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Distributed Generation Impact on Fault Response of a Distrubution [I.E., Distribution] Network

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DISTRIBUTED GENERATION IMPACT ON FAULT RESPONSE OF A

DISTRUBUTION NETWORK

By

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DISTRIBUTED GENERATION IMPACT ON FAULT RESPONSE OF A DISTRIBUTION NETWORK

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Electric power systems are a key infrastructure today. Power systems can be divided into three major parts: generation, transmission, and distribution. Out of these the distribution system is the most complex part and least studied system. In order to have continuous and reliable power to all customers it is necessary to have a good protection system. Major disturbances that are caused and last for a very short duration are called faults. With the advent of distributed generation (DG), the understanding of fault response has become more difficult. This thesis presents the study of the fault response and the factors that influence the fault response with and without DG. As a part of the fault analysis line to ground faults are placed at various locations on the IEEE 13 node feeder test case. Simulations are conducted in PSCAD and the results are analyzed. At each node the voltage and the current changes at the time of the fault are recorded. A DG is added to the system and is located at various nodes for each fault and the impact of the DG on the fault voltage and current

quantities is recorded. A comparison of the impact of faults at various locations is presented. The impact of faults without DG and with DG is also analyzed.

DEDICATION

I would like to dedicate this research to my grandfather late Mr. Kanduri Venkatacharyulu

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Chapter I

Introduction

I.I Introduction

Electric power is the major source of energy to the world today. The power is generated at the generating stations and brought all the way to our premises. Due to economics of scale and environmental concerns, generation facilities have been large power plants (100s of MW) and were located in non-populated areas away from loads. There are many power system components that are necessary to accomplish this. Power lines, cables, transformers and many such devices are along the way from the generation plant to the customer premises. Each of these components has its own reaction (characteristics) to the flow of power.

1.2 New Interests in Distributed Generation

The generation plants that operate on coal or nuclear fuel cause a lot of pollution. The energy available from sun and wind are absolutely clean and do not produce any pollutants that can damage the atmosphere. And moreover this energy is free; all that is needed to be done is to fid a way to use this energy. Solar cells and windmills can be installed and electricity can be produced from them. Apart from this due to the increase in the demand the large generators cannot be over loaded but a cost efficient method was needed. DG costs have decreased because of new technologies and are more viable. The other major issue that triggered the start of distributed generators was the T&D costs from the 19th century [1]. Hard to get new distribution lines so current transmission lines are getting overloaded meaning the new generation needs to be closer to load. So new technologies like the distributed generation have come up.

1.3 Faults in power systems

Faults are a sudden short circuit in the network caused by various factors. The actual time for which these faults are present is very small when compared to the actual steady state condition to which the components are exposed. Yet the study of faults is very necessary, for it is at such times that the power system components are subjected to greatest stress. But unfortunately only a few Electrical engineers only have a very little conception of what might happen to the components during these times.

This document presents the study of reaction of the components to certain types of disturbances in the system. The disturbances are usually referred to as faults. There are many types of faults in a power system network. In this document only the single phase line to ground faults are addressed. The IEEE 13 node feeder is modeled in PSCAD and faults at various locations are simulated and the impact at various locations on the feeder is analyzed. Then a distributed generator is added at different locations and the impact of the above faults is analyzed in the presence of DG.

1.4 Overview of thesis and Organization

In this thesis, the research work consists of three parts: The first part focused on modeling of the IEEE 13 node feeder in PSCAD, which is a very powerful tool for transient simulation. The second part deals with the fault response of the network. On the technical side, an evaluation has been done to compare the differences in the results obtained by modeling the IEEE 13 node feeder in PSCAD and the standard results. The load data given in the literature and the configuration of the feeder model are well suited for any type of transient studies. Results obtained on this feeder can be generalized for any small distribution systems.

Second part of this thesis focused on the impact of faults on the distribution feeder. Faults at various locations have different impacts on the system. These are analyzed and a general conception on fault impact is obtained. Faults included are line to ground and line to line.

The third part includes the effect of distributed generation. The impact of location of DG, size of DG, and the type of DG are discussed. The effect DG on the impact of faults is also studied.

The theoretical concepts and the work done to understand the behavior of the distribution system to faults are discussed in this document. In this chapter faults and distributed generation were introduced with the causes and the necessities. Next, the need for distributed generation and the importance of the knowledge on faults explained. Chapter 2 will provide the background information about the project. This includes the discussion of types of faults, factors that contribute to faults like capacitor banks and various DG technologies.

Chapter 3 will focus on issues to be studied and literature review on fault studies and small-distributed generation technologies and its characteristics. Impact of load and capacitor banks on faults, location impact of DG, and the impact of size of DG are discussed. Chapter 4 includes the analysis of the IEEE 13 node feeder and the various issues covered in it. Chapter 5 deals with Results and discussion. And chapter 6 deals with conclusions, future work and chances of expanding the project.

CHAPTER II

BACKGROUND

2.1 Introduction of Power Systems

The world today is more dependent on the electrical energy than any other energy. The power systems consist of three major components: power generation, transmission and distribution systems. Figure 2.1 shows the basic divisions of power systems.

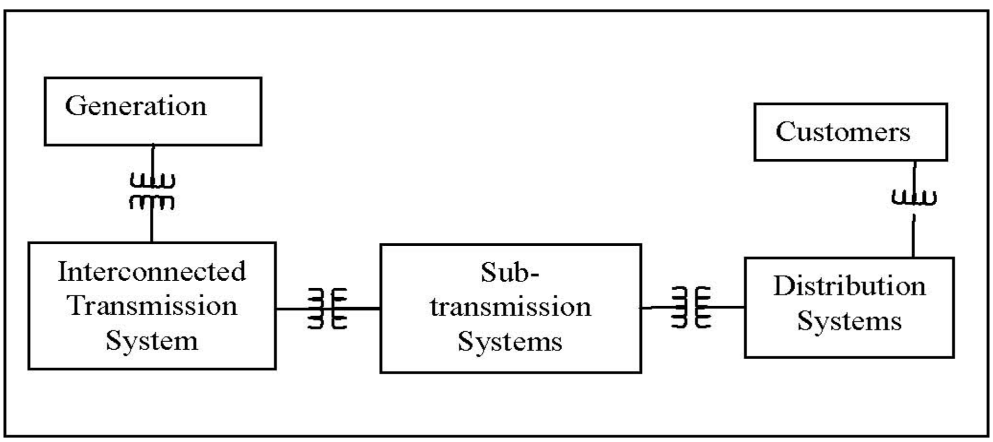


Figure 2.1 Typical Power System Components [2]

2.2 Generation

The bulk of the electrical power used today is produced at a centralized station. Most of these use large fossil fuel combustion engines, nuclear boilers, or the kinetic energy of water available at dams [4]. These generators are usually very large and at times they are a group of two or more generators. These generating stations are usually located a large distance from the urban environments. The main reasons are due to the pollution and the requirement of very large area for the construction of such a huge structure.

2.3 Transmission

The power that is produced at a distant location has to be brought to the load centers in cities. The only way this can be accomplished is over some conductors. The conductors that transmit power from the generation plants to the substations located in the cities are called transmission lines. These transmission lines are also a major component of the electric power network.

2.4 Distribution

The power from the generation stations is brought to the distribution substation over the transmission lines. The power is distributed to all the customers from the substations. So a typical power system is a combination of generation, transmission and distribution.

With such a complex system there is always a chance of some disturbance. This disturbance can occur at any point in the network shown in Figure 2.1 above. These faults last for a very short time but still have significant effects on the system. So the study of the impact of faults becomes very necessary.

2.5 Distributed generation

The demand for electricity has increased a lot from the early 19^{th} century. Due to the increase in the demand the large generators cannot be over loaded but a cost efficient method was needed. Apart from that the transmission and distribution (T&D) costs also increased a lot from the 19th century [3]. So new technologies such as distributed generation have come up. These technologies are cost efficient and easy to install. Small-distributed generators can be used to serve the peak loads, which are present during a particular time of the day [4]. These are not only economical but they are with in the vicinity of the customer and hence reduce the T&D costs also. With the inclusion of these small generators, the power system network has become even more complicated to understand. In such a situation it is very necessary to know ahead of time the reaction of the components to any changes in the system. So the response of the system under the influence of DG to any faults should be understood.

2.6 Types of distributed generation technologies

The available small-distributed generation technologies in the market with their applications are shown in Table 2.1.

Table 2.1
Options for small-scale distributed generation [5]

Type	Size range (kW)	Electrical Efficiency (%)	Applications
Reciprocating Engines	5-7000	25-45	Backup power, base load, grid support and peak shaving
Fuel cell	1-10000	40-65	Co-generation, grid support
Photovoltaic Arrays	<1-100	5-15	Base load, peak shaving
Stirling Engines	1-25	12-20	Vehicles, Refrigeration, Aircraft, Space

Wind systems	Several kW-5000	20-40	Remote power, grid support
Micro Turbines	30-500	20-30	Stand-by power, power quality, reliability, peak shaving, and cogeneration
Biomass energy	5-10000	40-50	Co-generation, grid support

There are other technologies that are also being used but they are the latest forms of distributed generation. The next generation of turbines, fuel cells, and reciprocating engines is the result of intensive, collaborative research and development. More information about individual technologies can be found in reference [6].

2.7 Types of distributed generators

In the previous section the different types of technologies that are used as prime movers are discussed. The actual generators can be further classified as, synchronous generators, induction generators, and DC to AC converter types of sources. Each of these generators has different characteristics. So it is necessary to know the characteristics before integrating them into the electrical network. In this document a voltage source is used as the DG.

2.8 Transients in power

These transients are of different types and occur due to different reasons. A transient is initiated whenever there is a sudden change of circuit conditions; this most frequently occurs when a switching operation takes place.

2.9 Types of transients

The main causes of excessive voltages and currents are: (i) Lightning (ii) Switching (iii) Short circuits and (iv) Resonance conditions. Out of these, lightning and switching are the most common types of transients and they cause the most severe damage. But transients caused due to short circuits and resonance conditions are small compared to the lightning but yet very severe at times and can lead to the shut down of the system. Depending upon the speed of the transients, these can be classified as: surge phenomena (extremely fast transients), short-circuit phenomena (medium fast transients), and transient stability (slow transients).

2.9.1 Surge phenomena

These transients are caused by switching actions and lightning surges falling on any of the power system component, usually the transmission lines. These transients are characterized by traveling waves traveling at the speed of light. In a 150-km line, the traveling wave completes a round trip in 1 milli second [7]. Thus the transient phenomena associated with these traveling waves occur during the first few milli seconds after the initiation. The transmission line resistance causes some attenuation to these traveling waves, so they die out after a few reflections. These waves get reflected when they reach a junction such as a transformer or an open transmission line. Some times at these junctions the waves overlap and increase in magnitude. This can damage the equipment. The traveling charges in the surges are discharged to the ground via lightning arresters without the initiation of a short circuit. Thus protecting the equipment. [7]

2.9.2 Short circuit phenomena

Short circuits take place mostly on exposed overhead lines. These take place due to g to the insulation failure resulting from over-voltages generated by surge phenomena described above, tree branches falling on the conductors and other mechanical reasons. Short circuits result from symmetrical and unsymmetrical faults. The occurrence of symmetrical faults brings the power supply to zero immediately, whereas the impact is partial in the case of unsymmetrical faults [7]. Like surge phenomena short circuits are also electric in nature. The speed of the fault is decided by the time constants of the generator windings, so their speed is less when compared to the surges[7]. The time constants of the windings vary from a few cycles for the damper windings and up to 4 seconds for field windings [7]. If these short circuit currents are allowed to persist they can damage the equipment due to over heating. So the fault section should be quickly isolated. As soon as the fault is isolated the charges are de-ionized and so the insulation is restored [7]. Faults come under the short circuit phenomena. They are presented in the sections to follow.

2.9.3 Transient stability

When there is a short circuit in a system there is a sudden voltage drop. The generator output is reduced because of this short circuit. Due to the presence of some time delay in the corrective action of the controllers the turbine power remains constant for some time. So the generator is subjected to a positive accelerating torque [7]. This condition if allowed to continue for some more time can cause mechanical oscillations of the rotors [7]. These can cause the generators go out of synchronism with the system and the system can be said to have reached the transient stability limit. Since these are mechanical in nature the study of these transients is in the order of milli seconds [7]. In this chapter we are more concerned about the short circuit type of transients.

2.9.4 Symmetrical faults

These are also called three phase faults. Such conditions are caused in the system accidentally through insulation failure of equipment or flashover of lines initiated by a lightning stroke or through accidental faulty operation [7]. The system should be protected against heavy short circuit currents. The majority of the faults are not three phase faults. In this kind of fault all the three phases are grounded with a very little impedance. This causes the bus voltage to almost zero. These are the most severe types of faults [7].

2.9.5 Unsymmetrical faults

If the fault is not on all the three phases but on one or two of the phases then the fault is said to be an unsymmetrical fault. These faults do not completely shut down the power supply but only affect it partially [7]. The analysis of such a condition is not simple because the system is no longer balanced.

Different types of unsymmetrical faults are

(i) Single line to ground fault.

(ii) Line to line fault.

(iii) Double line to ground fault.

To understand these faults and the system condition the concept of symmetrical components was developed.

2.9.6 Sources that contribute to faults

A fault presents a low impedance path to the current. So all the voltage sources in the network tend to contribute to the fault. Apart from the sources the capacitor banks also tend to dump their charge as soon as there is a drop in voltage due to the fault. So the fault current flowing in the ground is the sum of all these. Different generators contribute different amounts based on the time constants of their windings and location of the fault. The contribution of a generator to a fault depends on the sub transient reactance of the generator.

With the presence of the small DG sources the system response to a fault has become more complex. In this thesis the various components that contribute to the faults and the magnitude of the fault current contribution is estimated by simulating a DG source in the IEEE 13 node feeder test case.

Chapter III
Literature Review

3.1 Introduction

This chapter reviews the previous work done on transient analysis with a focus on faults in distribution systems. It also includes the literature review of the way PSCAD is used for studies on power systems. Studies conducted on impact of distributed generation on the operations of distribution networks are also presented.

3.2 Previous work on faults

Faults in power have been a topic of interest for many people both in the industry and academia. Many researchers tried to understand the phenomena and the impact of the faults on the distribution network. In a paper [8] the authors M. A. Chapman, A. Martinez, E Sabir, Z. Wang, and Y. Liu describe different types of transients in power systems. They describe the switching transient as a very critical issue for power system networks. Since this type of transients are responsible for majority of power system failures. They describe different switching scenarios and the impact on the system during the switch transition. The different scenarios include energization, deenergization and transients due to faults. They also describe the impact of a switching action, which includes a capacitive or inductive element. A review of all the above conditions is presented.

Paragi Erezaghu Crossley in paper [9] describes the impact of an impedance-restricted fault on the operation of a protective device. In this paper they show in a PSCAD simulation the effect of impedance on the fault current and the distance of the fault on a distance relay. The paper shows the effect of faults and the impedance effect on the detection system.

Heine and Lehton, M. in paper [10] describe the effect of faults on voltages at different points on a distribution network. A mathematical model of the system and the impact on the voltage is given. In their analysis they compare the voltage sags at different levels of faults. An expression based on the network impedances for voltage sags was derived. This gives a comparison between the impacts of faults occurring at different voltage levels and the effect on a LV network due to a fault at some point up at the HV level of the network. This can be considered as propagation of transients in the network.

In paper [11] authors Stojanovic, D. Nahman, present the impact of generator dynamics on the currents distribution in a fault condition. A qualitative analysis of electromechanical transient process influence to a more complex power system is shown in this work. Special software is used to implement the generator dynamics and calculation of currents along system elements. Qualitative analysis of rotor swing influence to a fore mentioned currents changing in time are given. It is given that at longer faults (t>0.15s), neglecting the rotor swing can bring error in the calculation of fault current.

Author McQuin, in paper [12], presents the impact of faults on the induction generators. In that the author discusses the voltage dips, which can cause runaway of the generators. The maximum voltage dip that can be sustained by a particular induction generator is given. In paper [13] presented by Dr. Sioe .T .Mak the propagation of transients is discussed. His main emphasis was on a very small (short duration) short circuit at the remote customer end, which travels all the way to the substation. He discussed the distribution network as described below. Feeders emanate in a radial fashion in all directions from the bus to the remote customers. In the path from the customer to the substation there are many energy-storing devices like the capacitor banks, the inductances of the transmission lines and various inductive loads. All these make the study of the network very complicated. There is some energy exchange between the energy storage devices, which produces oscillations in the network [13].

The figure 3.1 below shows a single feeder model of a distribution line.

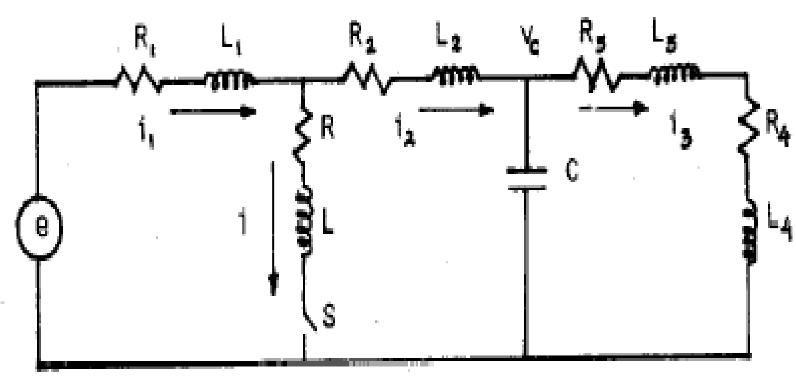


Figure 3.1 simple network models. Closing the switch S. simulates fault [13]

3.3 Mathematical analysis of a fault on the line (as described in ref [13])

Consider a fault at the bus. Let the voltage at the faulted bus be v (t). Then at the instant of fault let the fault current be I (t). To analyze the condition of fault voltages and currents at three time regions are required. The three time regions can be divided from:

i. -∝ To t when the fault is initiated. Let t=0. So -∝ to 0 is the first time region.

ii. $0 < T < T_1$ is the second region from the instant the fault is initiated and to the moment when the fault is cleared.

iii. T1 to ∝ is the third and final region.

The first part is a more steady state response, which can be easily solved using the Kirchoffs laws directly.

I (t) = v (t) / z (t).

Most of the above quantities are constant, and hence can be solved by knowing the parameters of the network.

To analyze the second part of the equations given below are useful. The exact waveforms for the above fault conditions can be obtained by integrating the equations.

3.4 Distributed generation

Distributed generation has been a topic of research for the past two decades. A lot of study is carried out in this area. In paper [14] the author's presentation deals with both technical and economical feasibility of the distributed generation concept highlighting a set of items that must be investigated before this opportunity can be adequately pursued. Among them are understanding the technological impact, evaluating the kind of penetration in the distribution grid, quantifying the power quality problems related to its implementation, developing planning procedures that incorporate dispersed generation into distribution systems, designing interfaces between distributed generation technologies and existing distribution systems, quantifying the flexibility and defining characteristics of new management control systems. An integrated and coordinated approach based on theoretical design, simulation analysis and experimental is discussed.

In paper [15] the authors Celli and Pilo, discuses the necessity of knowing the power system impacts with DG and hence proposes a new software procedure, based on a genetic algorithm, capable of establishing the optimal distributed generation allocation on an existing MV distribution network, considering all the technical constraints, like feeder capacity limits, feeder voltage profile and three-phase short circuit current in the network nodes.

