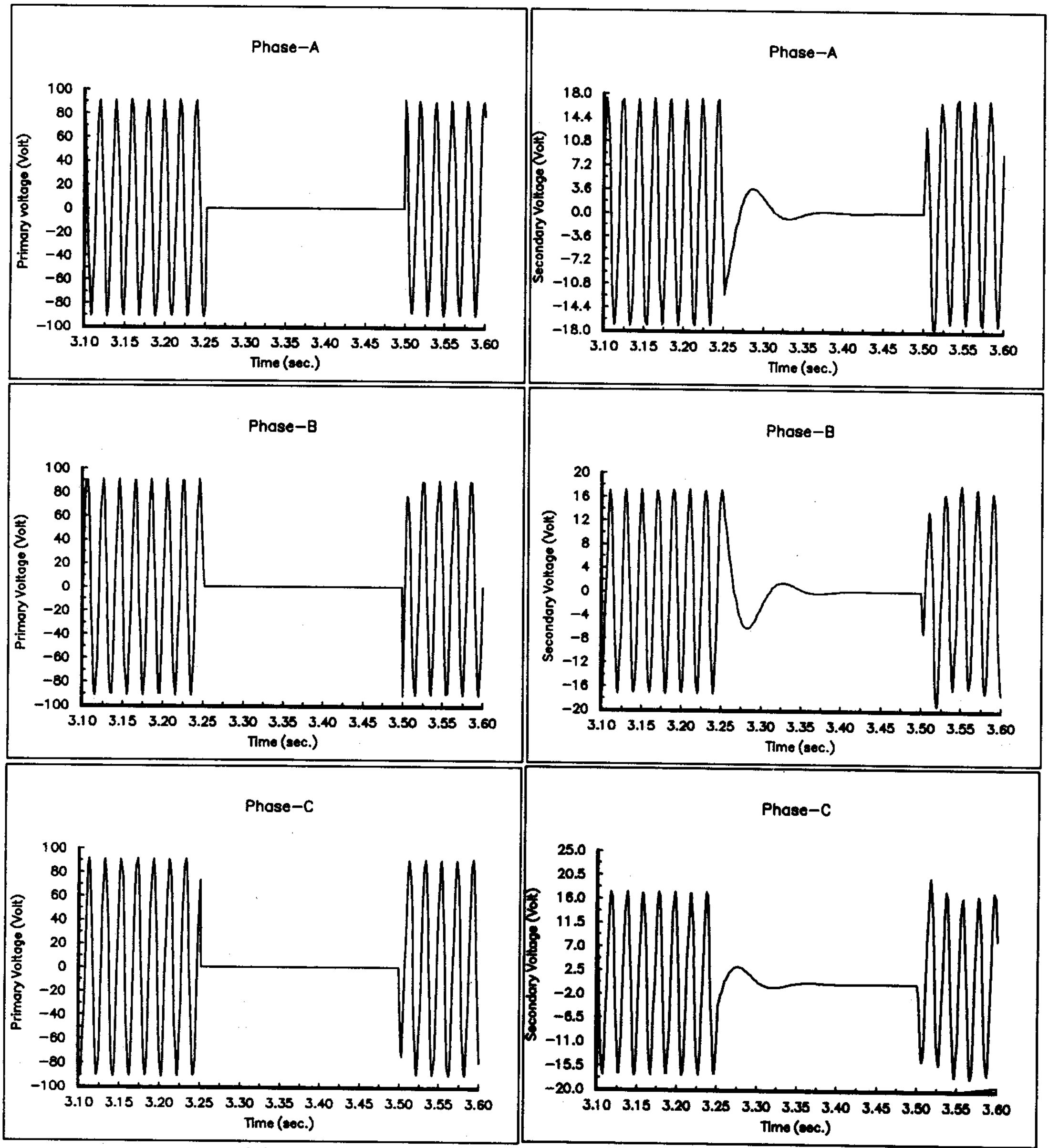


Fig. 3: Flow Chart of the Digital Test Bed and the Integration of the Transducers

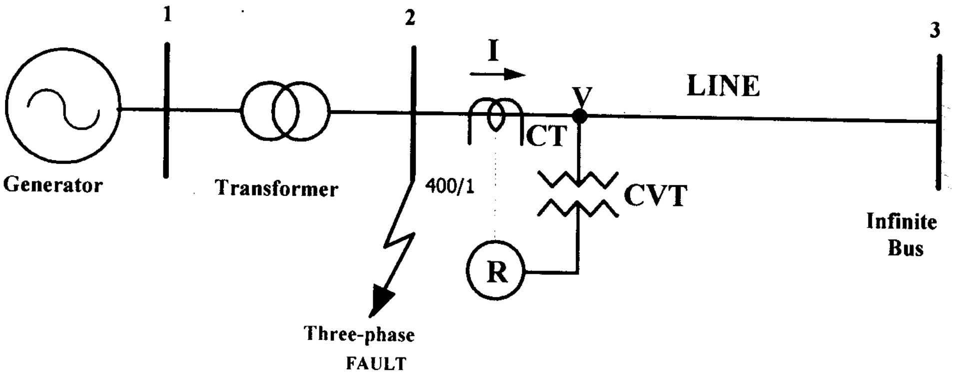


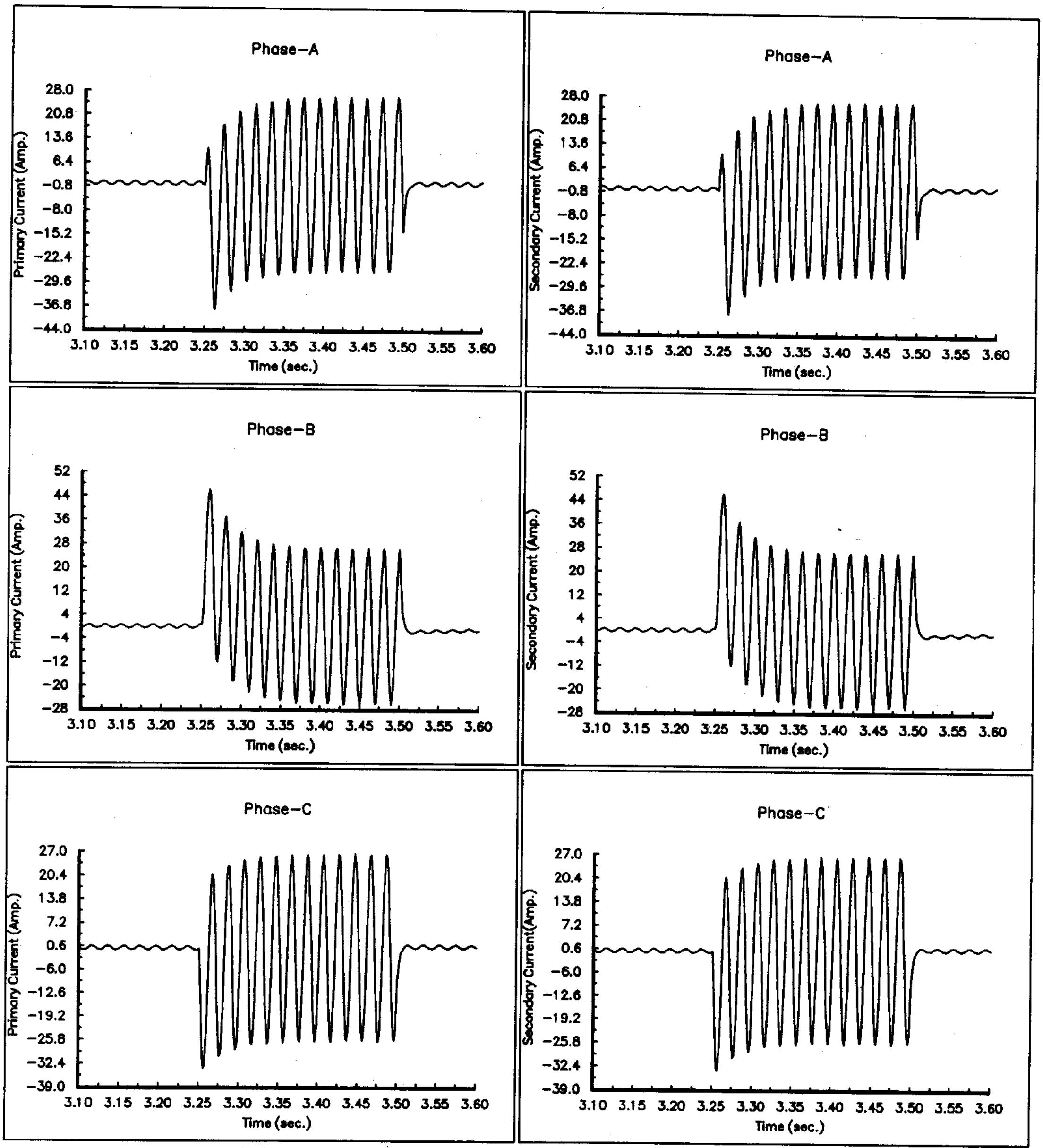


(a) (b)