Papers [15 – 21] discuss the issues of planning of distributed generation and optimization of operation. They also discuss the reliability issues in distributed generation.

3.5 Impact of Distributed generation on faults and protection

The protection system has traditionally been designed assuming the system to be radial. After connecting DG, part of the system may no longer be radial, which means the coordination might not hold [22]. In paper [22] the authors describe the problems that arise due to the integration of distributed generation. In this paper they describe that the effect of DG on coordination will depend on size, type and placement of DG. This paper explores the effect of DG on protective device coordination such as fuse-fuse, fuse-recloser and relay-relay. In each case, depending on size and placement of DG, there are some margins in which the coordination may hold and certain cases, where no margin is available. These conditions are identified for each case through coordination graphs.

3.6 Impact of placement of Distributed Generation in distribution system

Conventionally, it is assumed that electric power in distribution systems always flows from substations to the end of feeders in planning and operation. However, introduction of distributed generators under de-regulated environment causes reverse power flow and complicated voltage profiles in the distribution systems. This type of complication in the systems depends on the strategic placement of DG. Therefore it is required to focus on optimal placement of distributed generation in the distribution systems.

In distribution systems, key information includes system state variables such as voltage, current magnitudes and corresponding phase angles at every node of the feeder. Once the system state variables are known, the flows on the distribution system can be acquired, which is very important in keeping the system operating in a secure and economical state. This state variable can be obtained by the analysis of power flow in distribution systems. But the placement of DG changes these system variable and losses. The following section highlights some of the key work that has been done in the optimal placement of DG in distribution system.

In paper [23], the authors demonstrated a methodology for deploying dispersed fuel cell generators throughout a power system to allow for more efficient operation. This works presented an algorithm to determine the near optimal, with respect to system losses, placement of these units on the power grid. Further, the impacts of dispersed generation at the distribution level were performed with an emphasis on resistive losses, and capacity savings.

Wang and Nehrir in paper [24] presented analytical methods to determine the optimal location to place DG in radial as well as interconnected distribution systems to minimize the power loss of the system. This paper also carried out the simulation studies to verify the results obtained analytically for both radial and network connected systems.

In paper [25], Rau and Yih-heui Wan proposed a method to allocate optimal quantities of distributed resources in selected nodes of distribution system such that system will have reduction of network losses, var losses, or loadings on selected lines. An optimization method was presented to minimize the losses in distribution system.

3.7 Previous Work done using Simulations

A simulator is a collection of hardware and software systems which are used to mimic the behaviour of some entity or phenomenon. Simulators may also be used to analyze and verify theoretical models which may be too difficult to grasp from a purely conceptual level [26].

One of the primary advantages of simulators is that they are able to provide users with practical feedback when designing real world systems [26]. This gives the designer a scope of the correctness and efficiency of a design before the system can actually be constructed. Consequently, the user may explore the merits of alternative designs without actually physically building the systems [26]. By investigating the effects of specific design decisions during the design phase rather than the construction phase, the overall cost of building the system diminishes significantly.

In paper [27] the authors Olimo Anaya-Lara and E. Acha decribe present electromagnetic transient models of custom power equipment. They use PSCAD simultions to condut all aspects of model implementation. Simulation of a D-statcom , Solid state transfer switch and various control schemes are presented.

In paper [28] presented by A.M.Gole, the role of simulation and different tools for simulating transients are discussed. A comparision of different types of tools is presented. PSPICE, MATLAB and EMTDC are compared. And it is given that for transient simulation PSCAD is the best tool.

Authors Wang and Pahalawaththa in paper [29] present a technique for power system load modelling. Simulation studies were carried out using PSCAD.

3.8 Simulation of impact of Distributed generation on power system faults

The above sections so far discussed the work previously done on simulations, faults and DG. In Paper [30] Authors Paulsen and Makram present the impact of distributed generation on faults. Two generator models synchronous and induction machines were modeled in PSCAD. A fault was placed at a particular node and the variation in the currents was recorded. The simulations were carried out for various generator sizes and the reults are analyzed. This thesis is a similar work done on IEEE 13 node feeder with faults at various locations.

All the work done above are my key references for my thesis work.

Chapter IV

Problem Statement

4.1 Introduction

In this thesis the main focus is on simulating the fault response of a distribution network. The IEEE 13 node feeder is taken as reference for the simulations. The IEEE 13 node feeder is modeled in PSCAD. Faults are placed at various locations on the system and the response at the substation and other important nodes is obtained in the form of graphs. The simulation is done in PSCAD. A distributed generator is placed at different locations to see the impact of DG on the fault response of the system. The results are compared and the impact of DG on the faults is analyzed.

4.2 IEEE 13 Node Case

The IEEE 13 node feeder is a very small feeder, but it displays many features. The following are the key features of the IEEE 13 node test feeder.

- Short and relatively highly loaded feeder for 4.1 kV level.
- One substation voltage regulator consists of three single-phase units connected in Wye. Overhead and under ground lines with variety of phasing.
- Shunt capacitor banks.
- Inline transformer.
- Unbalanced spot and distributed loads.

The details of each of the components will be given in the sections to follow in the chapter. The modeling challenges and the assumptions taken are also given in the sections to follow.

Figure 4.1 shows the physical lay out of the IEEE 13 node feeder case.

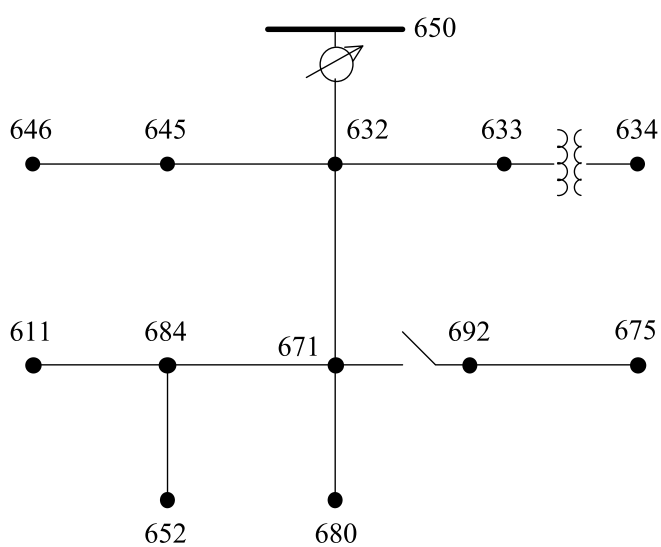


Fig. 4.1 IEEE 13 feeder test case [30].

4.2.1 Load models

Load models are both spot and distributed loads [30]. The loads are both three phase and single phase. The table 4.1 below gives the different types of loads and the models. Each model is given a separate code.

Table 4.1
Load models and codes. [30]

Code	Connection	Model
Y-PQ	Wye	Constant kW and kVAr
Y-I	Wye	Constant Current
Y-Z	Wye	Constant Impedance
D-PQ	Delta	Constant kW and kVAr
D-I	Delta	Constant Current
D-Z	Delta	Constant Impedance

All the loads are specified in kW and kVAr.

The spot load in the IEEE 13 node feeder is given in table 4.2. And the nodes where there is no load data, a zero load is assumed.

Table 4.2
Load data. [30]

Node	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-3 kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	1158	606	973	627	1135	753

4.2.2 Shunt Capacitor banks

The shunt capacitors are modeled as constant susceptance and specified at nameplate rated kVAr. The capacitor bank details used in the IEEE 13 node feeder are given below in table 4.3.

Table 4.3 Capacitor bank data [30].

Node	Ph-A kVAr	Ph-B kVAr	Ph-C kVAr
675	200	200	200
611			100
Total	200	200	300

4.2.3 Over head line data

Each line is given a different configuration. And to match each line with its tower data a code is given to each line. The table 4.4 below gives the overhead line spacing.

Table 4.4
Overhead line spacing [30]

Spacing ID	Type
500	Three-Phase, 4 wire
505	Two-Phase, 3 wire
510	Single-Phase, 2 wire

Figure 4.2 below shows the tower configurations for each line segment.

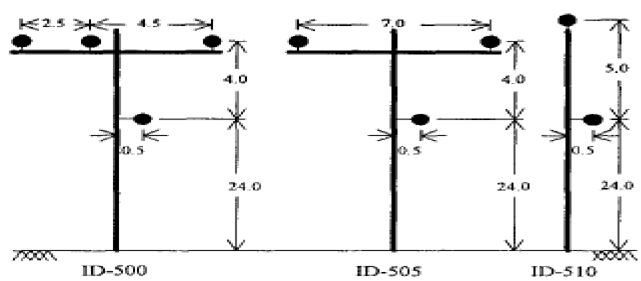


Figure 4.2 Tower configurations. [30]

Overhead line configuration data is given in table 4.5.

Table 4.5
Overhead line data. [30]

Config.	Phasing	Phase ACSR	Neutral ACSR	Spacing ID
601	B A C N	556,500 26/7	4/0 6/1	500
602	C A B N	4/0 6/1	4/0 6/1	500
603	C B N	1/0	1/0	505
604	A C N	1/0	1/0	505
605	C N	1/0	1/0	510

The above-mentioned test case is modeled in a soft ware called PSCAD.

4.3 PSCAD

PSCAD/EMTDC is a powerful electromagnetic transients simulation program [31]. It is most suitable for time domain simulations of the systems. It is an industry standard simulation tool [31]. The graphical interface of the software makes it very easy to build the circuit and observe the results in with in a single integrated environment. Due to the presence of the graphical interface the time for the development of the program is drastically reduced [31]. PSCAD/EMTDC uses subsystems, which breaks the whole job into smaller units and makes the understanding easy. In EMTDC there the user can write his own program, which best suits, his simulation and integrate it to the main program.

4.4.1 Modeling of IEEE 13-node feeder in PSCAD

A step-by-step approach for modeling of the IEEE 13 node feeder in PSCAD is presented in the sections to follow. The IEEE 13 node feeder in PSCAD looks as shown in figure 4.3.

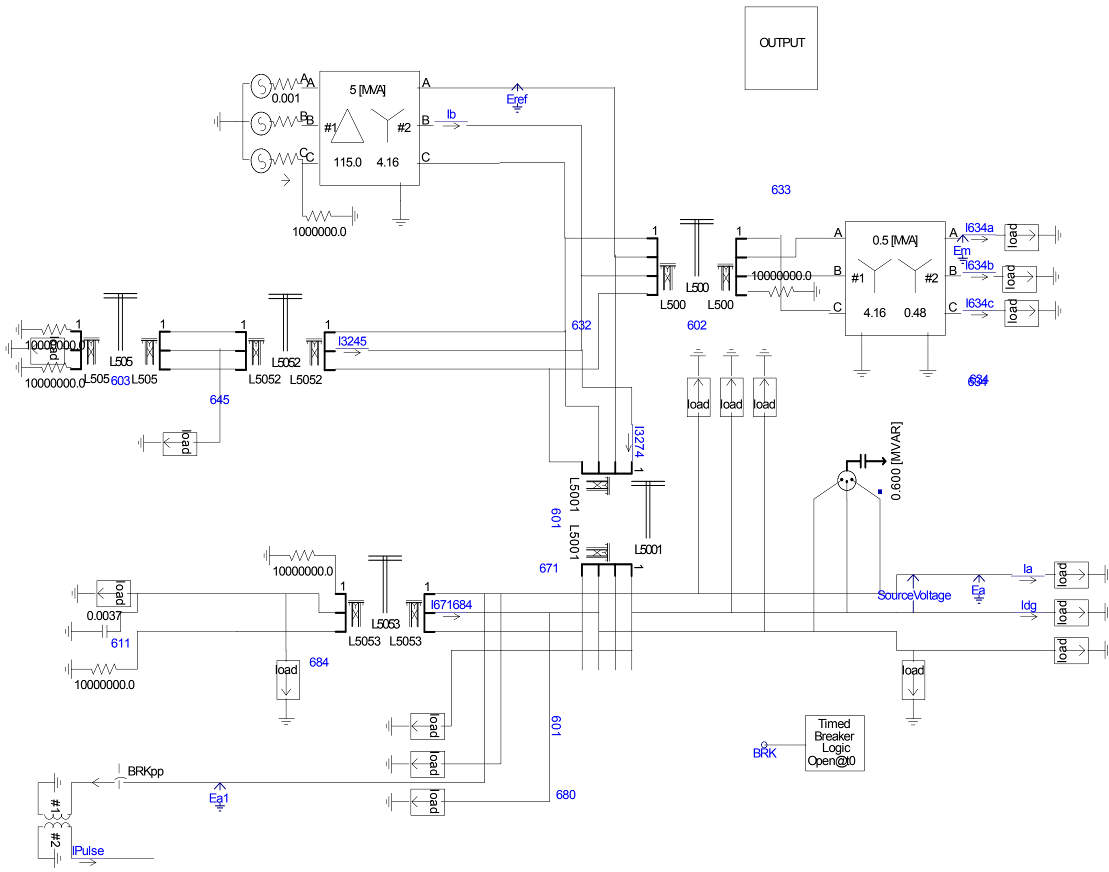


Figure 4.3. IEEE 13 node feeder in PSCAD.

4.4.1 Modeling of the overhead lines

Modeling of Distribution lines in PSCAD is very easy if we have all the data. This data includes the conductor type the tower data and the length of the Distribution line. The figure 4.4 shows the interface of a transmission line to the circuit model.

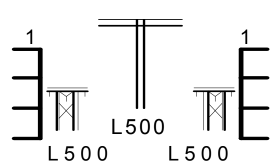


Figure 4.4 Distribution line interface.

The basic input to the distribution line is the length and the frequency of operation and number of equivalent conductors present. This is shown in figure 4.5.

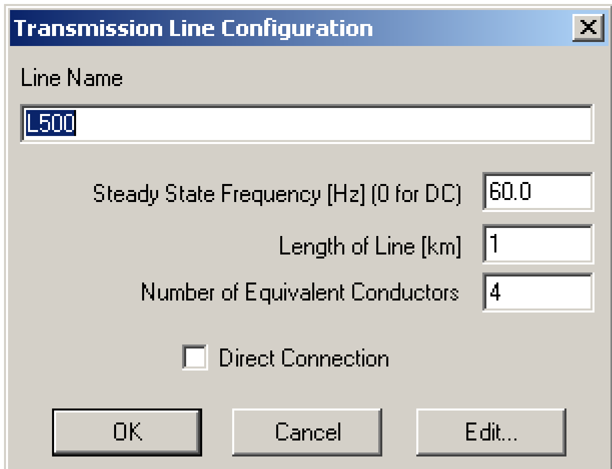


Figure 4.5 Basic input to a distribution line.

Since the conductor data is not much important, the basic inputs, the line length and the frequency of operation can be used for simulation. The software automatically assumes certain generic conductor types. If we need to specify the conductor types then we have to go to the edit section and input the conductor data. The input format is shown in figure 4.6.

Line Model General Data

Name of Line: L500

Steady State Frequency [Hz]: 60.0

Length of Line [km]: 1

Number of Conductors: 4

Frequency Dependent (Phase) Model Options

Travel Time Interpolation: On
Curve Fitting Starting Frequency: 5 [Hz]
Curve Fitting End Frequency: 1.0E4 [Hz]
Maximum Order of Fitting for YSurge: 20
Maximum Order of Fitting for Prop. Func.: 20
Maximum Fitting Error for YSurge: 0.2 [%]
Maximum Fitting Error for Prop. Func.: 0.2 [%]

Tower: 3H5 Tower Centre 0 [m]
Conductors: 556500 26/7 --> Ground_Wires: 4/0 6/1 acsr

Cond. #	Connection Phasing #	X (from tower centre)	Y (at tower)
1	1	-0.762 [m]	8.53440 [m]
2	2	0 [m]	8.53440 [m]
3	3	1.3716 [m]	8.53440 [m]

GW. #	Connection Phasing #	X (from tower centre)	Y (at tower)
1	4	0.1524 [m]	7.315[m]

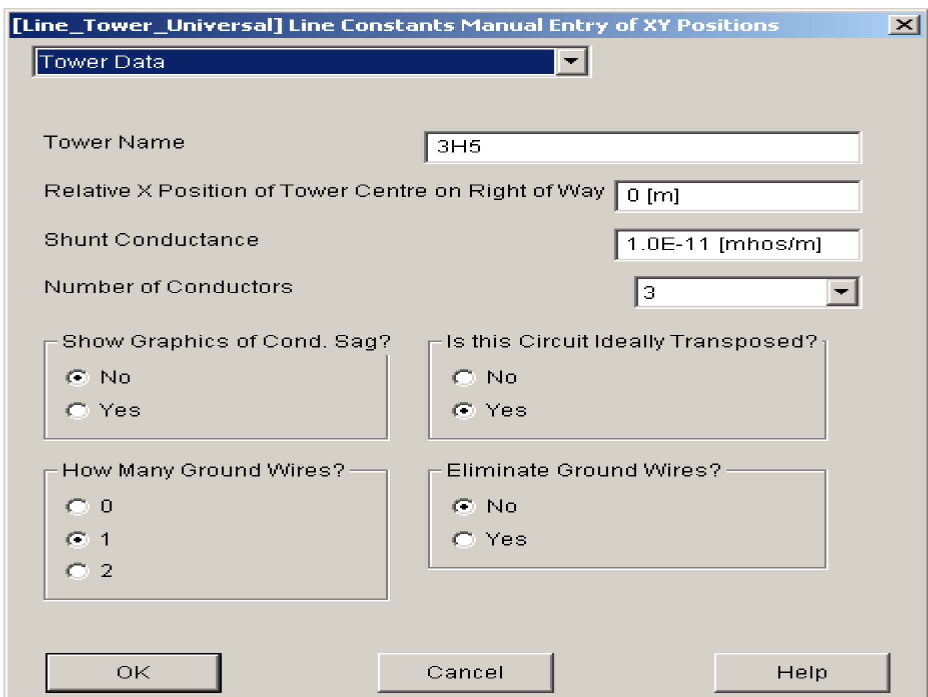


Figure 4.6. Tower data.

The conductor input data format is shown in figure 4.7.

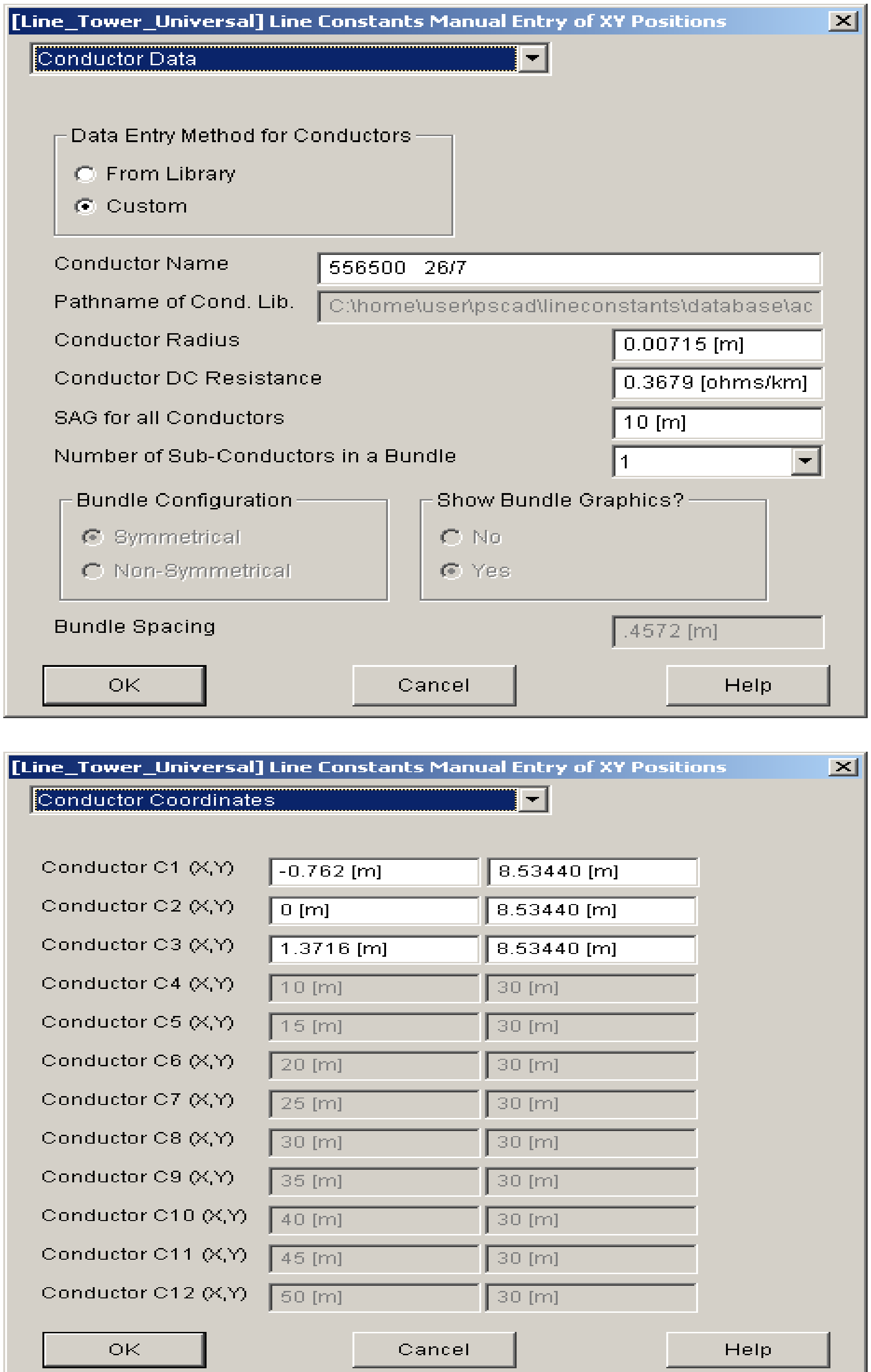


Figure 4.7. Conductor data input format.

The conductor resistance radius can be specified in the blocks shown in the above figure 4.7. The other way to input is to give input of the conductor data from a file, which has the conductor data. By specifying the file path the data can be given directly.

4.4.3 Source modeling

The substation given in the literature for IEEE 13 node feeder can be modeled as a source in PSCAD. The source interface and the data input format are given in figure 4.8.

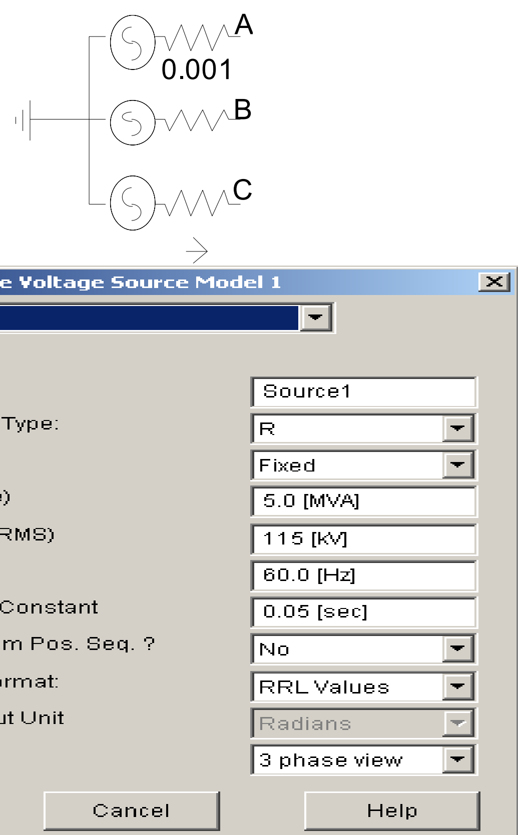


Figure 4.8. Source interface and the input for the source.

The voltage level, frequency, and the power output can be specified in the columns given in the window shown in figure 4.8.

4.4.4 Transformer modeling

The transformer interface in PSCAD is given in figure 4.9

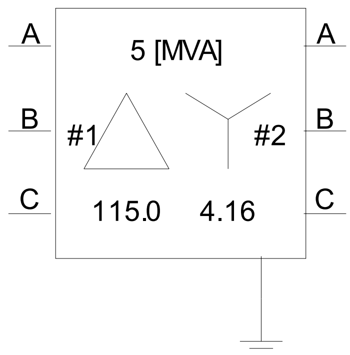
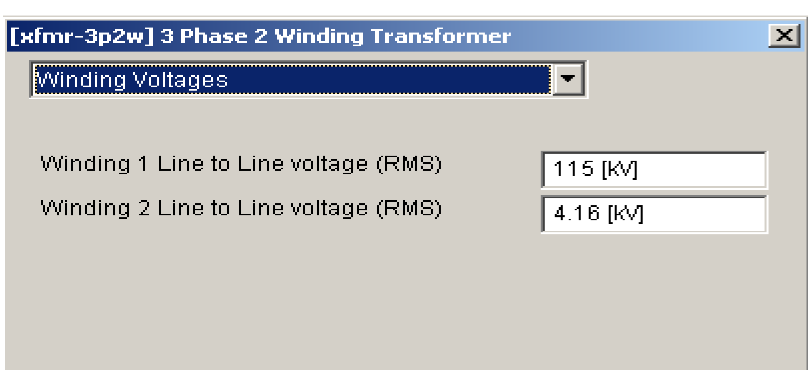


Figure 4.9-transformer model in PSCAD.

The transformer model includes all the required data for distribution system modeling. The data input format is shown in figure 4.10. The power rating and the frequency of operation can be mentioned in the configuration of the transformer. The winding type and the reactance can be specified in the columns given, as shown in figure 4.10. The winding saturation effect can also be taken into effect.



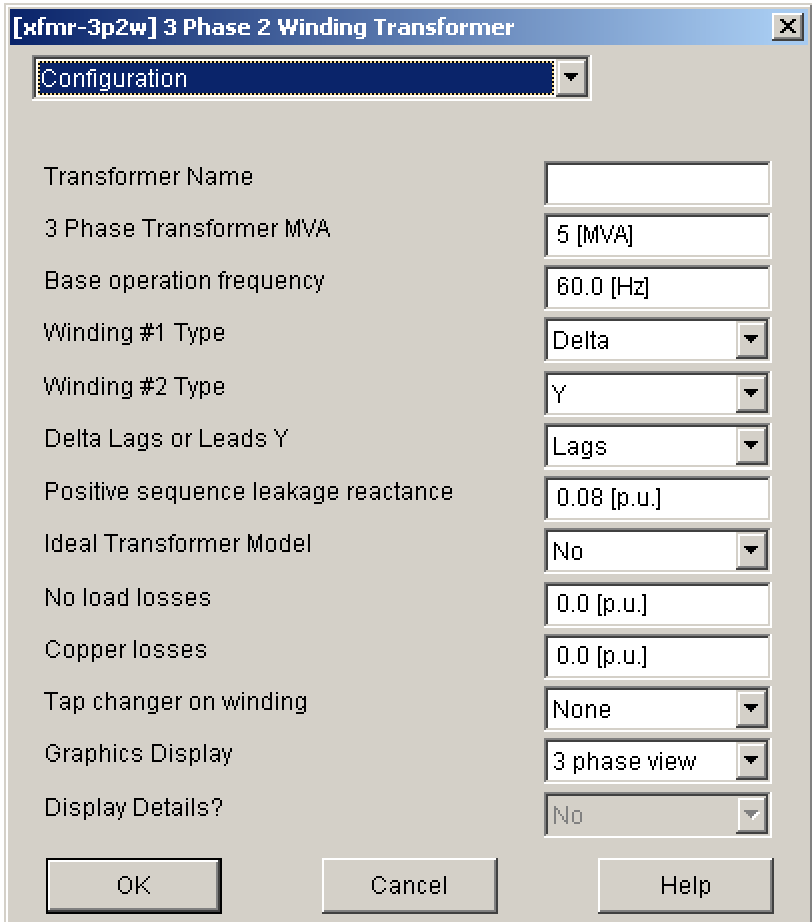


Figure 4.10 Transformer configuration in PSCAD.

4.4.5 Load models in PSCAD

Both three phase and single-phase loads are present in PSCAD. By changing certain indices in the data input window all three types of loads can be obtained i.e. constant current, constant power or constant impedance. Figure 4.11 shows the load model in PSCAD.

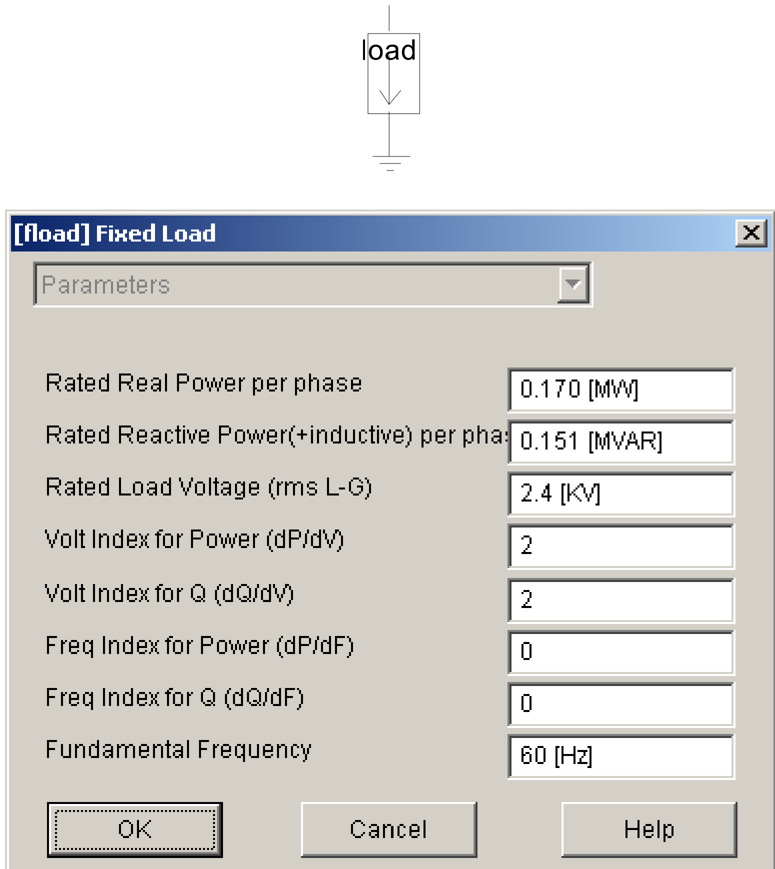


Figure 4.11 Load model and data input window.

All the input should be given in the form of MW and MVAR. The voltage and frequency indices decide the type of load.

4.4.6 Fault simulator

Faults are simulated using a timed circuit breaker. Just by giving the time to initiate the short circuit and open the short circuit are to be specified. The Figure 4.12 below shows the circuit breaker and the timing block.

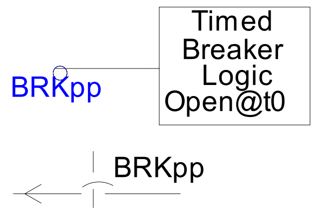


Figure 4.12. Circuit breaker and timing block.

The Figure 4.13 shows the data input for the breaker.

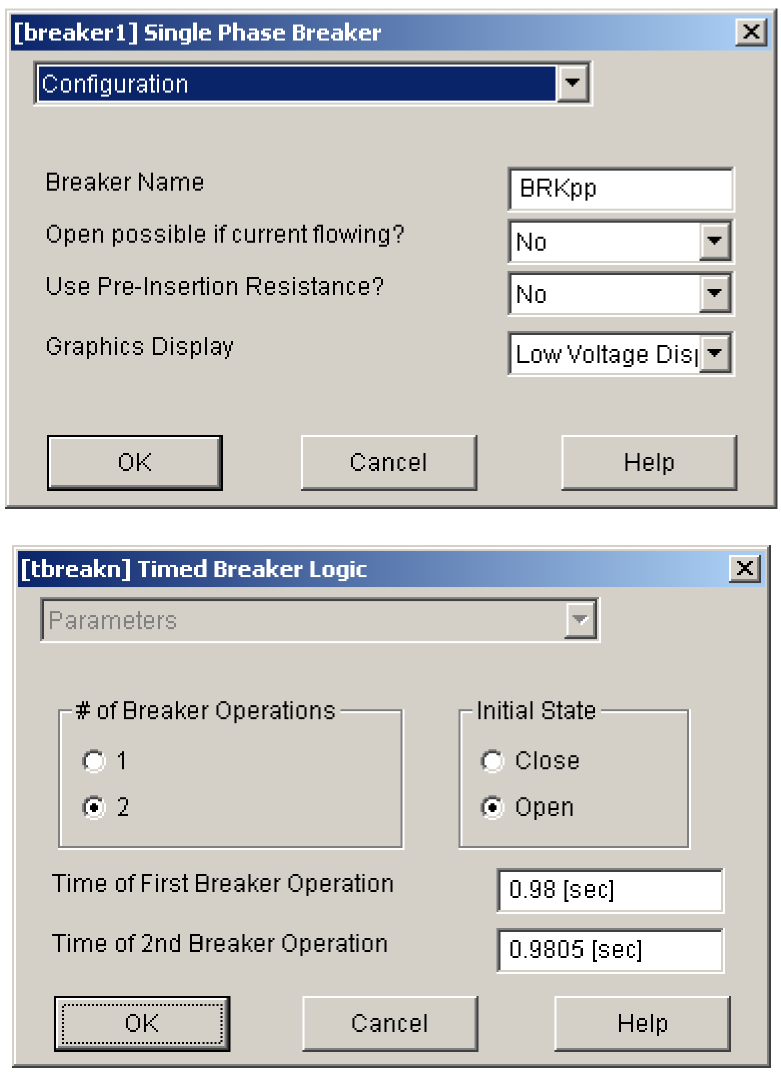


Figure 4.13 input data format for breaker and timing logic.

Using the timed breaker logic the temporary short circuit is controlled. This can be analyzed as a fault in a real system.

4.5 Assumptions

The following assumptions were taken while modeling the :

1. Voltage regulator was eliminated.
2. Cable in the circuit is removed.
3. Distributed load is taken as a spot load at the end of the segment.

4.6 Summary

In this chapter the various features of the IEEE 13 node feeder and the way it was modeled in PSCAD are presented. The next chapter presents the simulation results and a brief discussion on the obtained results.

Chapter V

Results and Discussion

5.1 Introduction

Results from the simulations are presented in this chapter. First the results obtained for the base case and the various parameters of the IEEE 13 node feeder are compared to standard results. In section 5.1 the results of the base case IEEE 13 node feeder are presented. Section 5.2 deals with the impact of faults on IEEE 13 node feeder. In sections 5.3 and 5.4 responses to faults with DG sources at nodes 675 and 633, respectively, are presented.

5.2 IEEE 13 node base case

The impedances of the distribution lines are compared with the results given in the literature.

Table 5.1 shows the distribution line impedances given in the literature.

Table 5.1
Z (R +jX) in ohms per mile for Configuration 601

0.3465+1.0179i	0.1560+0.5017i	0.1580+0.4236i
0.1560+0.5017i	0.3375+1.0478i	0.1535+0.3849i
0.1580+0.4236i	0.1535+0.3849i	0.3414+1.0348i

The results for steady state currents are shown in the figures shown in the Figure 5.1.

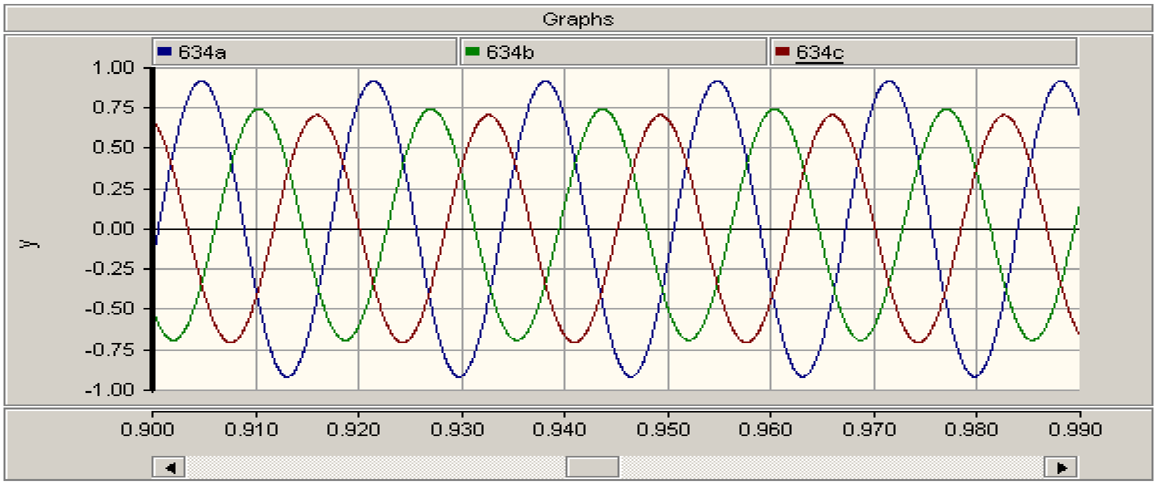


Figure 5.1. Currents flowing into node 634 obtained in PSCAD.

The rms values of the currents shown in the above figure are: 675, 510, and 510 A, respectively. The values in the literature are: 704.83, 529.73, and 543.45 A, respectively. So the results are with in 5% error.

5.3 Fault response of the 13-node feeder base case

The faults are simulated at the nodes 645, 633, 692, and 684. Figure 5.2 shows the fault locations.

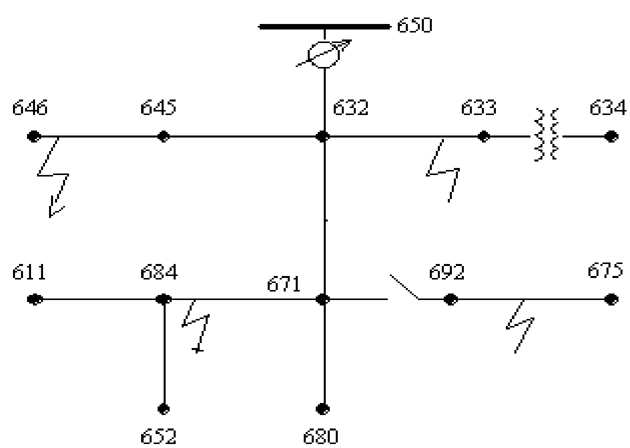


Figure 5.2 IEEE 13 node feeder with the fault locations.

The fault currents at each node are shown in Table 5.2.

Table 5.2
Fault currents at different nodes.

Fault Location & Phase	Fault Current	Distance from Source
645 B	6 kA	500 ft
684A	4 kA	2300ft
692 B	6 kA	2000ft
633 A	6.5 kA	500ft

Figure 5.3 shows the change in the fault current with location.