Fig. 4a: Primary Voltages, $R_b = 2.5\Omega$

Fig. 4b: Secondary Voltages, $R_b = 2.5\Omega$

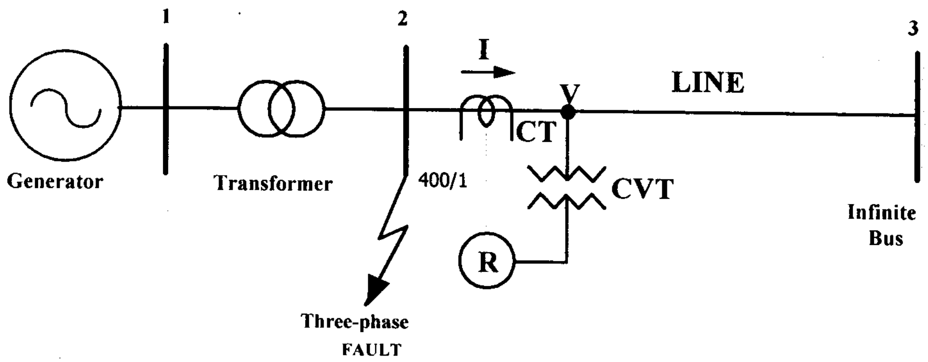


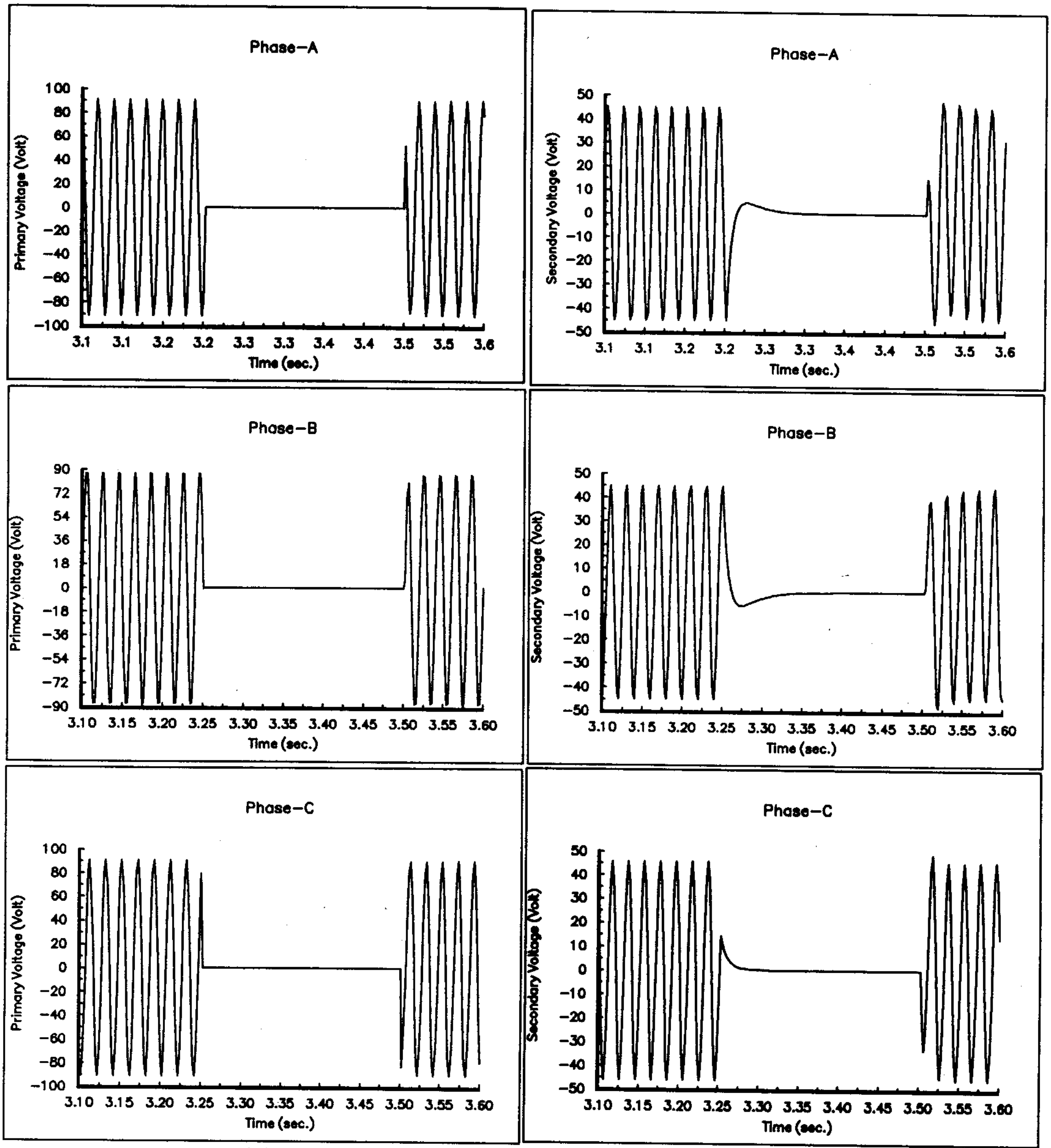


(a) (b)