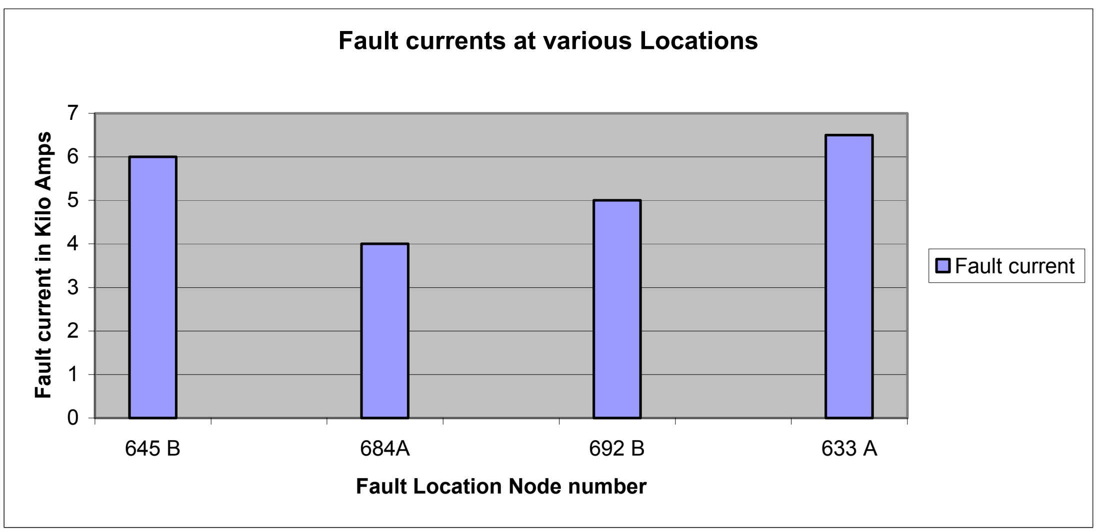


Figure 5.3 Fault locations Vs Fault current.

In the IEEE 13 node test feeder there are different distribution line lengths to various nodes and each distribution line has different impedance. There is a change in the frequency of operation during fault. The impedance difference is more significant. It can be seen that since the only damping factor of current is the distribution line impedance and a small series resistance, there is a difference in the fault current. It can be seen from the Table 5.3 above node feeder that nodes 684 and 692 are far from the source when compared to nodes 633 and 645. So the fault currents at nodes 645 and 633 are greater than the fault currents at nodes 684 and 692. Table 5.3 shows the source voltages at the time of fault.

Table 5.3 Source voltages during faults.

Fault Node	Source Voltage during fault	Before fault
645 B	2.4 kV	3.4 kV
684A	2.6 kV	3.4 kV
692 B	2.5 kV	3.4 kV
633 A	2.2 kV	3.4 kV

Figure 5.4 shows the drops in voltages at node 632 due to faults at nodes 645, 633, 692 and 684.

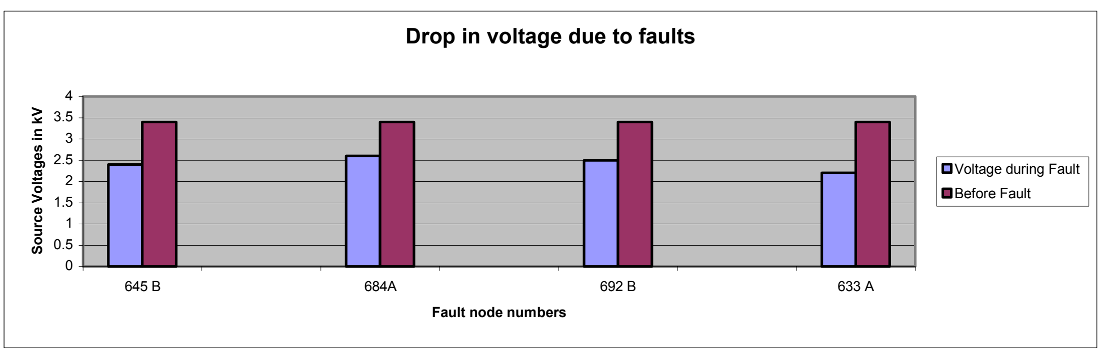


Figure 5.4 Voltage drop during faults at nodes 633, 645, 684 and 692.

It can be seen that there is a decrease in the voltage level due to faults. Figure 5.5 shows the PSCAD plot of the source voltages.

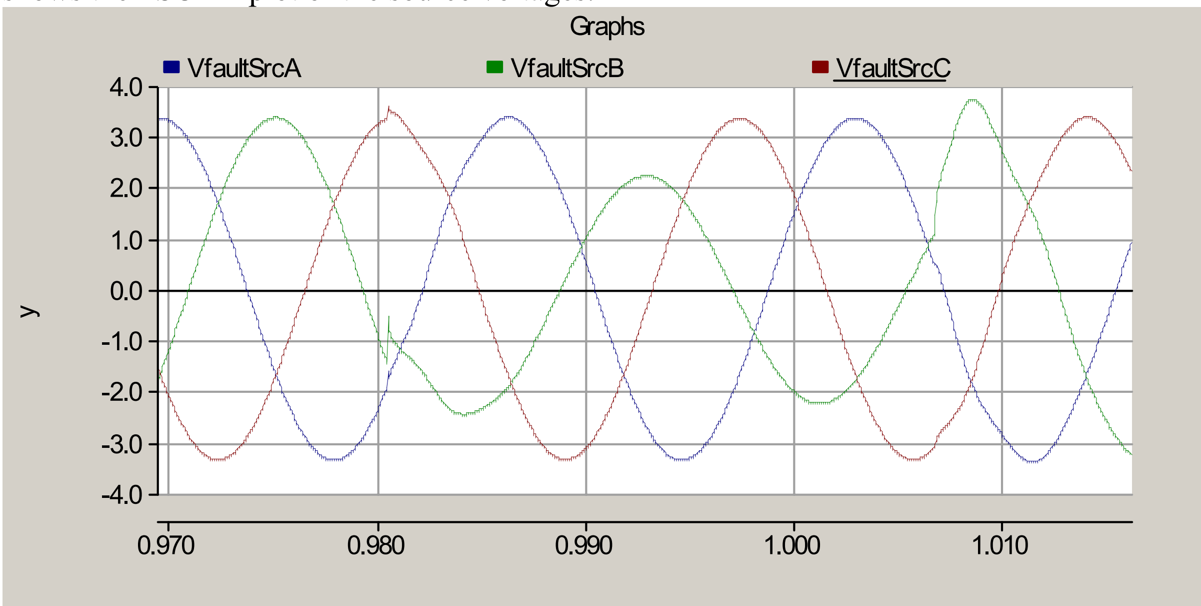


Figure 5.5 Source voltages during fault at node 645.

The changes in currents and voltages at various other locations are shown in the appendix.

5.4 Fault response with DG source at node 675

A DG unit is placed at node 675. The faults are simulated the same locations again. The results obtained are presented below. Table 5.4 shows the fault currents due to faults at nodes 645, 633, 692, and 684 with DG and without DG.

Table 5.4 Fault currents at different nodes.

Fault Node	With DG	No DG
645 A	6	6
692 B	9	5
684 A	4	4.2
633 B	8	6.5

Figure 5.6 shows the change in the currents due to introduction of DG in to the network.

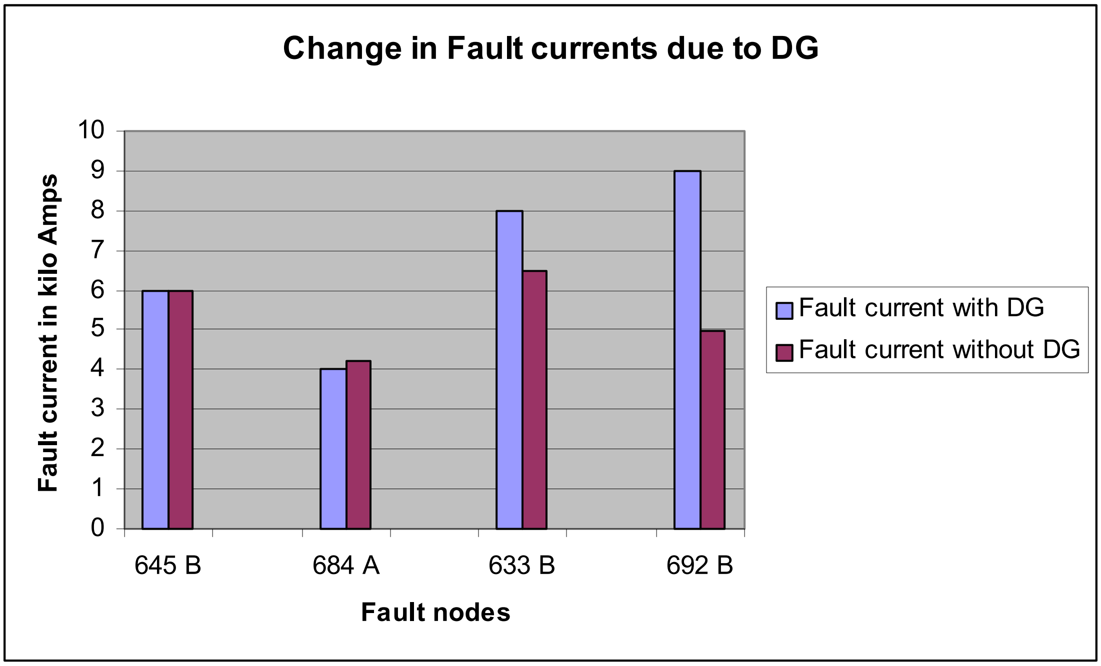


Figure 5.6 Fault currents with and without DG.

It can be seen that there is a huge increase in the fault current at node 692. This is because the DG source is very near to the fault location. So the impedance from the source to the fault is very less. So there is an increase in the fault current. The contributions of the main source and DG unit to the fault are shown in figure 5.7.

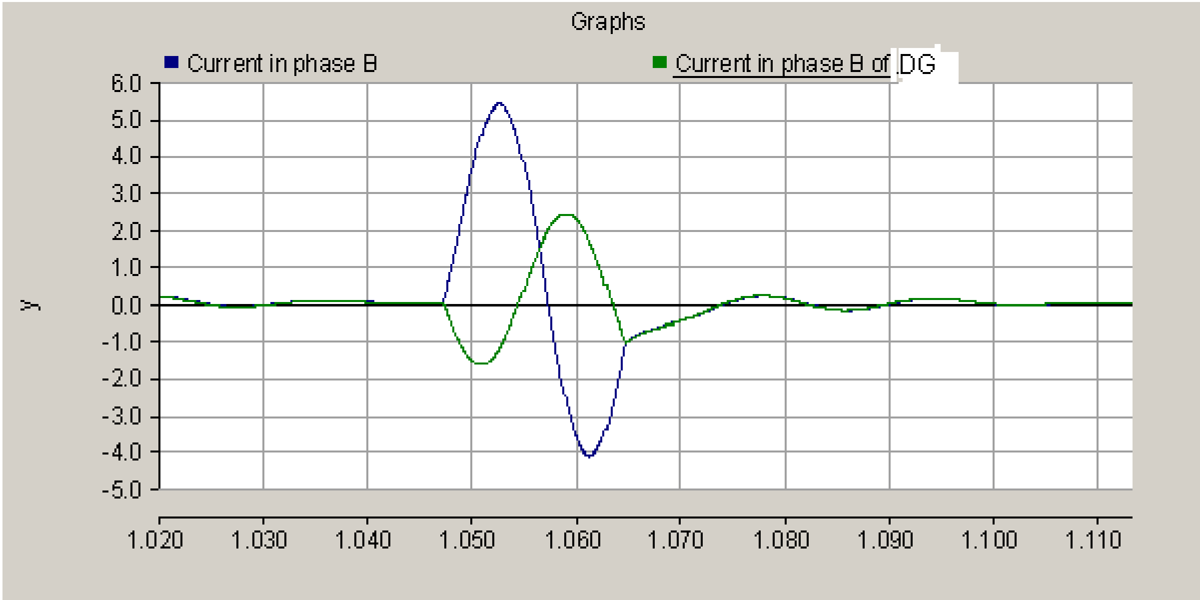


Figure 5.7 Fault currents of DG and main sources.

The changes in currents at other nodes are presented in the Appendix. Change in the voltage at the source during the fault is shown in Figure 5.8.

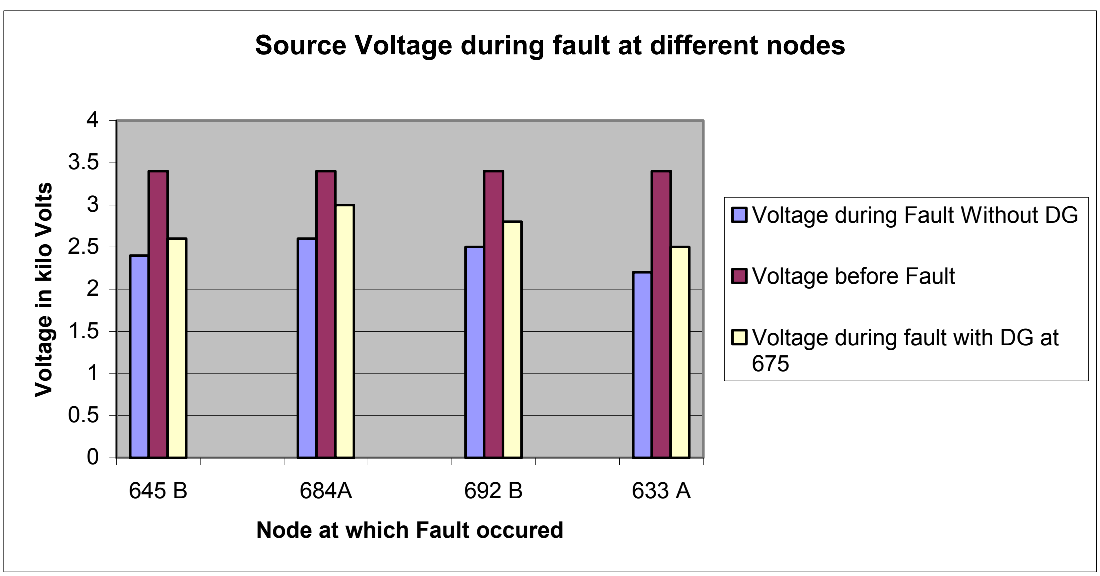


Figure 5.8 Voltage at source during fault.

It can be seen that there is an increase in the voltage during the fault with the inclusion of DG. This is because the DG unit is providing voltage support. The changes at various other nodes are presented in the appendix.

5.5 Fault response with DG source at node 633

A DG unit is placed at node 633. The faults are simulated the same locations again. The results obtained are presented below. Table 5.5 shows the fault currents due to faults at nodes 645, 633, 692, and 684 with DG and without DG. Figure 5.9 shows the fault currents with and without DG.

Table 5.5
Fault currents due to faults at different nodes.

Node	With DG	No DG
645 B	7 kA	6 kA
684 c	5 kA	4 kA
692B	6 kA	6 kA
633 B	9 kA	6.5 kA

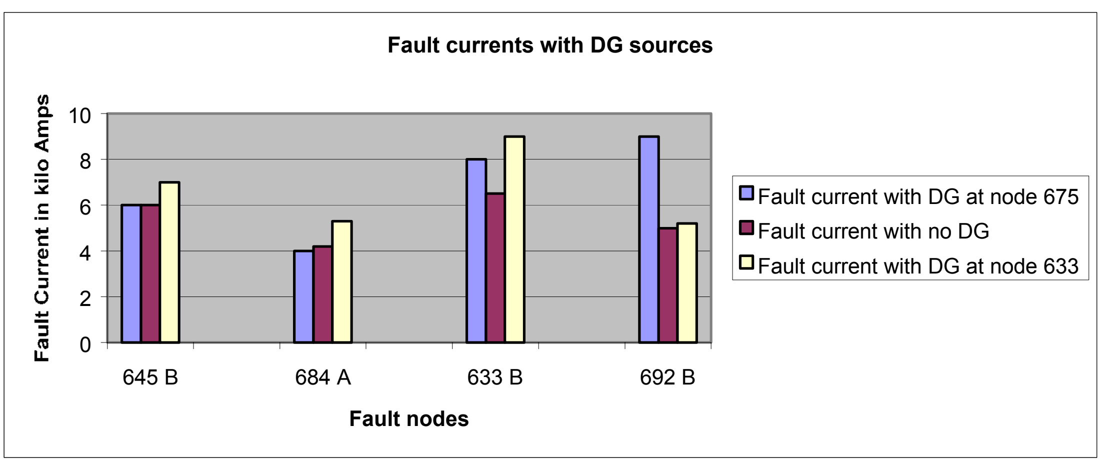


Figure 5.9 Fault current with and without DG.

It can be seen from the above figure that the fault current at nodes 645 and 633 increased a lot because they are nearer to the DG source at 633 and the main source. Whereas node 692 is nearer to node 675 so the fault current is high when there is a DG source at node 675. Currents and voltages at various other nodes are shown in the Appendix.

5.6 Impact of each fault on the network

Figure 5.10 shows the impact of fault 645 at four junction nodes in the network.

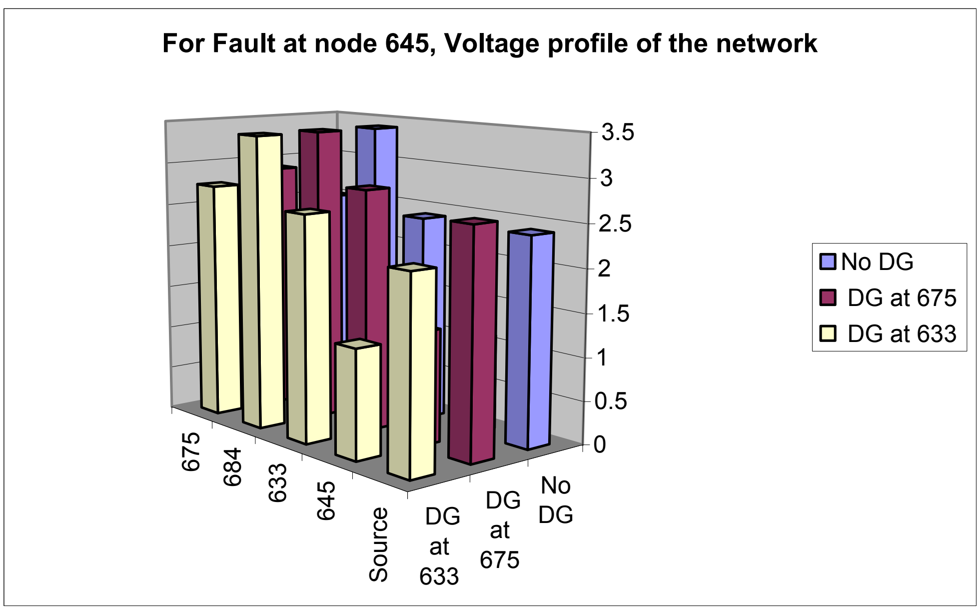


Figure 5.10 Voltage profile with a fault at node 645.

The impact of fault at node 684 is shown in figure 5.11.