Fig. 5a: Primary Currents, $R_b = 1.0\Omega$

Fig. 5b: Secondary Currents, $R_b = 1.0\Omega$

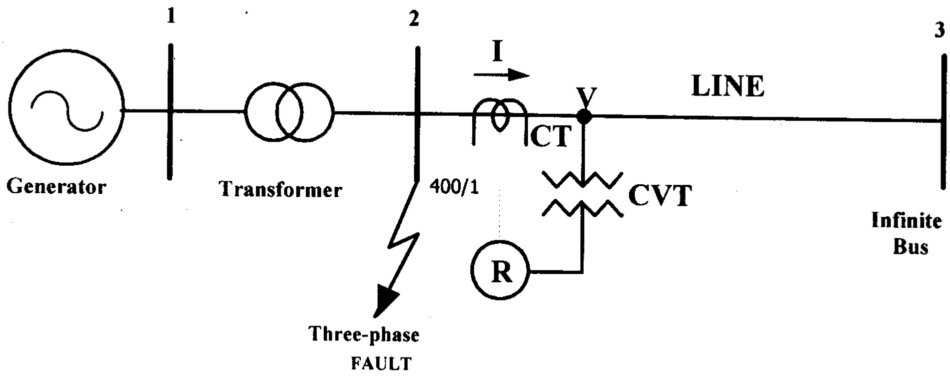


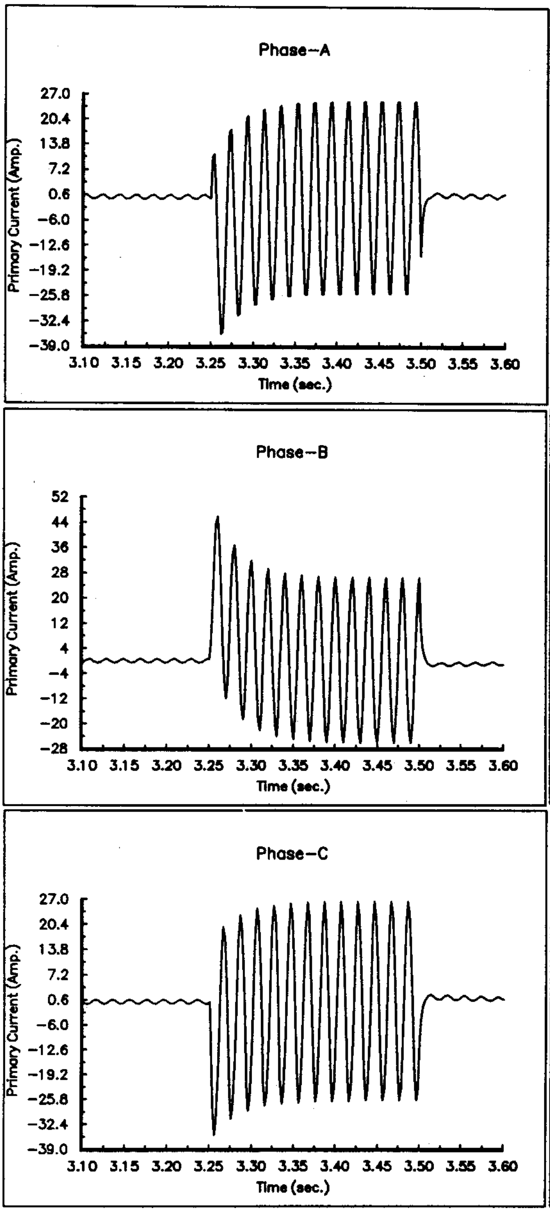


(a) (b)

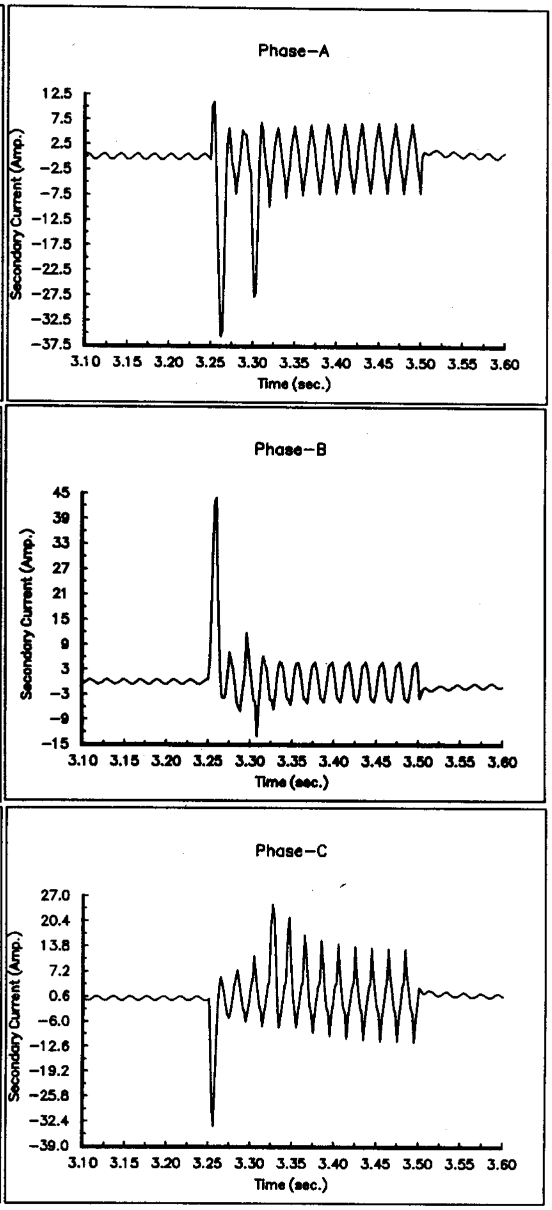
Fig. 6a: Primary Voltages, $R_b = 7.5\Omega$

Fig. 6b: Secondary Voltages, $R_b = 7.5\Omega$





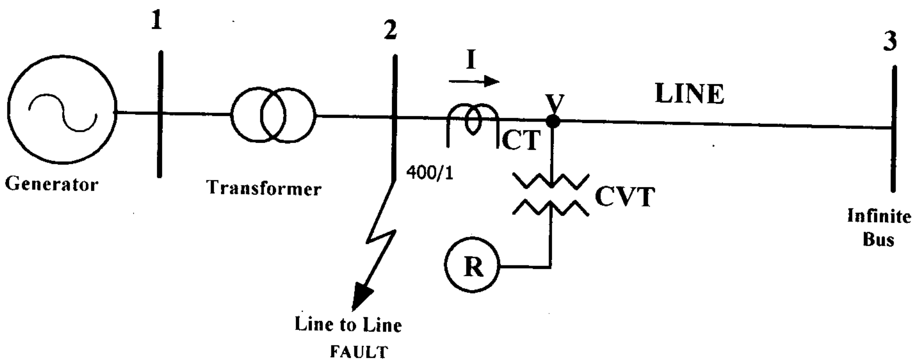
(a)

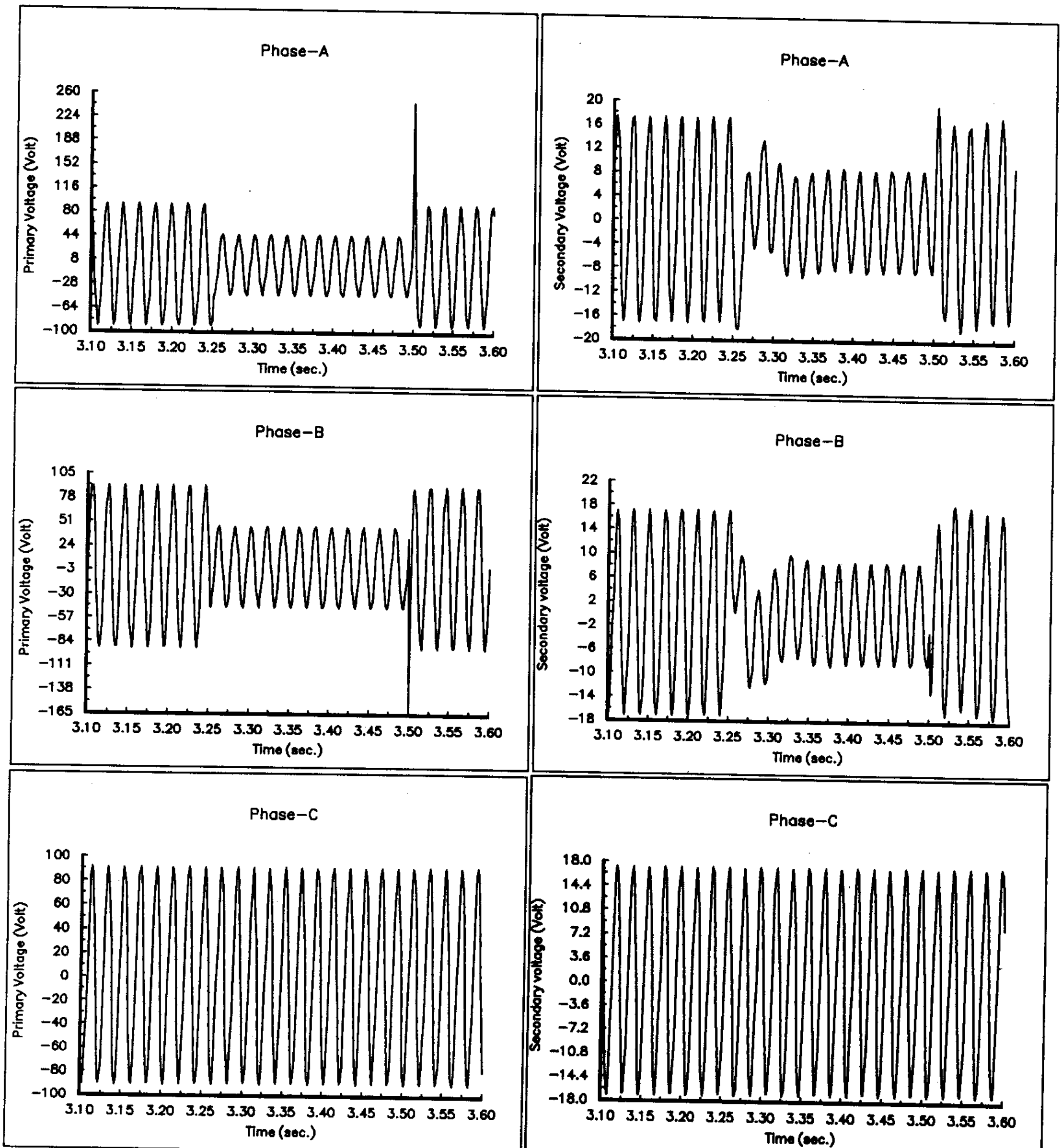


(b)

Fig. 7a: Primary Currents, $R_b = 5.0\Omega$

Fig. 7b: Secondary Currents, $R_b = 5.0\Omega$

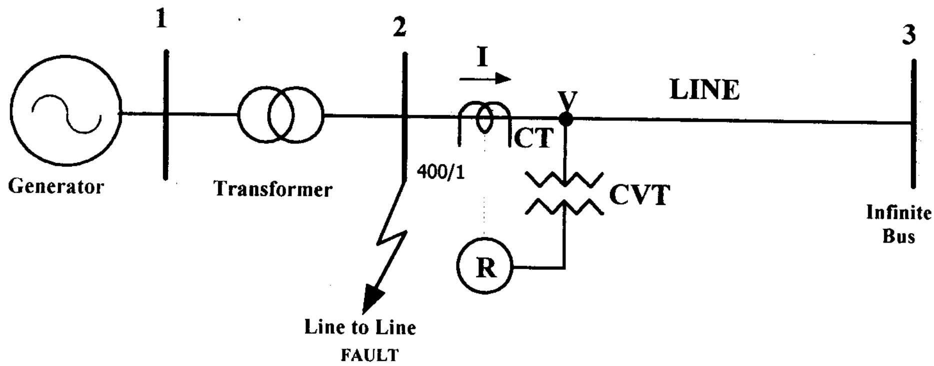




(a) (b)

Fig. 8a: Primary Voltages, $R_b = 2.5\Omega$

Fig. 8b: Secondary Voltages, $R_b = 2.5\Omega$



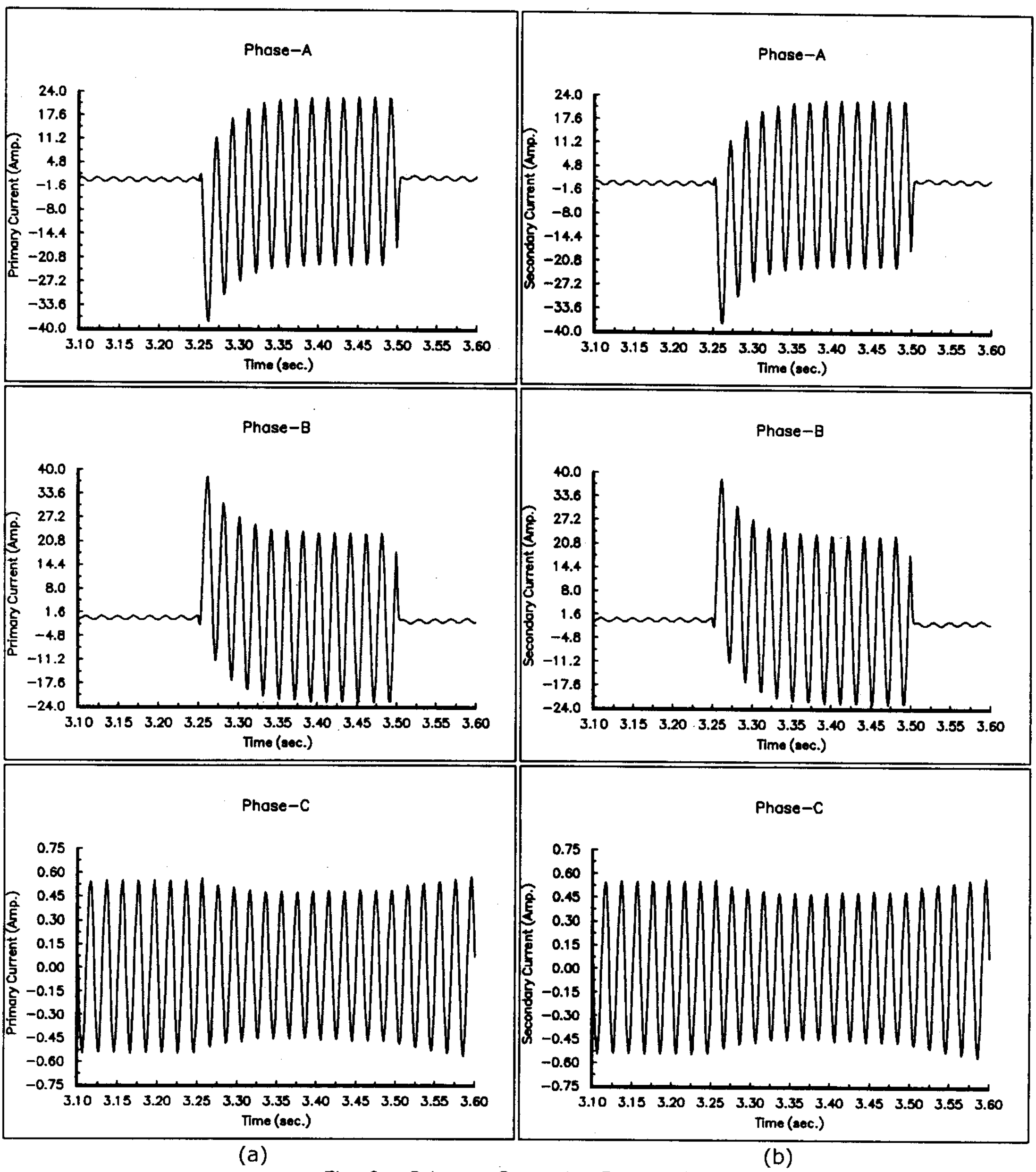
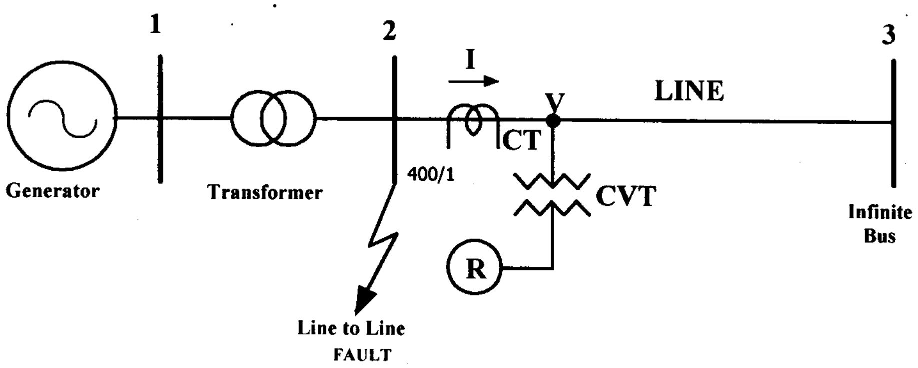
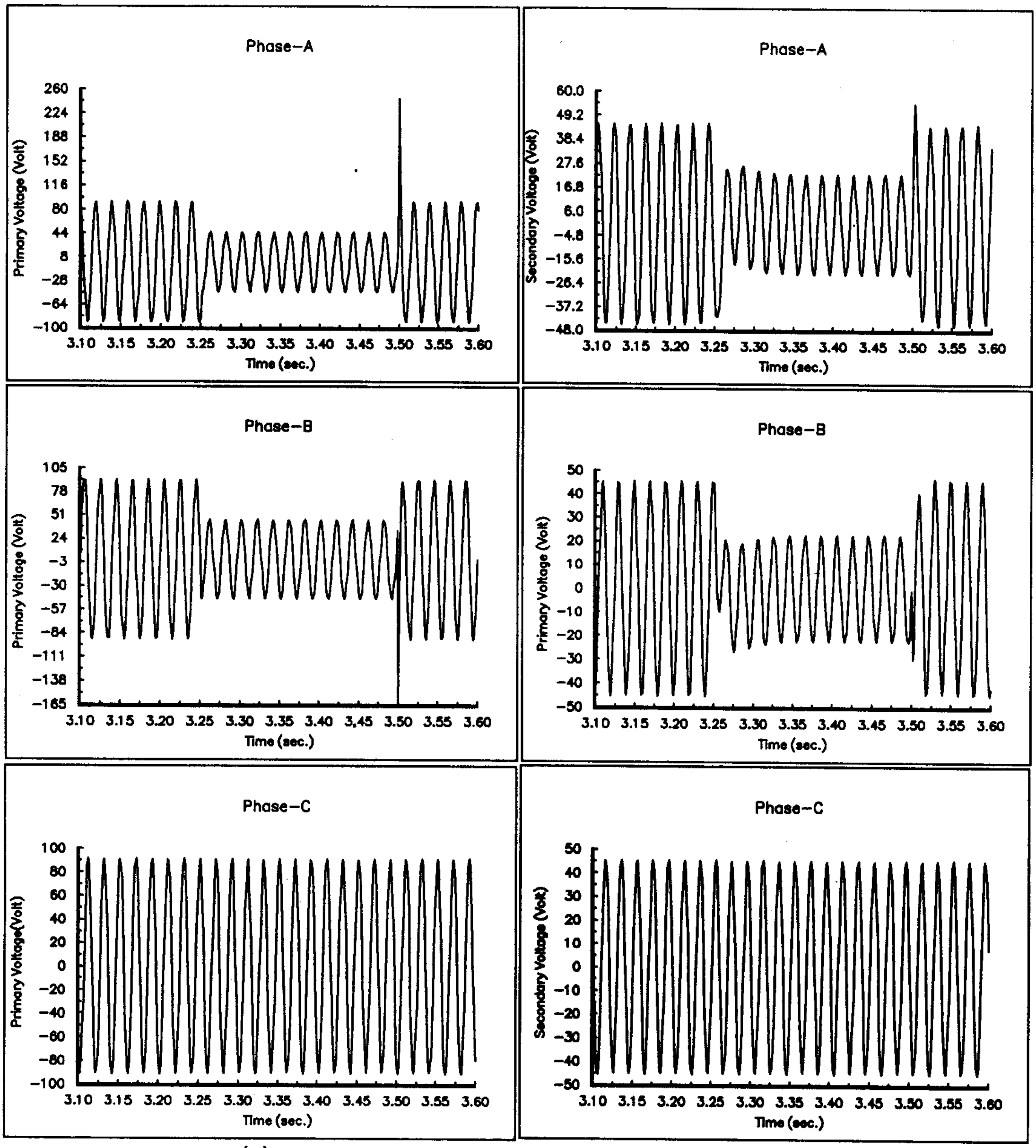