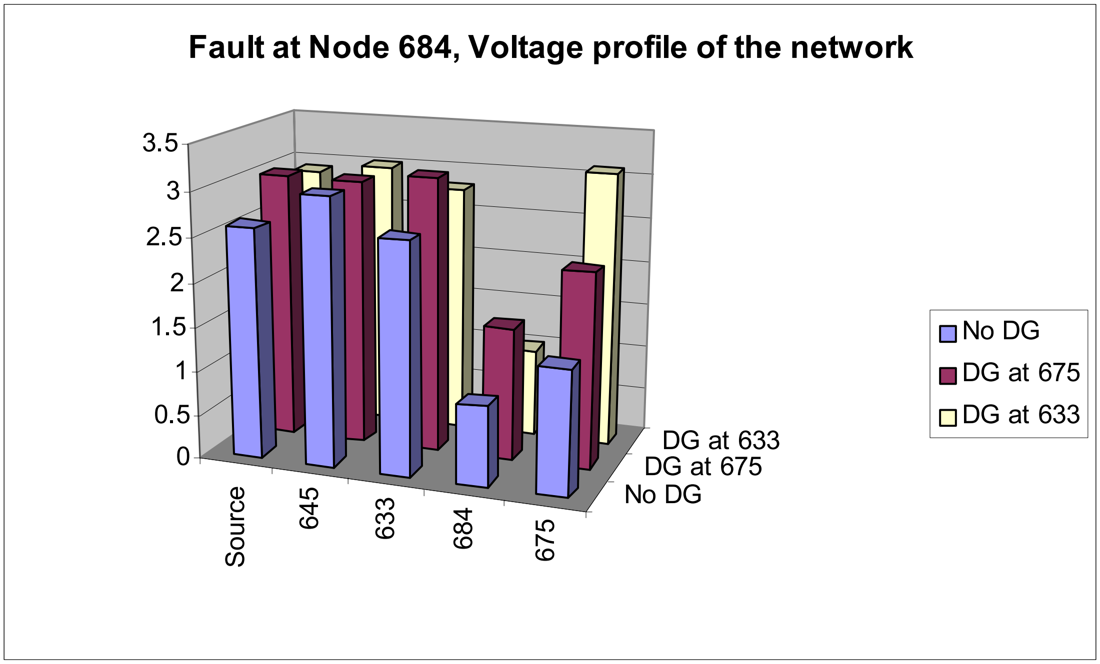


Figure 5.11 Voltage profile during the fault at node 684.

It can be seen that with the DG unit present in the network the voltage profile looks improved when compared to the condition without any DG. There is also little improvement in the voltage profile with the DG at node 675 than at 633. This is displayed further in Figure 5.12 showing the impact of fault at node 633.

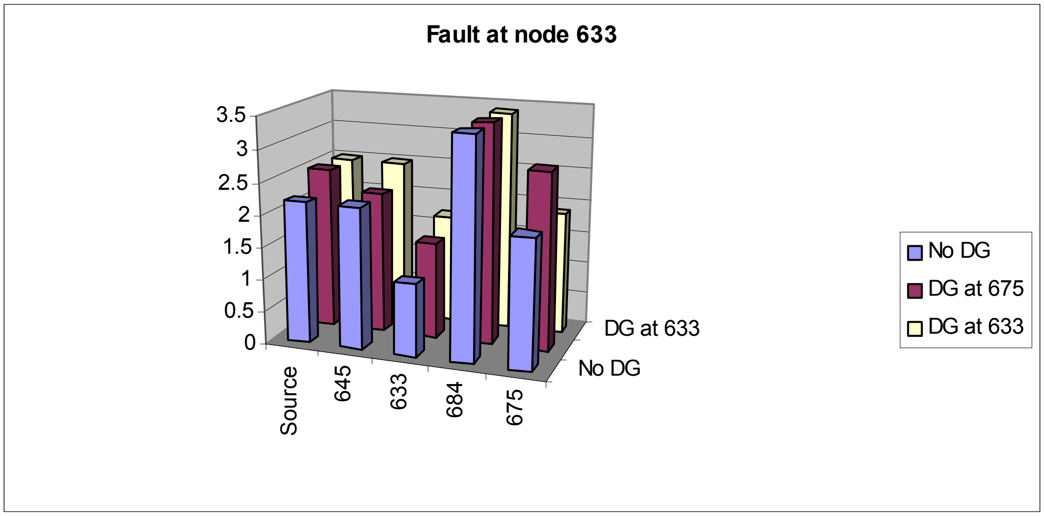


Figure 5.12 Voltage profile with fault at node 633.

A similar picture can be found with a fault at node 692 as shown in Figure 5.13.

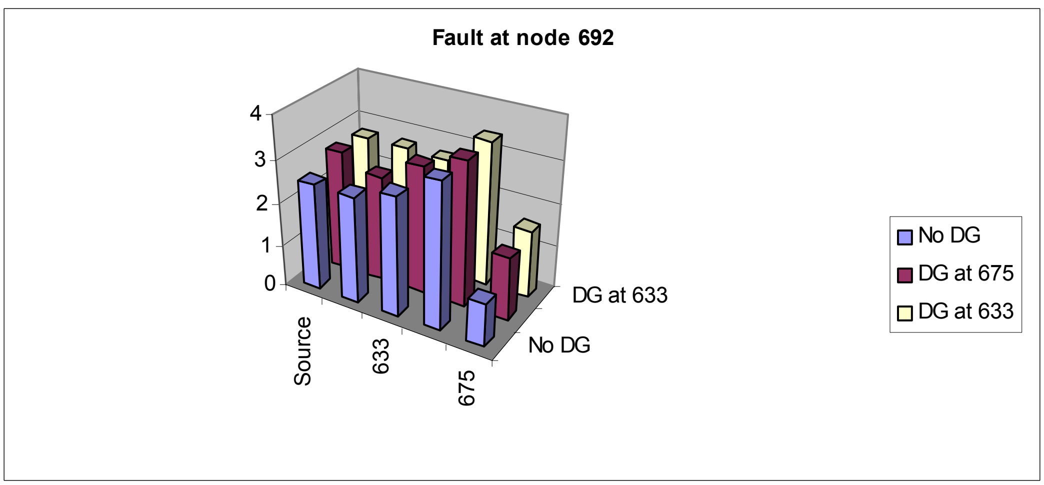


Figure 5.13 Voltage profile of the network with a fault at node 692.

From the above figures it can be said that placing a DG unit at node 675 would give a better voltage profile than placing a DG at 633, during faults.

5.7 Impact of Capacitor Bank

Figure 5.14 below shows the impact of capacitor bank on the fault current.

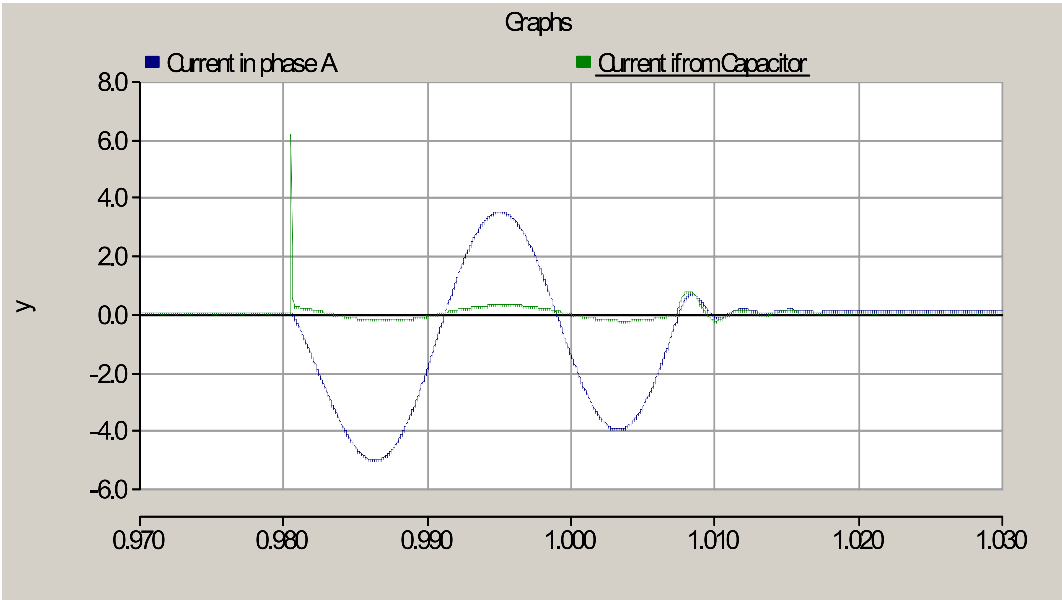


Figure 5.14 Contribution of capacitor bank to the fault current due to a fault at node 692 without any DG.

In the above figure trailing oscillations can be seen these are caused by the energy storage devices like capacitor banks, line impedances etc. in the network.

5.8 Summary of results

Tables 5.5 show the voltage response at all the major nodes due to faults at the chosen nodes.

Table 5.5
Voltage response of the network for faults at various locations.

Fault Location & Phase	Distance from Source	Fault Voltage	Source Voltage	645Voltage	633Voltage	684 Voltage	675 Voltage
645 B	500 ft	1.1kV	2.4kV	0	2.4kV	No Phase B	2.5,4intrail
684A	2300ft	0.9kV	2.6kV	litldistinB	2.6kV	0.9kV	1.4kV
692 B	2000ft	0.8kv	2.5kV	2.5kV	2.8kV	No Phase B	1kV,4.2trail

Fault Locatio And Phases	Distance From source	Fault Voltage	Source Voltage	645 Voltage	633 Voltage	684 Voltage	675 Voltage
633 A	500ft	1.3kv	2.2kV	2.2kV,3.8trail	1.12kV(130)	No phase B	2kV
With DG at 675.							
645 B		1.2kV	2.6	1.3	2.8kV		2.9kV
684 A		1.5 kV	3	3	3.1kV	1.5	2.2
633 B		1.51 kV	2.5	2.2	1.51kV	no impact	2.75
692 B		1.5 kV	2.8	2.5	3.0kV	No impact	1.5kV
DG at 633							
645 B		1.2 kV	2.2	1.25	2.6	no impact	2.75
684 c		0.8 kV	2.9	3	2.8	1	3.1
692B		1 kV	2.75	2.75	2.7	No phase B	
633 B		1.3 kV	2.5	2.5	1.7	No phase B	1.9

Table 5.6 shows the currents at various nodes during faults at various nodes.

Table 5.6
Currents at various nodes during fault.

Fault Location & Phase	Fault Current	Distance from Source	Source Voltage	Source Curret	645 Current	633 Current	SRCCOntri	Dgcontri	CAP BAN KNO AND CONTRI
645 B	6KA	500 ft	2.4kV	6	6	500-750A	6		
684A	4kA	2300ft	2.6kV		Noefect	littledistinb	4		
692 B	6&5	2000ft	2.5kV	5.5kA	200from275	50from75	5		cap692--6
633 A	6.5kA	500ft	2.2kV		170from275		6.5		
With DG at 675.									

645 B	6kA		2.6	5.6		500from750	5.5kA	2.3kA	
684 A	4.2 kA		3			650from750	3.5	1.5	
633 B	8kA		2.5	6	180Afrom 275	8kA	6	2.2	
692 B	9kA		2.8	4kA	210fro275		4	6	
DG at 633									
645 B	7		2.2	5	7		5	7	
684 c	5.3		2.9	1.75	no impact		1.75	1.2	5
692B	5.2		2.75	4.2	200fromm275		1.5	1	
633 B	9		2.5		1.9		4	6	

5.9 Summary

This chapter has discussed the various results obtained from the simulations. A comparison between the voltage profile of the network with and without DG is presented. The next chapter gives the various conclusions that can be drawn from the results shown in this chapter.

Chapter VI

Conclusions and future work

6.1 General Conclusions

The research work discussed in this thesis is related to fault analysis on a distribution system, impact of DG on the faults and impact of placement of DG on the system. The majority of the previous research on transients and faults was mainly focused on developing a mathematical model of the distribution system under transient condition. And the main aim was to design a protection scheme.

In this thesis a detailed modeling of IEEE 13 node feeder in PSCAD for fault analysis is presented. The response of the system to faults is analyzed. And the impact of distributed generation on faults is also presented.

Based on the results obtained it can be concluded that PSCAD is very much suitable for fault simulation. The user-friendly graphical interface makes it very easy to implement the components of power systems for simulation.

6.2 Conclusions from the simulations

The following conclusions can be drawn from the results presented in the previous chapter:

1. With a DG in the system the currents during the fault are increased especially when the fault is close to the DG unit.

2. With a DG in the system the voltage magnitude during the fault does not decrease as much as without a DG.
3. Based on the two locations used in this study having the DG further away from the source helped provide increased voltage support during a majority of the fault conditions.
4. Presence of capacitor banks also increases the fault currents. Capacitors also contribute to the fault current in a very short time. Apart from the capacitor banks the shunt admittance of the lines also contributes to the fault current.
5. Presence of these energy storage devices creates some oscillations in the fault current.

6.3 Future work

Future work to this thesis could be looking at the simultaneous impact of more than one distributed generator. Looking at the impact of loading on the fault and type of loads. If we have a spinning load like an induction motor then the transient response would be different than that if we have fixed loads. Further studies can include modeling a synchronous generator or an induction generator along with the dynamics of the prime mover.

In this thesis the cable in the IEEE13 node feeder was eliminated due to the time of each simulation. So the cable can also be included and the results can be estimated more accurately.

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Appendix A

The faults at different location have different effect on the generator and also on voltages at different locations on the feeder.

Initially the fault is at location 645 and on phase B.

The fault current and voltage at 645 and in phase B are shown in figure A.1

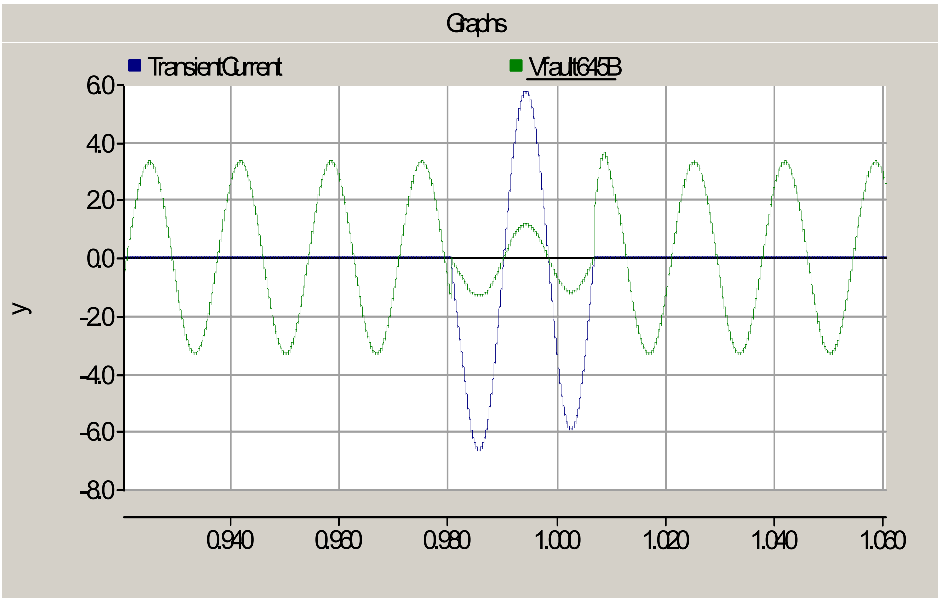
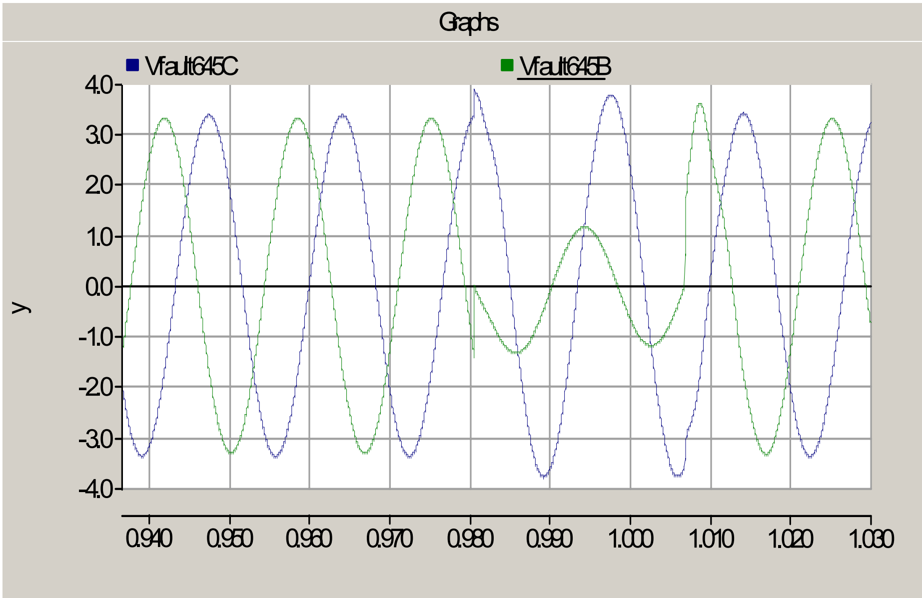


Figure A.1 Fault current and voltage at 645.

The Voltage affected at different locations is given in figures to follow.

The effect on Voltage in phase C is shown in figure A.2



FigureA.2. Voltages at the Node 645

Effect on source voltage and currents are shown in figures A.3 and A.4.

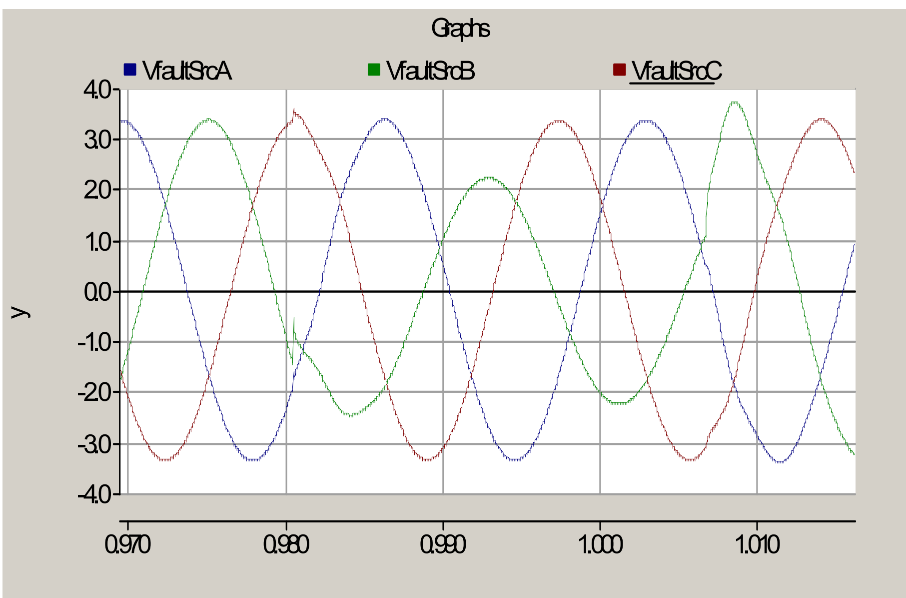


Figure A.3 Voltages at source.