Fig. 9a: Primary Currents, $R_b = 1.0\Omega$

Fig. 9b: Secondary Currents, $R_b = 1.0\Omega$

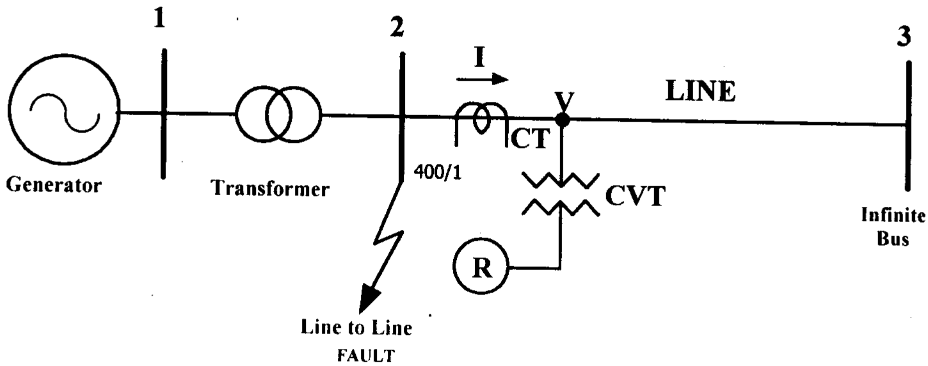


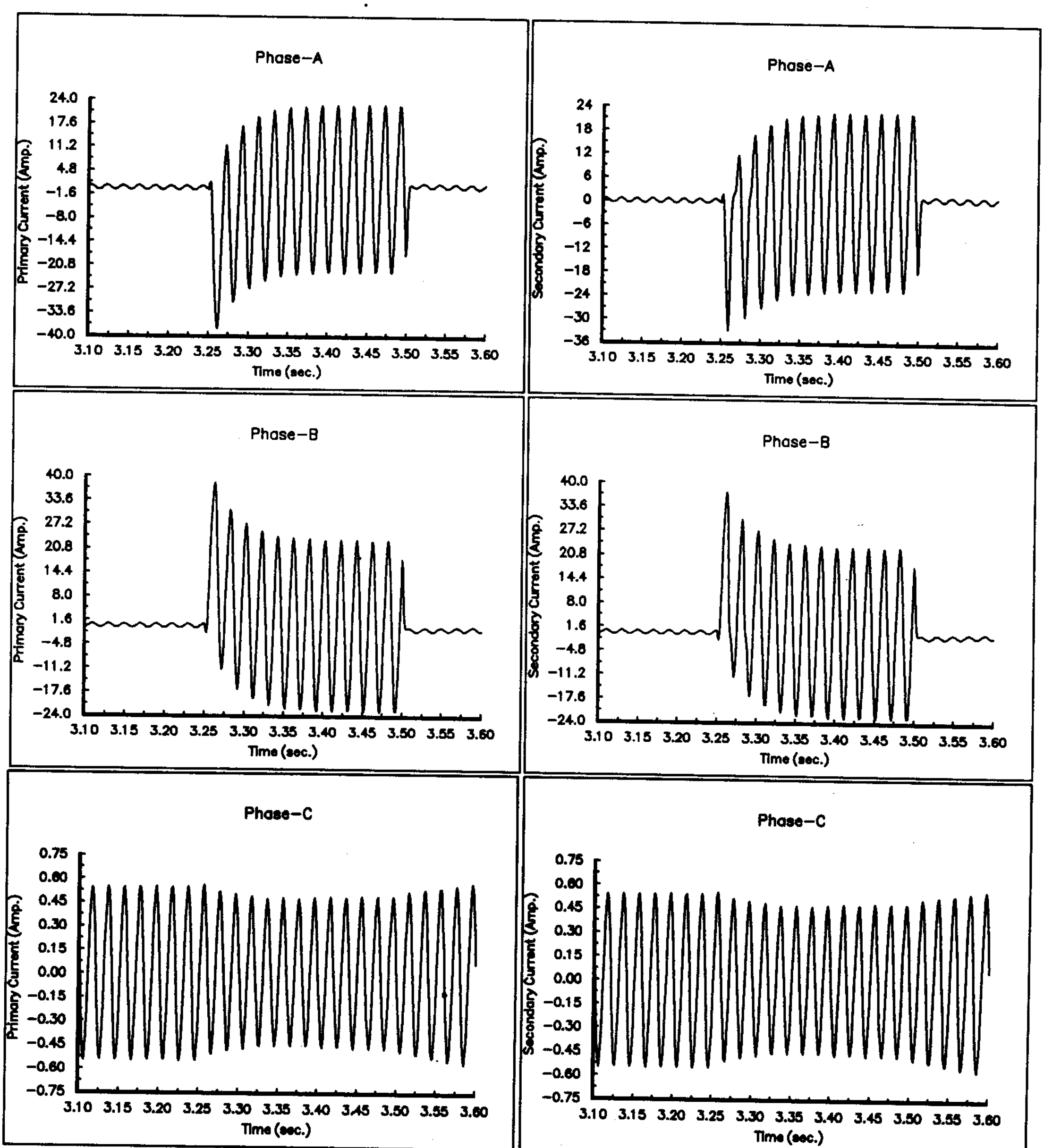


(a) (b)

Fig. 10a: Primary Voltages, $R_b = 7.5\Omega$

Fig. 10b: Secondary Voltages, $R_b = 7.5\Omega$

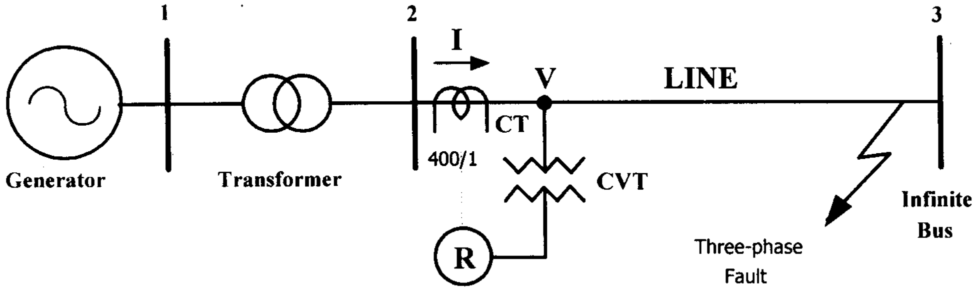


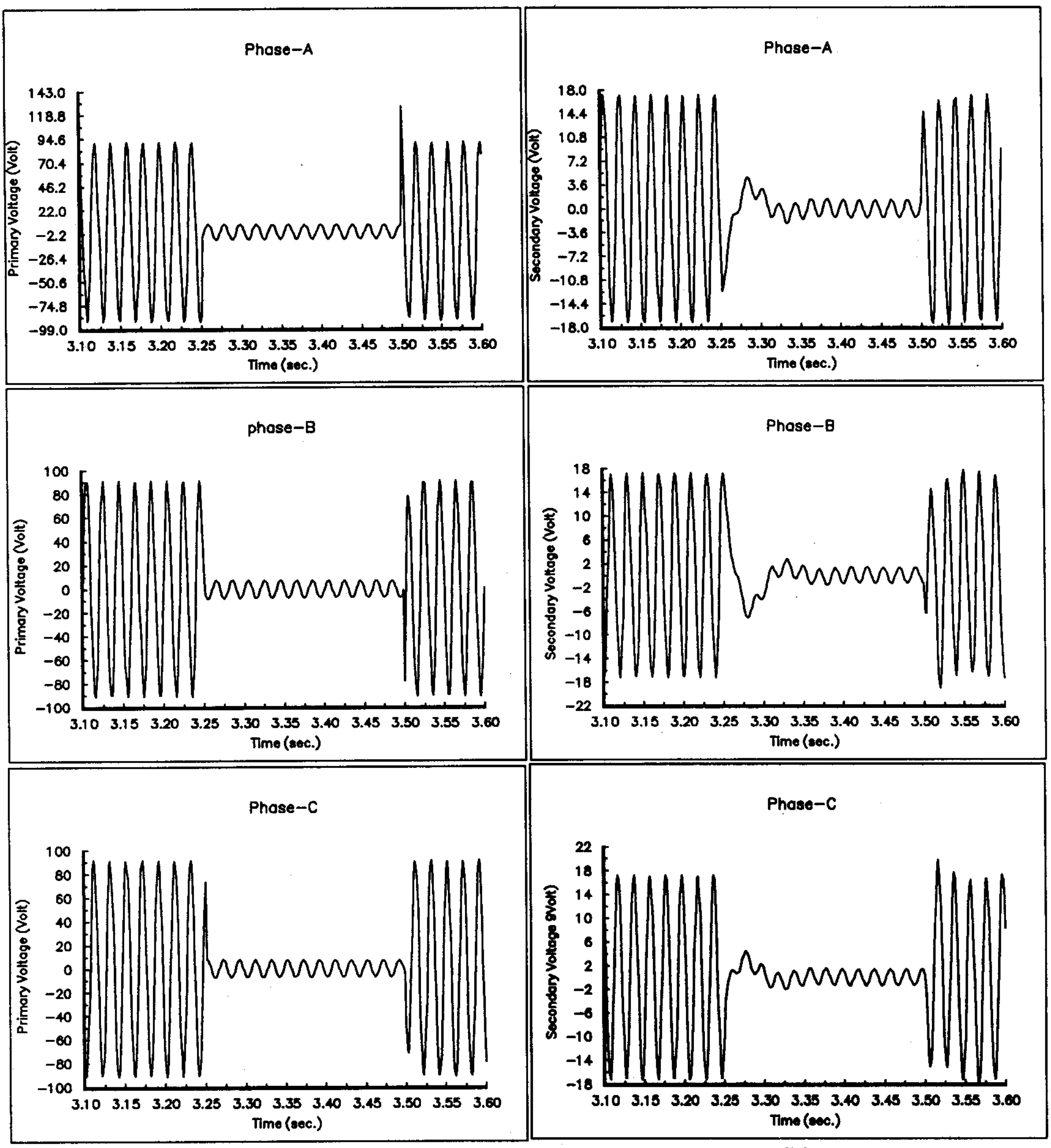


(a) (b)