The currents are shown in figure A.4

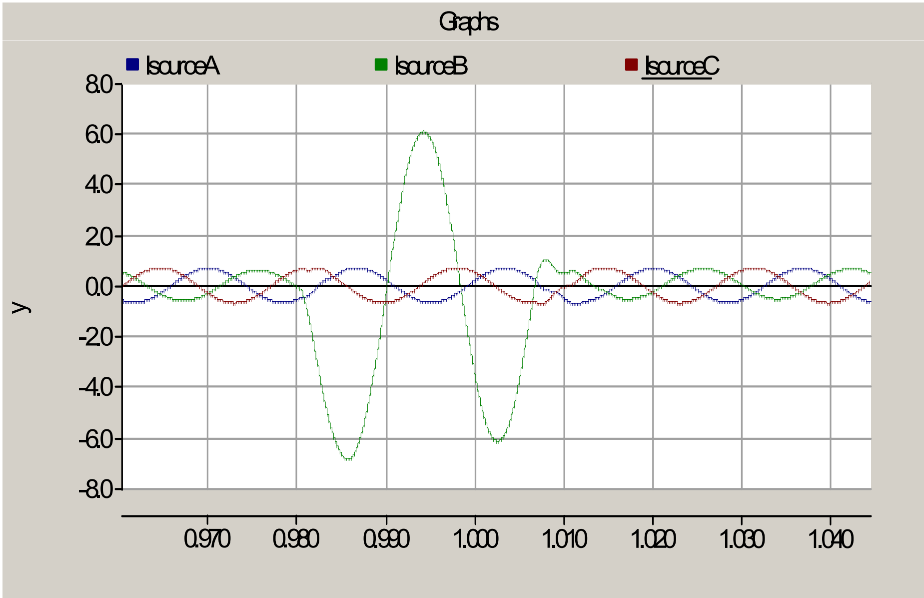


Figure A.4 Source Currents

The Voltages at nodes 684 are shown in figure A.5

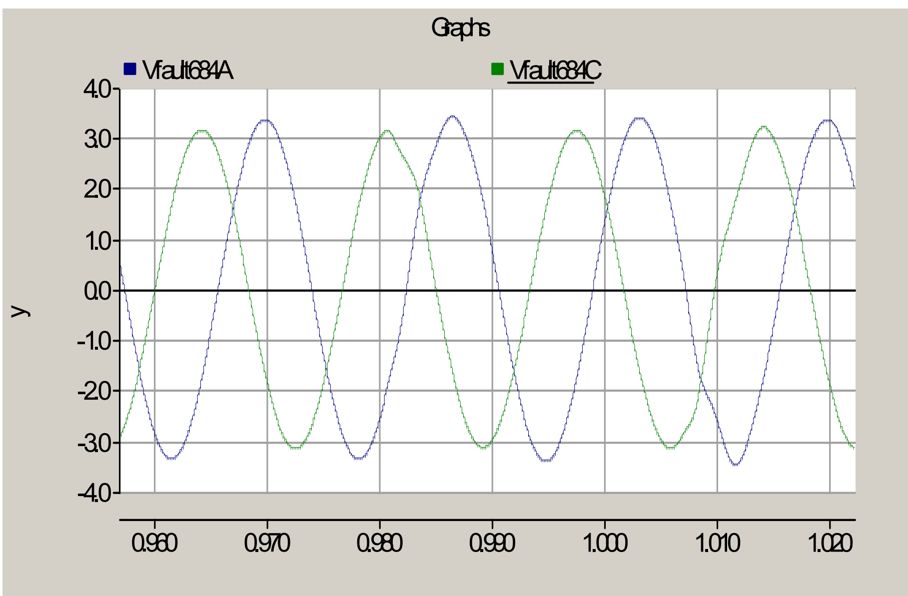


Figure A.5 Voltages at node 684.
Voltages at node 675 are given in figure A.6.

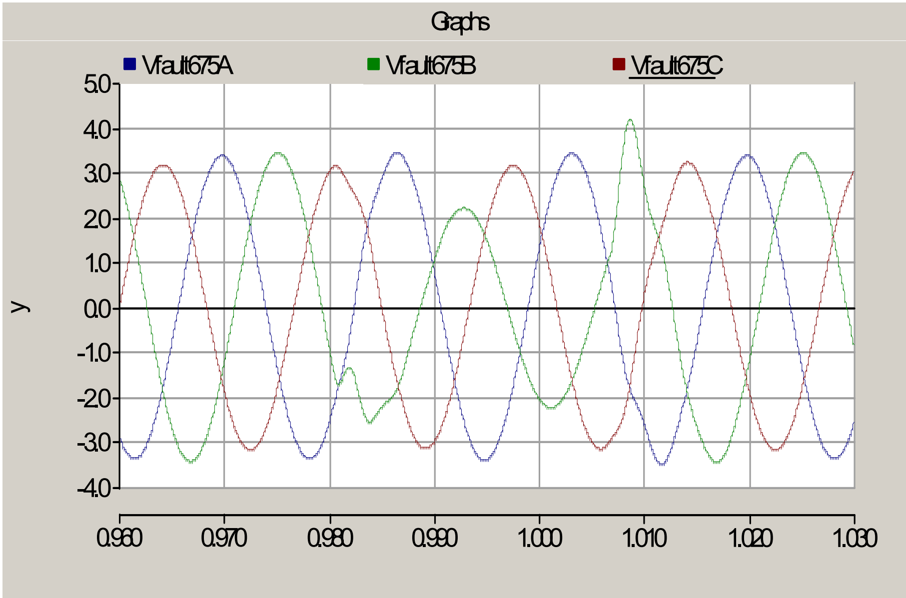


Figure A.6 Voltages at 675.
Voltages at 634 are shown in figure A.7

Fault at node 645 without any DG.
Fault current and voltage are shown in figure A.1

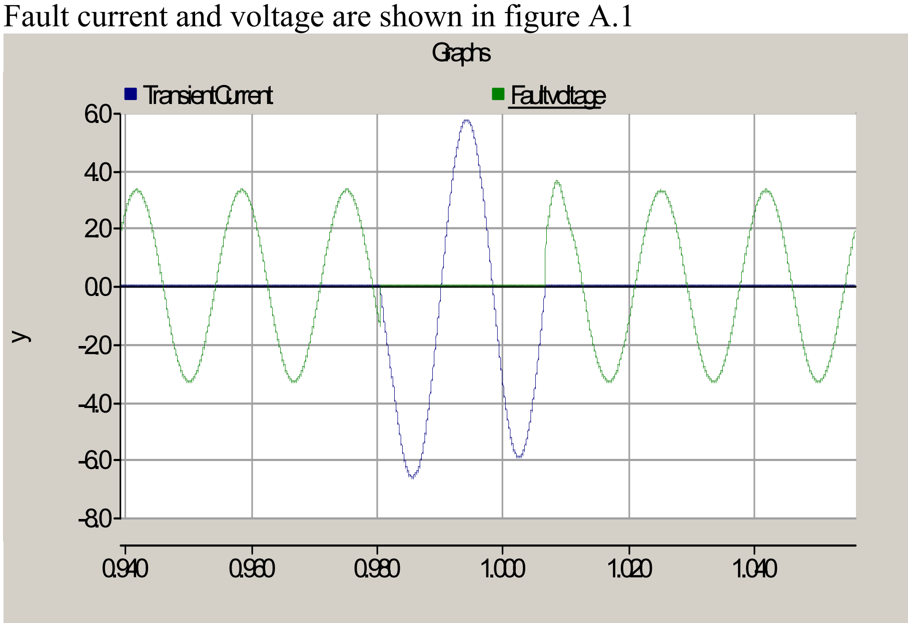


Figure A.7 Fault current and voltage.
Currents at various nodes are shown in figures to follow.

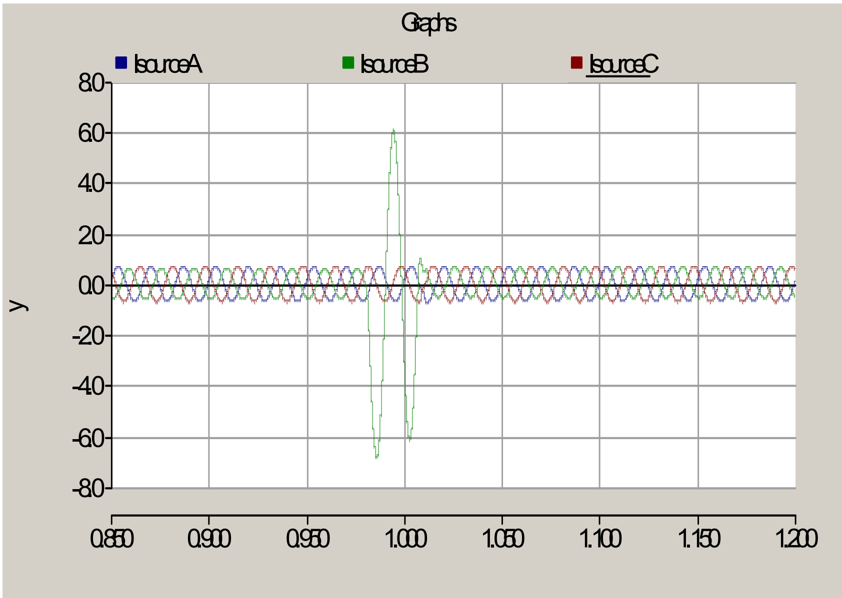


Figure A.8 Fault current at source.

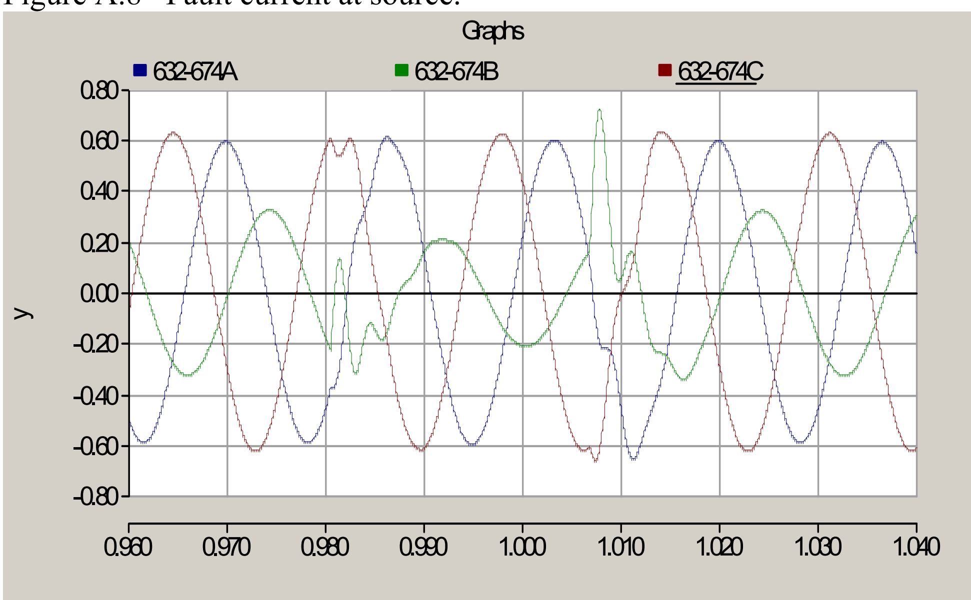


Figure A.9 Currents into the Node 632-674

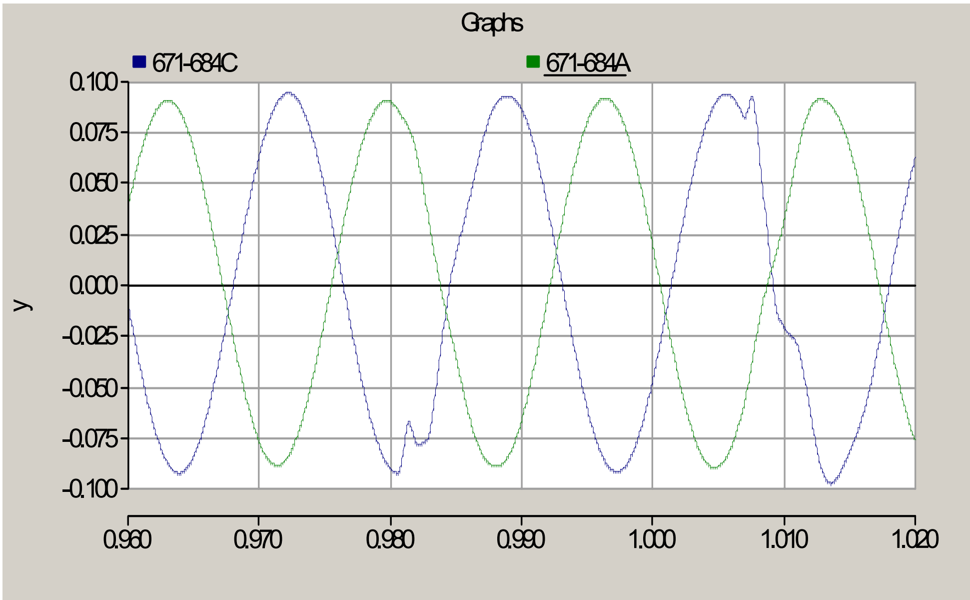


Figure A.10 Currents into the Node 671-684

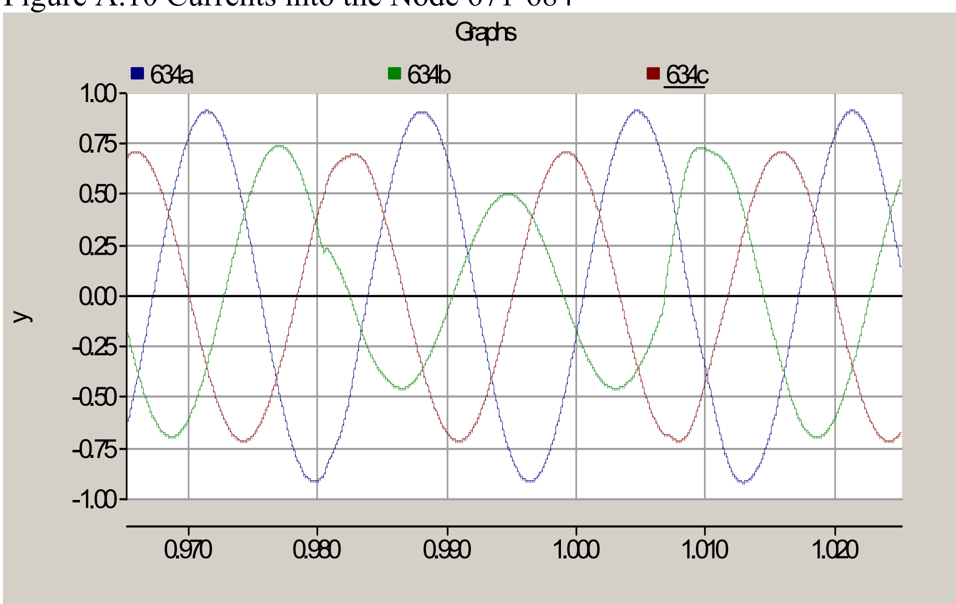


Figure A.11 Currents into the Node 634

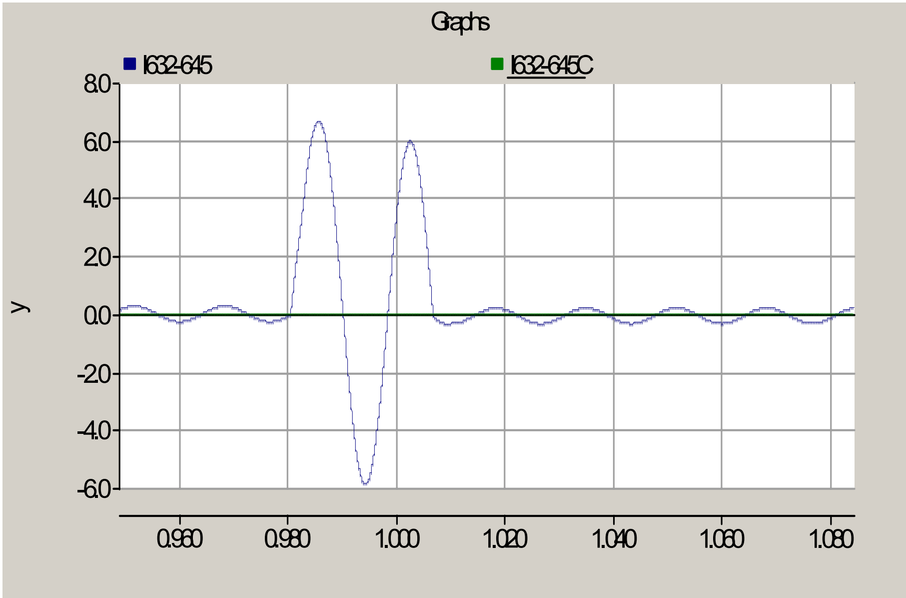


Figure A.12 Currents into the Node 632-645

Moving the fault location to 684 Phase A. The fault voltage and current at 684 are shown in figure A.13

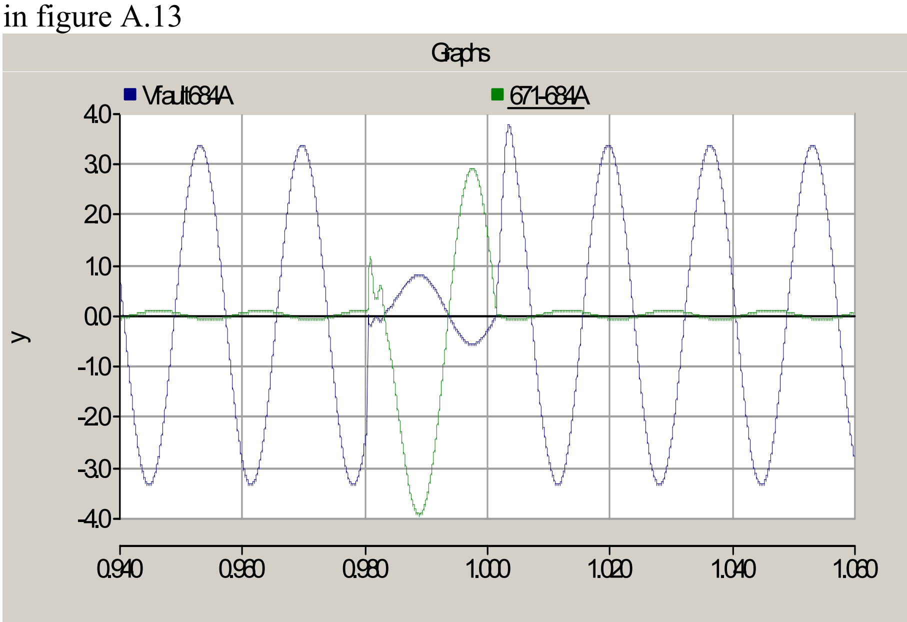


Figure A.13 Voltage and Current during the fault

The voltage and current at the source are shown in figure A.14

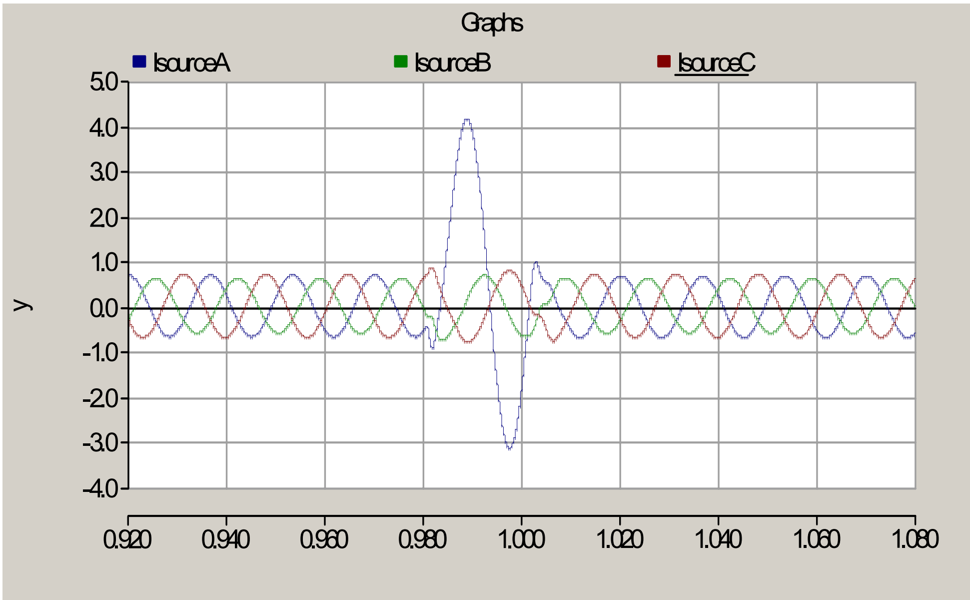


Figure A.14 Currents of source.