Fig. 11a: Primary Currents, $R_b = 5.0\Omega$

Fig. 11b: Secondary Currents, $R_b = 5.0\Omega$

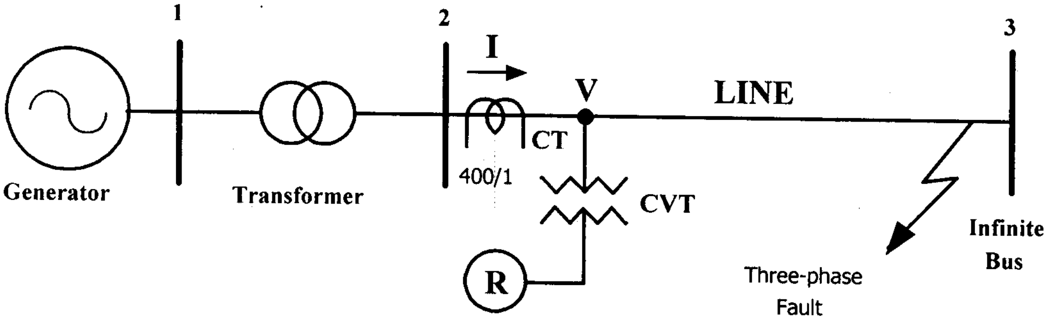


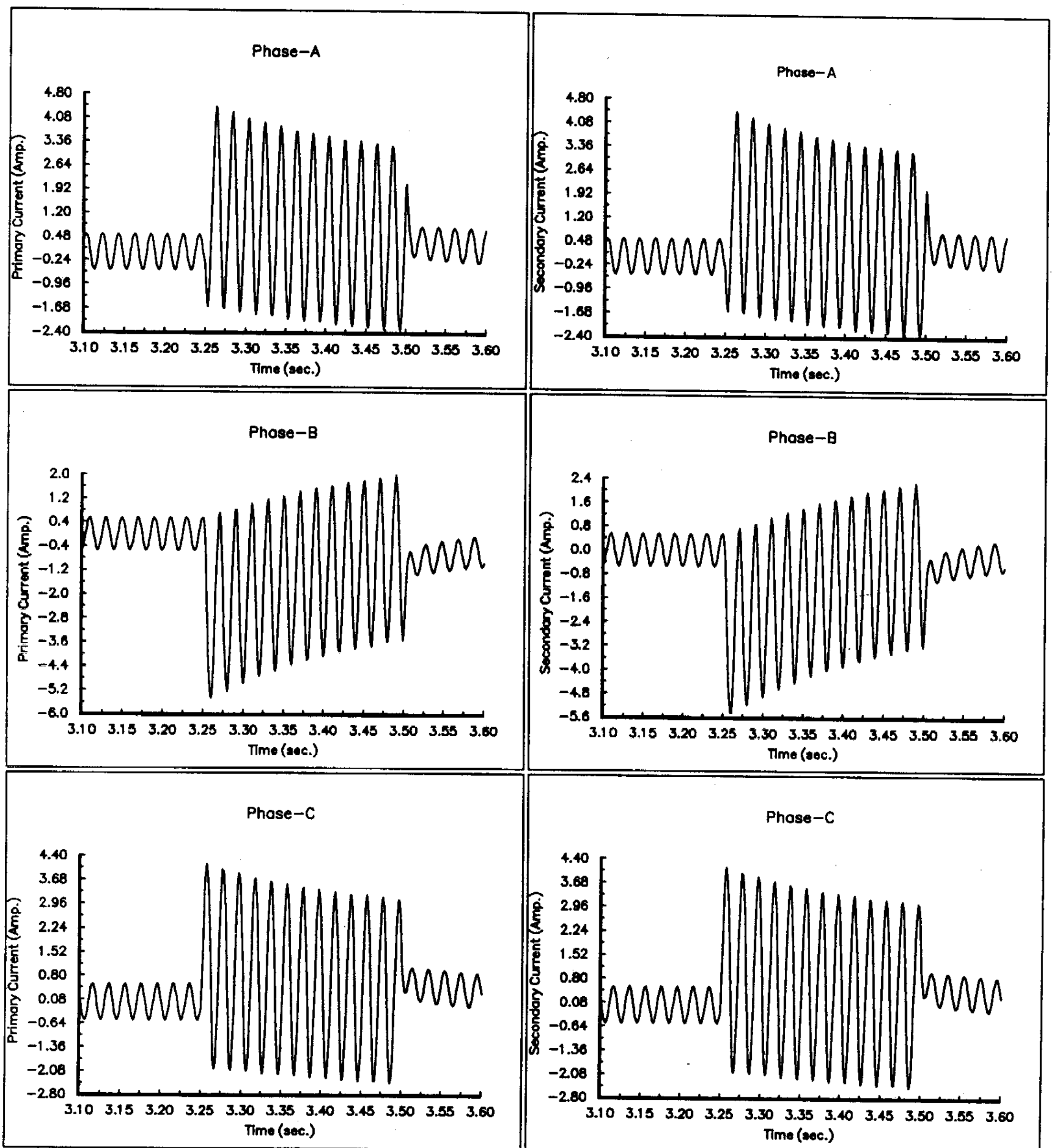


(a) (b)

Fig. 12a: Primary Voltages, $R_b = 2.5\Omega$

Fig. 12b: Secondary Voltages, $R_b = 2.5\Omega$

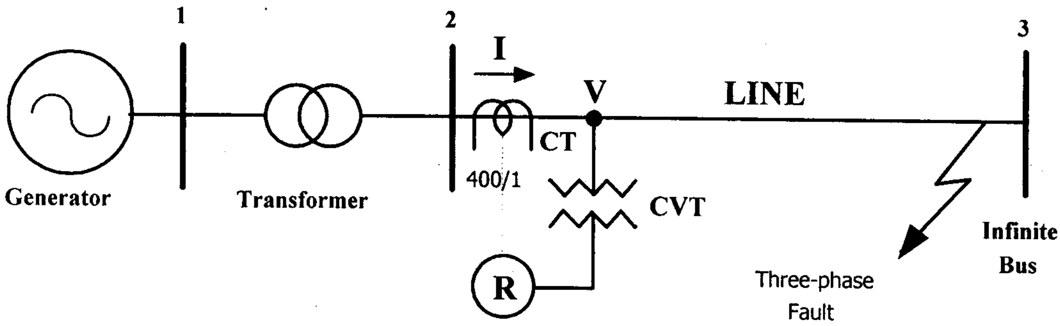




(a) (b)

Fig. 13a: Primary Currents, $R_b = 1.0\Omega$

Fig. 13b: Secondary Currents, $R_b = 1.0\Omega$



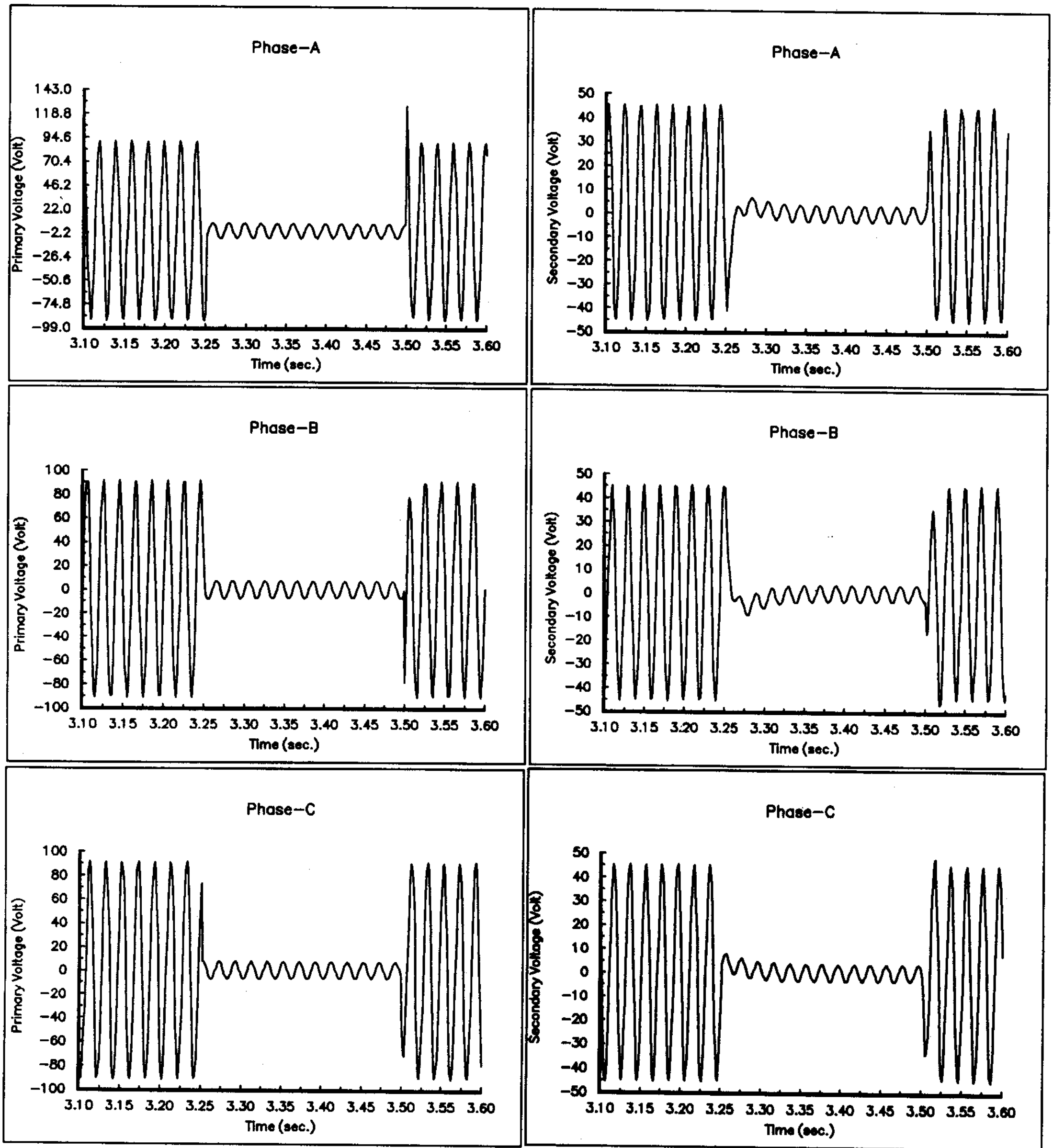
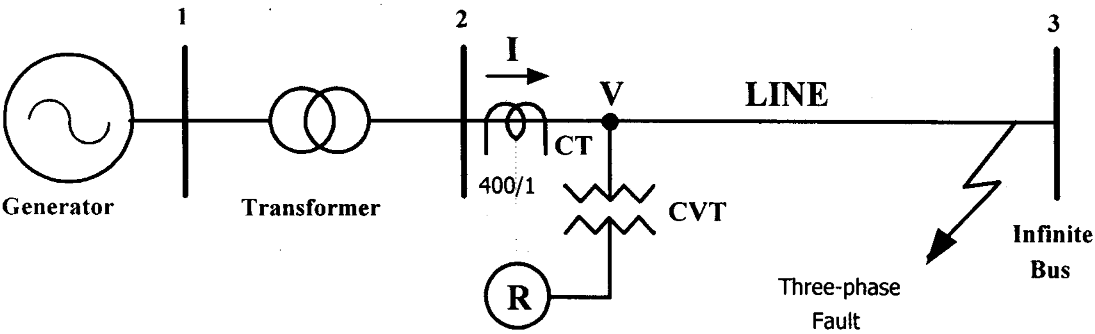
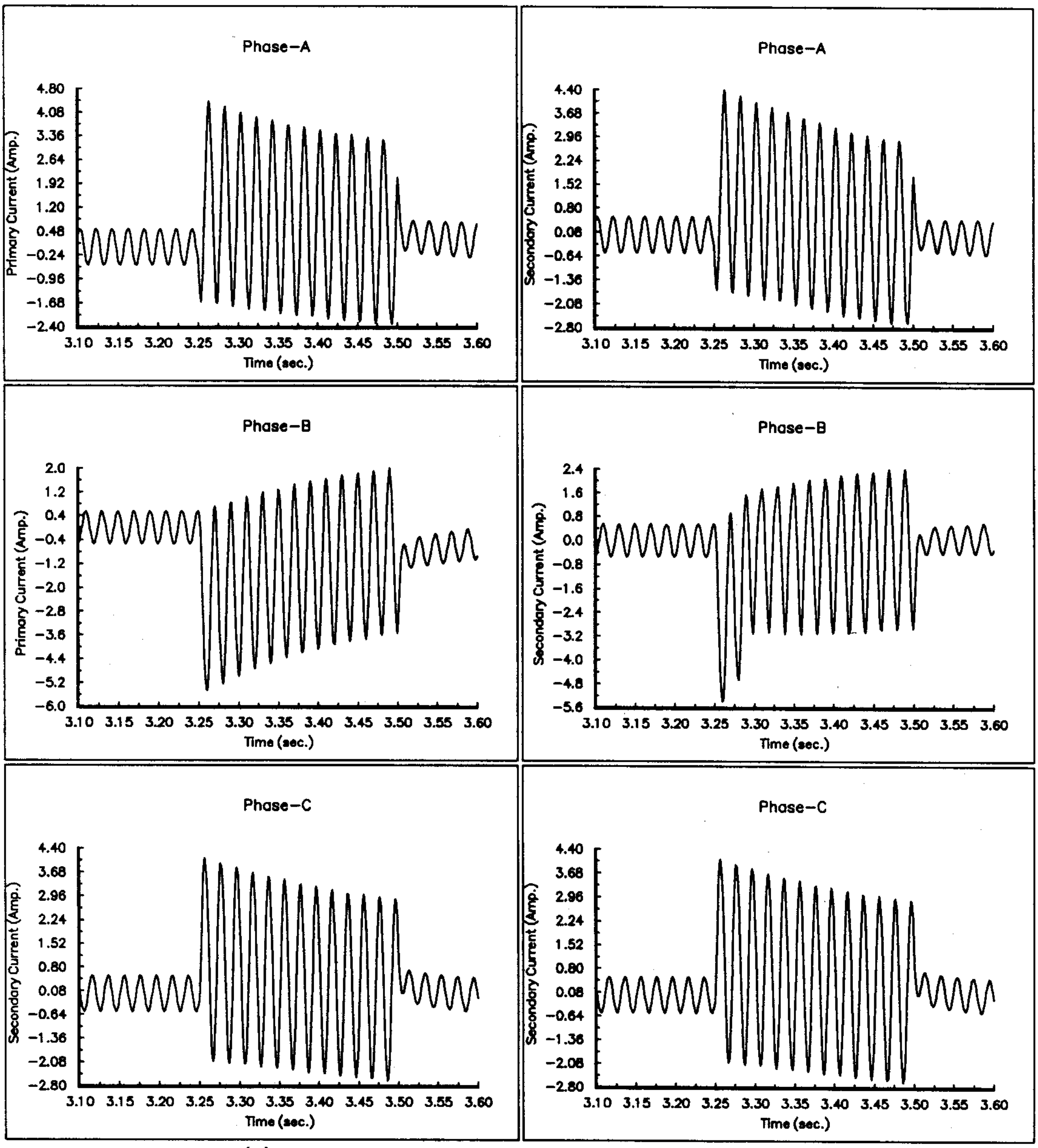


Fig. 14a: Primary Voltages, $R_b = 7.5\Omega$

Fig. 14b: Secondary Voltages, $R_b = 7.5\Omega$





(a) (b)

Fig. 15a: Primary Currents, $R_b = 5.0\Omega$

Fig. 15b: Secondary Currents, $R_b = 5.0\Omega$

Sort: This subroutine sorts switching sequences by time.

The transducer modelling programs are called after the line voltages and currents are calculated. The line voltages required for the CVT subroutine. The line currents are required for the CT subroutine. Per unit values are used in the main program but they are converted to the actual values when transducer subroutines are called. The flow chart of the system is shown in the Fig. 3.

Simulation Examples: Fig. 1 shows the schematic diagram of the system studied. This small power system is used as a digital test bed for testing the current and capacitive voltage transformer response. Different types of fault are applied to the different bus bars.

For the first simulation different faults are applied to the bus number 2. For the second simulation a three-phase fault is applied to the bus number 3. A series of graphical outputs were produced.

For the current transformer

a-) Primary current (phase-a,b,c referred to the secondary side)

b-) Secondary current (phase-a,b,c)

For the capacitive voltage transformer

a-) Primary voltage (phase-a,b,c)

b-) Secondary voltage (phase-a,b,c)

For the each simulations CVT and CT burden resistances are increased. The burden resistance of the current transformer is taken as 1, 5 ohms at each simulation examples. The burden resistance of the CVT is taken as 2.5, 7.5 ohms respectively. Figures 4 and 15 show some selected results for the simple power system network simulation examples.

Conclusion

This paper has described a general procedure for obtained a transient model of the primary power system and the transducers modelling in three-phase coordinates. The purpose of the simulation is to study the dynamic performance of a small power system and the transducers for power system protection signalling when subjected to fault conditions. To illustrate the versatility of the software, a study was conducted on the basis of the small power system shown in Fig. 1. The paper has also presented an explanation of the digital test bed and the integration of transducers for dynamic protection signalling. The effect of the CT and CVT burden impedances are examined by applying different faults to the different bus bars. The results show that increasing burden resistance causes distorted secondary waveforms.

Acknowledgements

I would like to thank Prof.J.R. Smith and Electrical Machinery Group of Strathclyde University for their help.

References

AIEE Committee Report, 1951. "The effect of coupling capacitor potential device transient on protective relay operation", AIEE Trans. Pp.2089-2096.

Cigre Study Committee, 1969. 34:"Considerations of dynamic performance and testing procedures for high speed protection and associated current transformers and voltage transformers" Study Committee: 34 Interim Report.

D.E.Marshall and P.O.Langguth, 1929. Current Transient Excitation Under Transient Conditions" AIEE Trans. 48,pp,1464-1474.

G.Shackshaft, O.C. Symons and J.G.Hadwick, 1977. "General Purpose Model of Power System Loads" IEE Proc. 124, pp.715-723.

G.Shackshaft, 1963. "General-Purpose Turbo-Alternator Models", IEE Proc. 110, pp.703-713.

IEEE Committee Report, " Transient Response of Current Transformers" IEEE Product: 76CH1130-4

J.R.Smith and Meng-Jen Chen, 1993. " Three-phase electrical machine systems computer simulation" Research Studies Press. Ltd.

M.S.Kew, 1990. " Dynamic Analysis of Multimachine electro-mechanical systems" Ph.D. Thesis, Uni. of Aberdeen.

M.Tümay, R.R.S.Simpson, 1994. " Dynamic Modelling of Hysteresis Loops for Power System Studies" Proceeding of the 29 th Universities Power Engineering Conference 1994 pp.629-632.

M.Tümay, R.R.S.Simpson, 1993. " Detailed Model of current Transformer including magnetic non-linearity and hysteresis effect" Proceeding of the 28 th Universities Power Engineering Conference pp.259-262

R. H.park, 1929. " Two Reaction Theory of Synchronous Machines-I", AIEE Trans. 48, pp.716-730.

R.H.park, 1930. " Two Reaction Theory of Synchronous Machines-II", AIEE Trans. 51, pp.352-355.

Sweetana A., 1971. "Transient Response Characteristics of Capacitive Potential Devices" IEE Winter Meeting, New York 71 TP197-PWR.