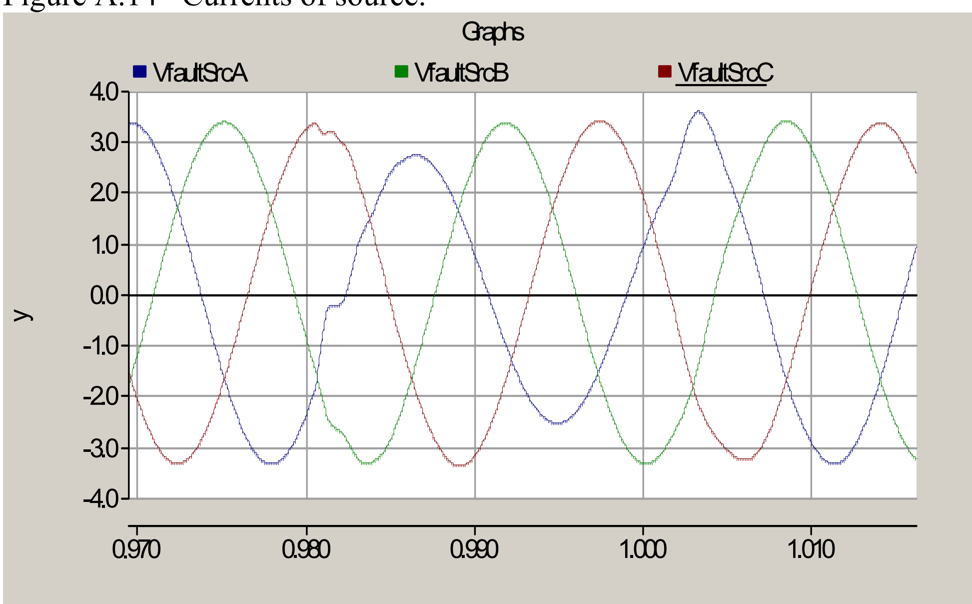


Figure A.15 Source voltages.

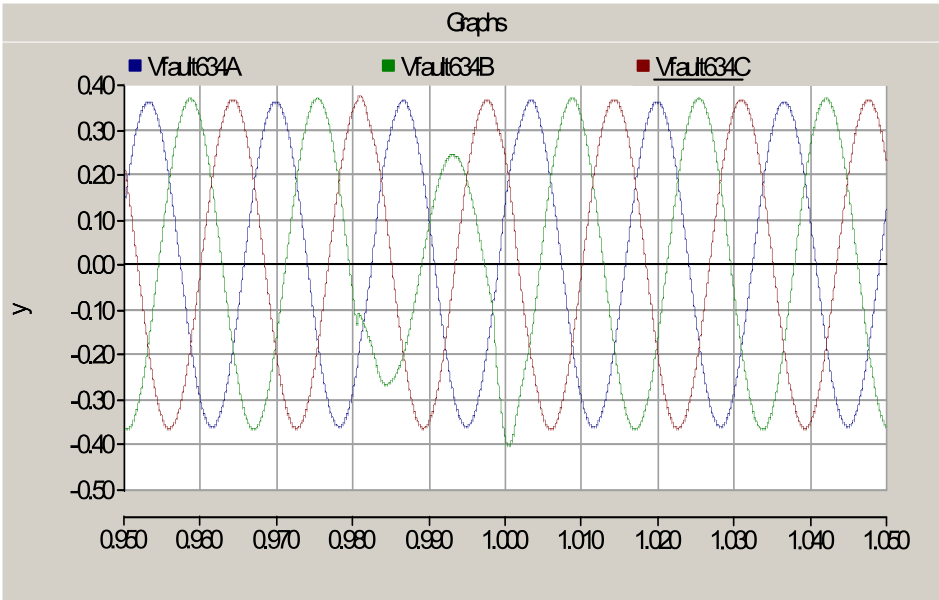


Figure A.16 Voltages at nodes 634.

Voltages at node 675

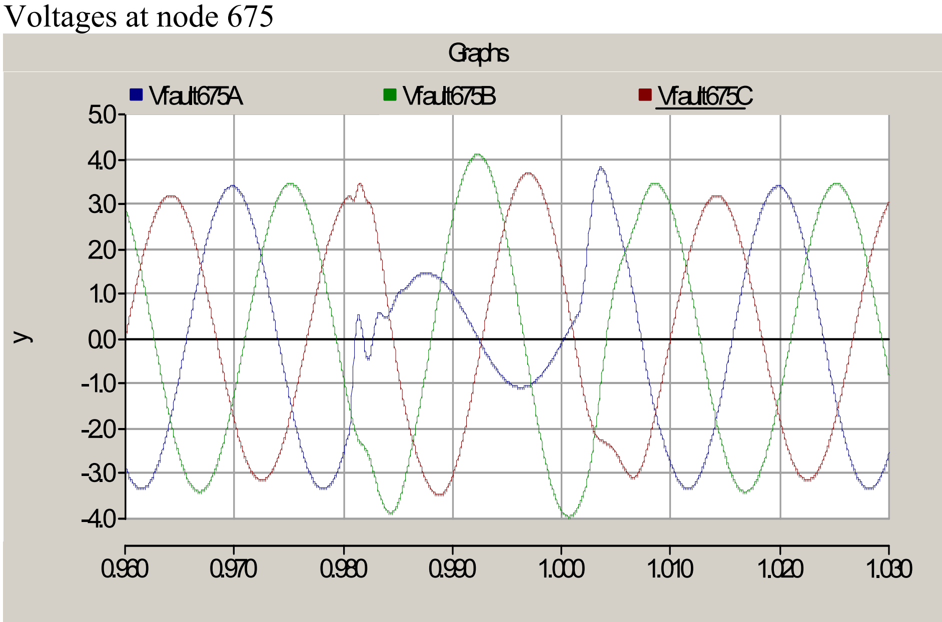


Figure A.17 Voltages at Node 675

Voltages at node 645.

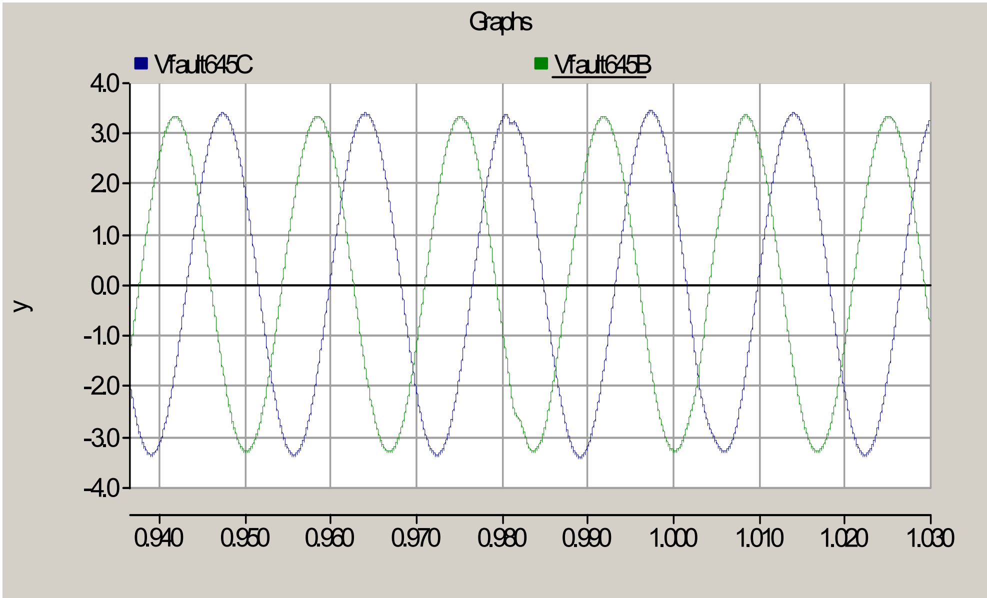


Figure A.18 Voltages at Node 645

Currents at different nodes. The contribution of the source to the fault is shown in figure A.19

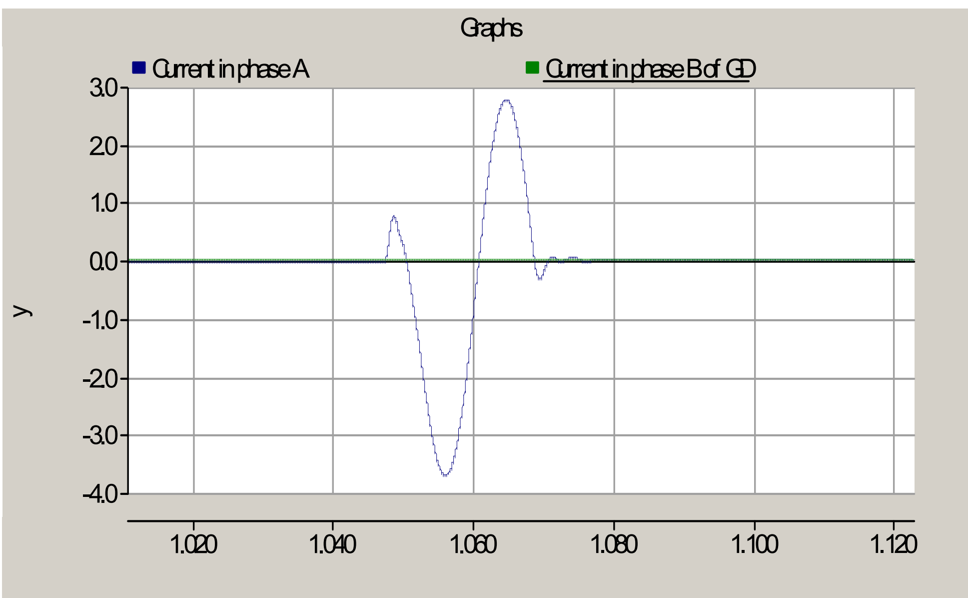


Figure A.19

The currents at node 675 are shown in figure A.20

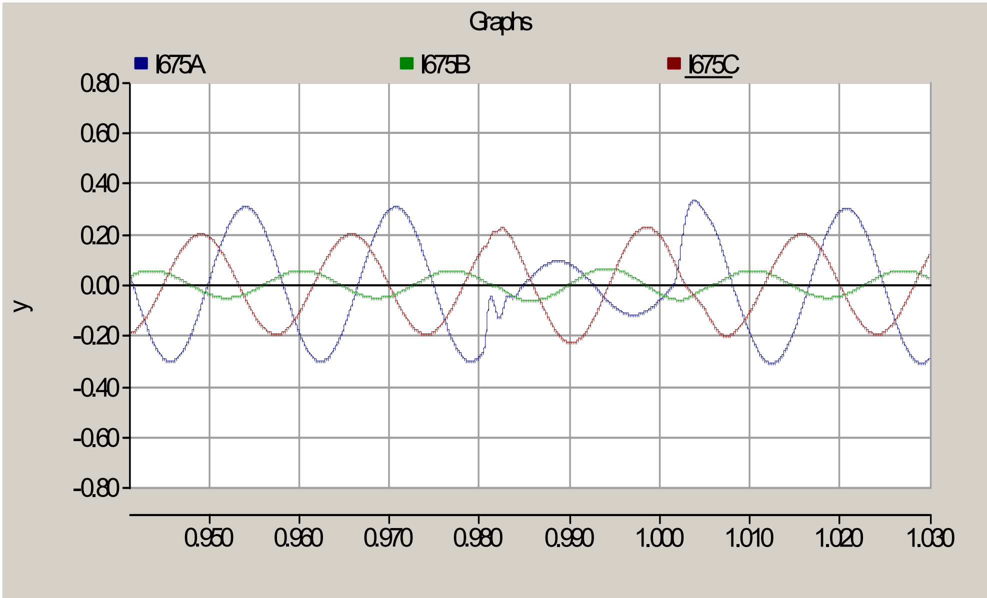


Figure A.20 Currents at Node 675

Currents at node 634 are shown in figure A.21

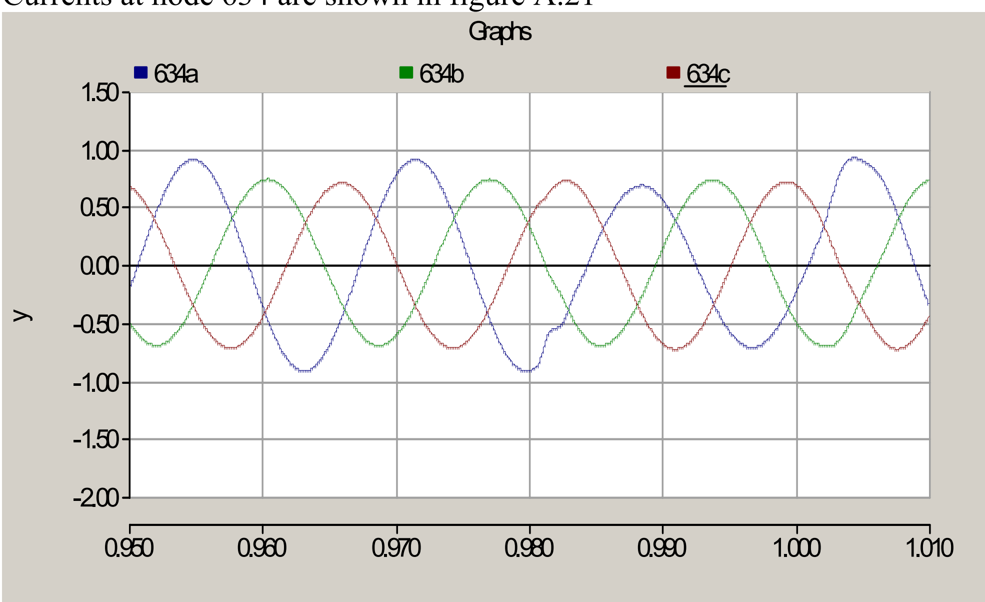


Figure A.21 Currents at Node 634

Currents flowing from 632 to 645 are shown in figure A.22

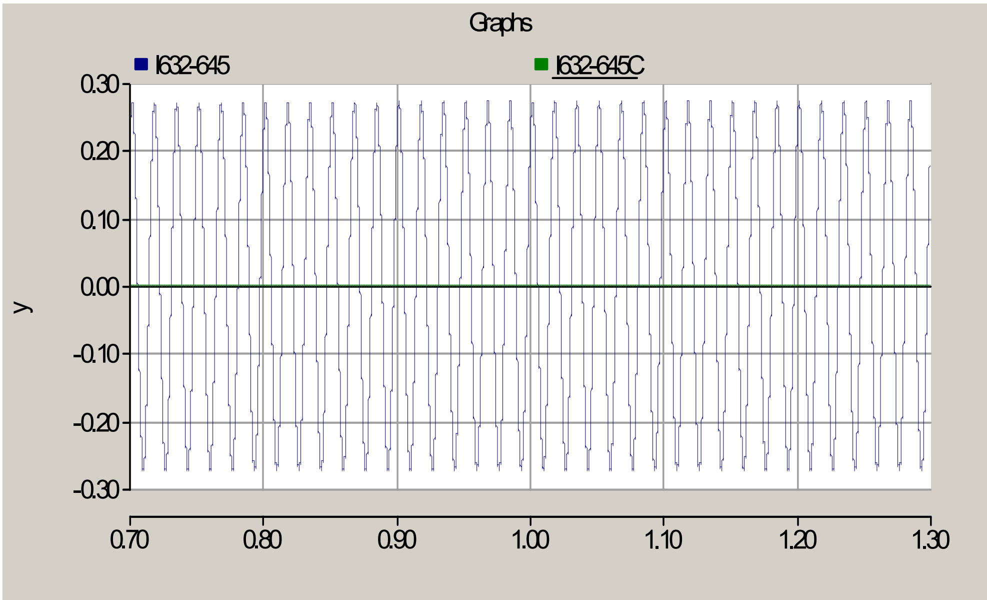


Figure A.22 Currents flowing from 632 - 645
Moving the fault to location to 692.

The fault current and voltage are shown in figure A.23

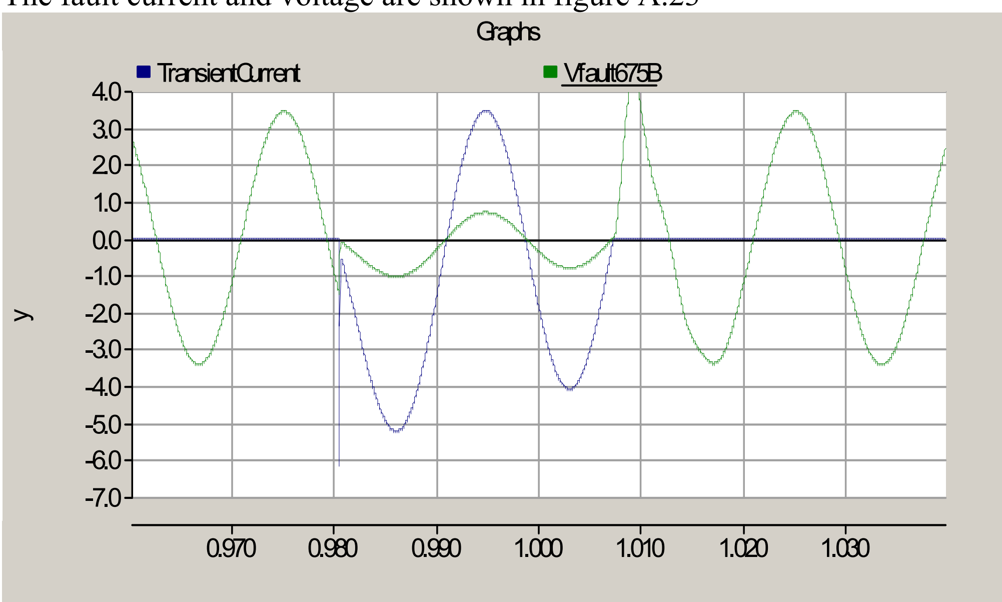


Figure A.23 Fault Current and Voltage at Node 675
The current from the source is shown in figure A.24

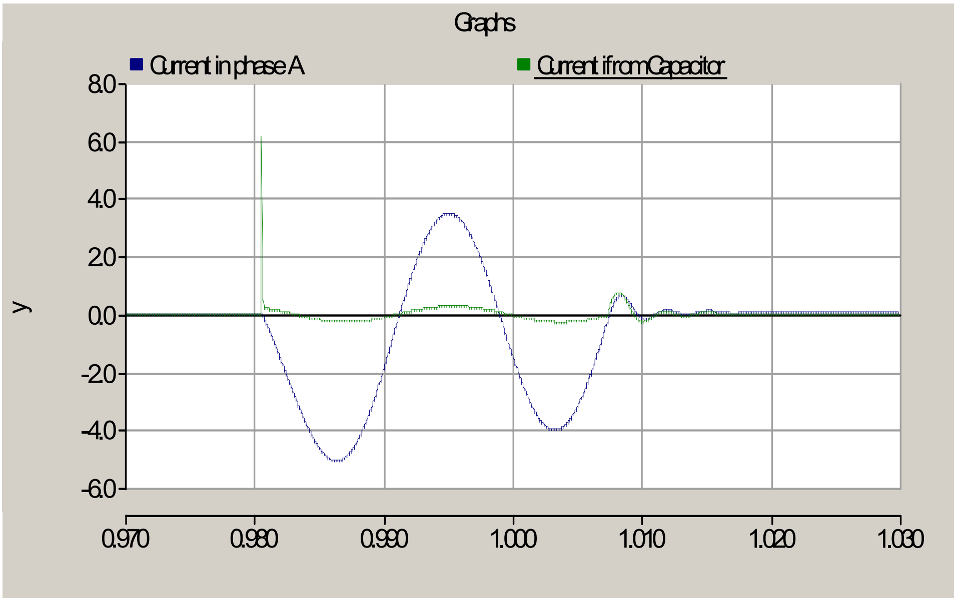


Figure A.24 Current from the Source

Voltages at various nodes are given in the figures that follow.

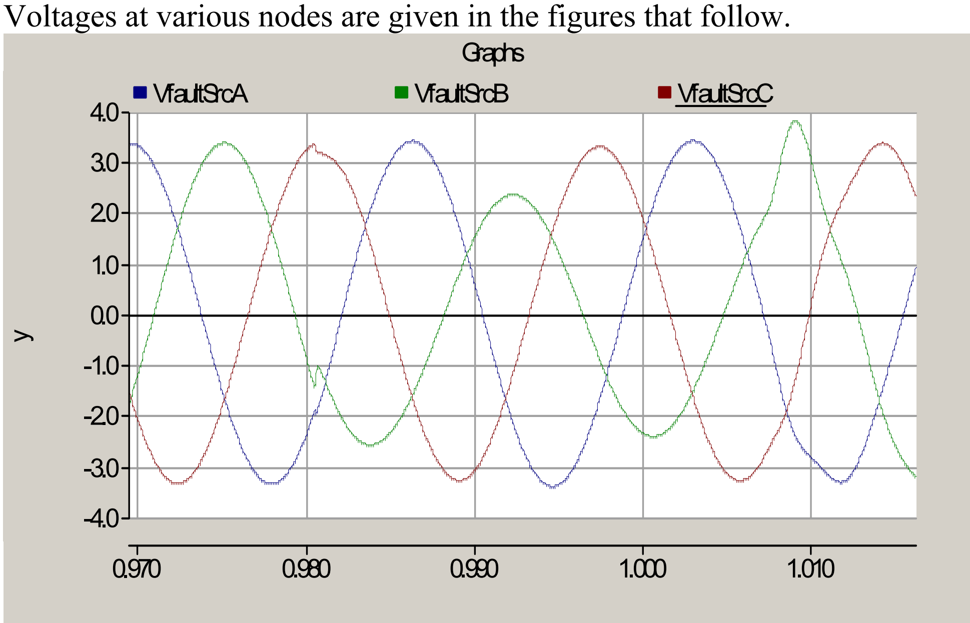


Figure A.25 Voltages at Source.

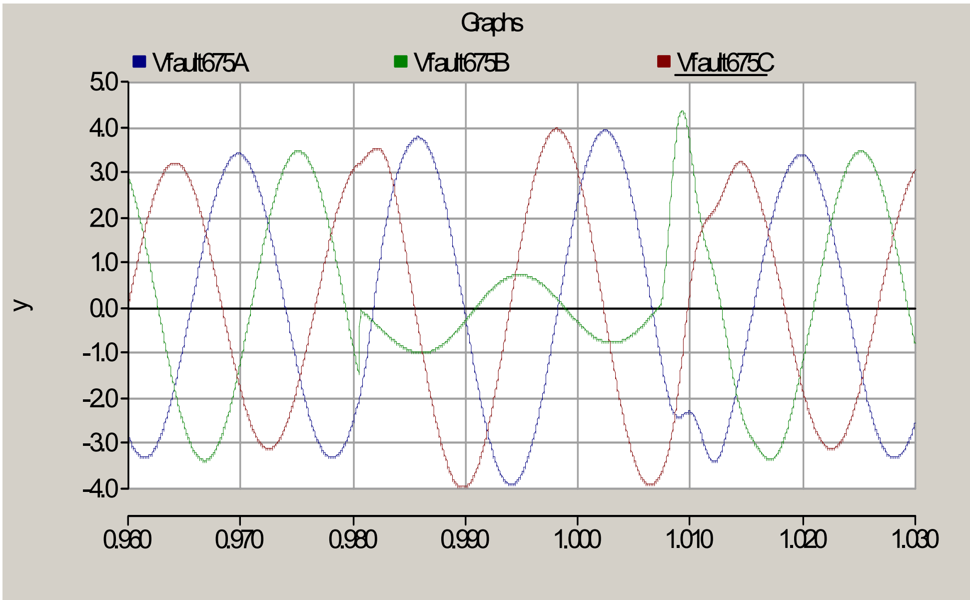


Figure A.26 Voltages at the fault location.

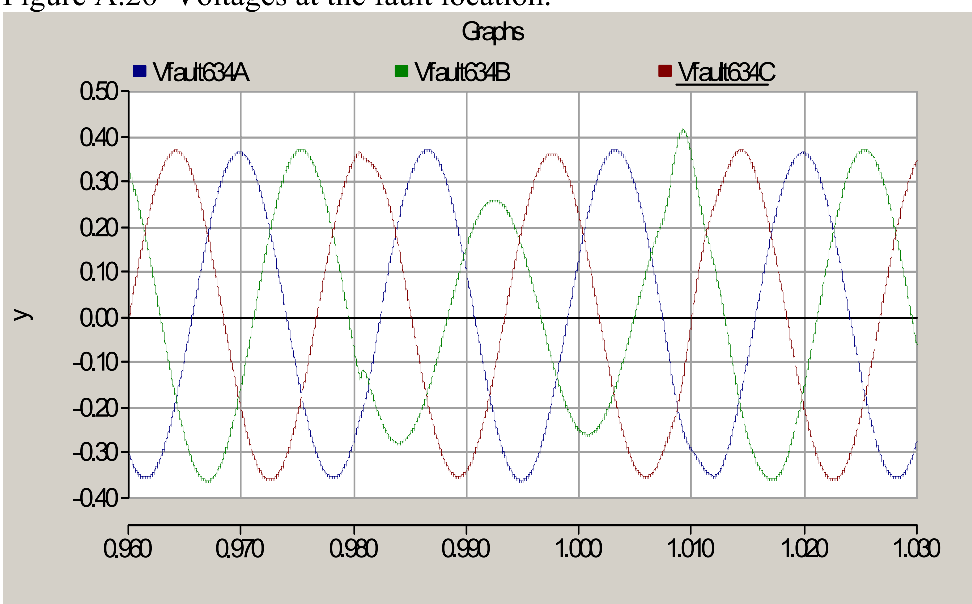


Figure A.27 Voltages at node 634.

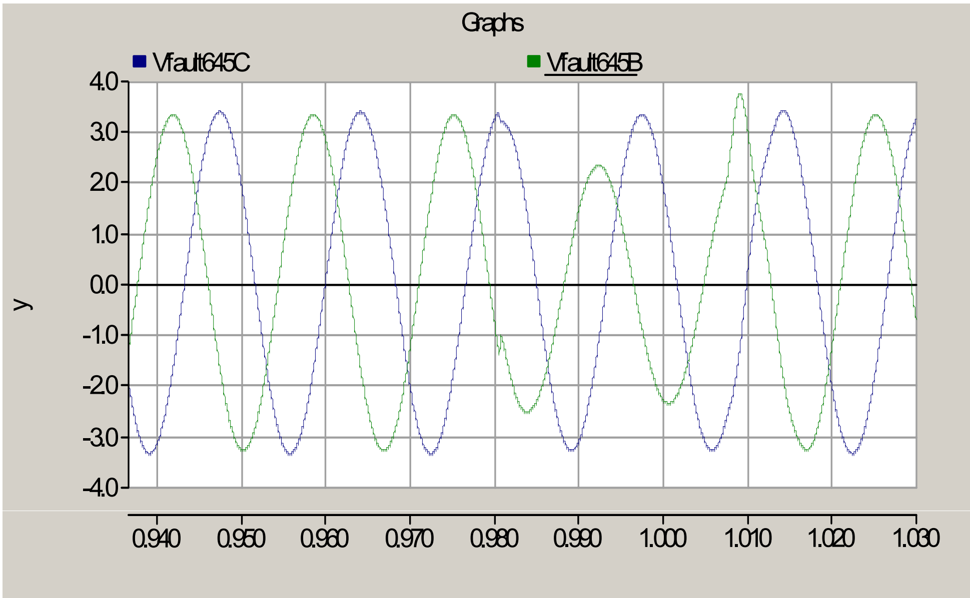


Figure A.28 Voltages at node 645.

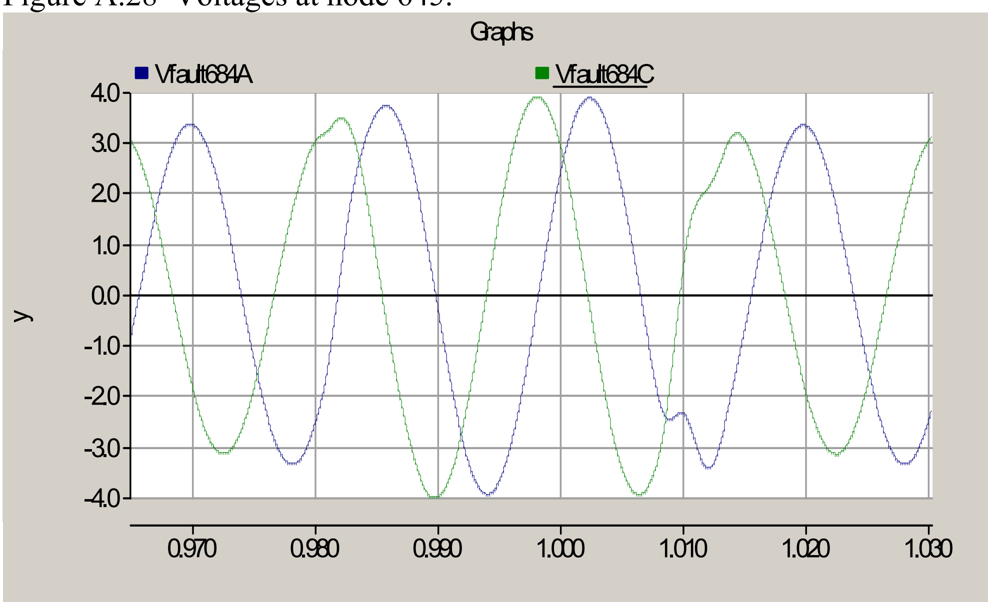


Figure A.29. Voltages at node 684.

Currents at various nodes are

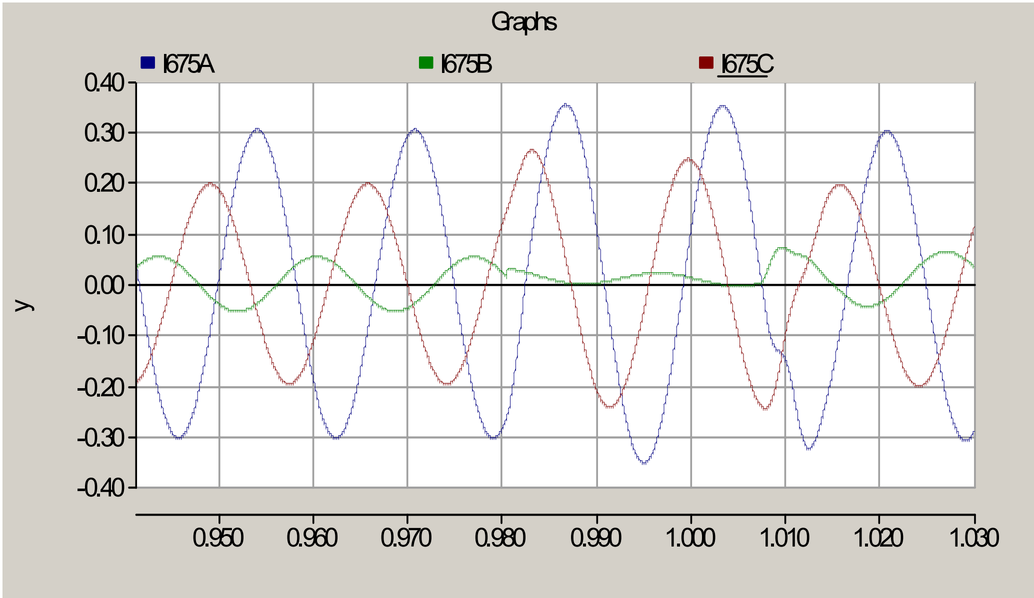


Figure A.30 Currents at node 675.

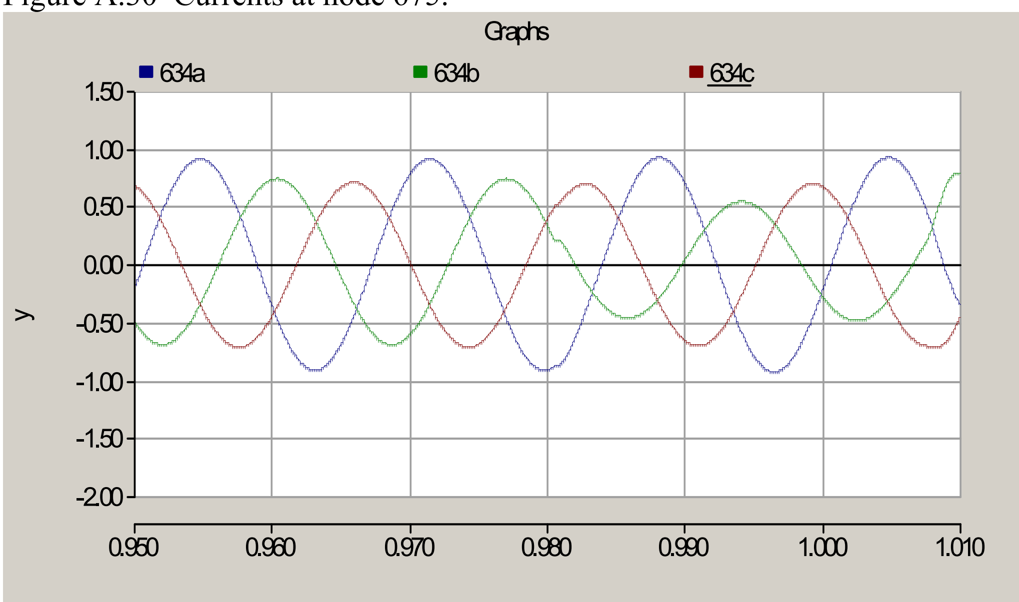


Figure A.31 Currents at node 634.

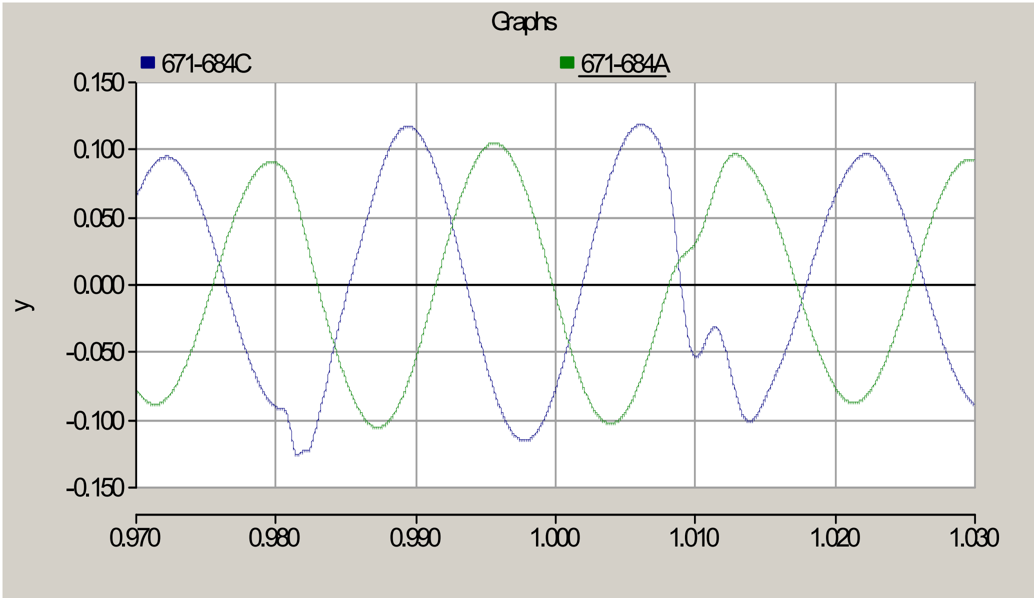


Figure A.32 Currents at node 671-684.

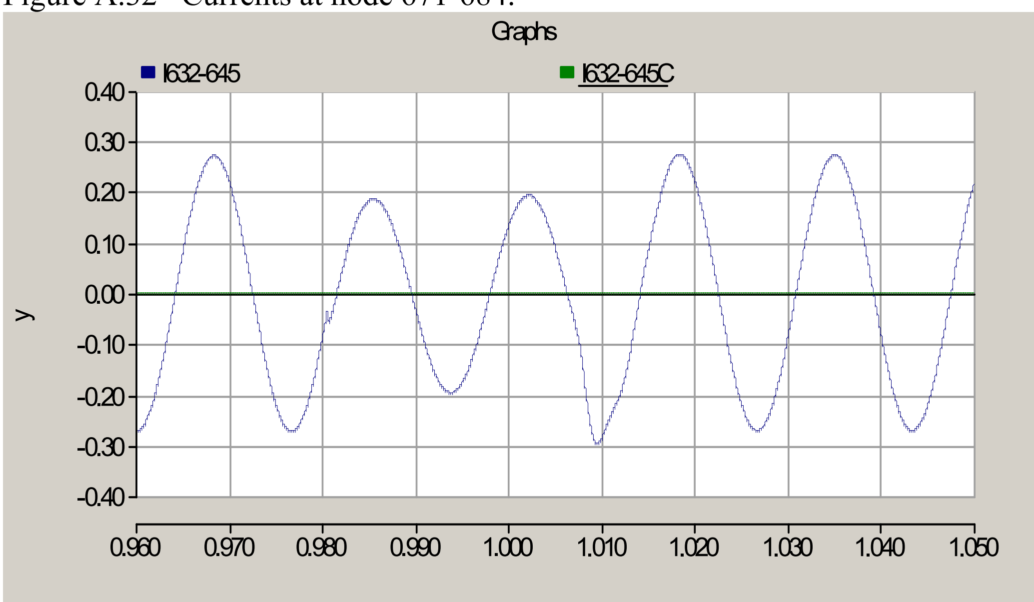


Figure A.33 Currents from Node 632-645

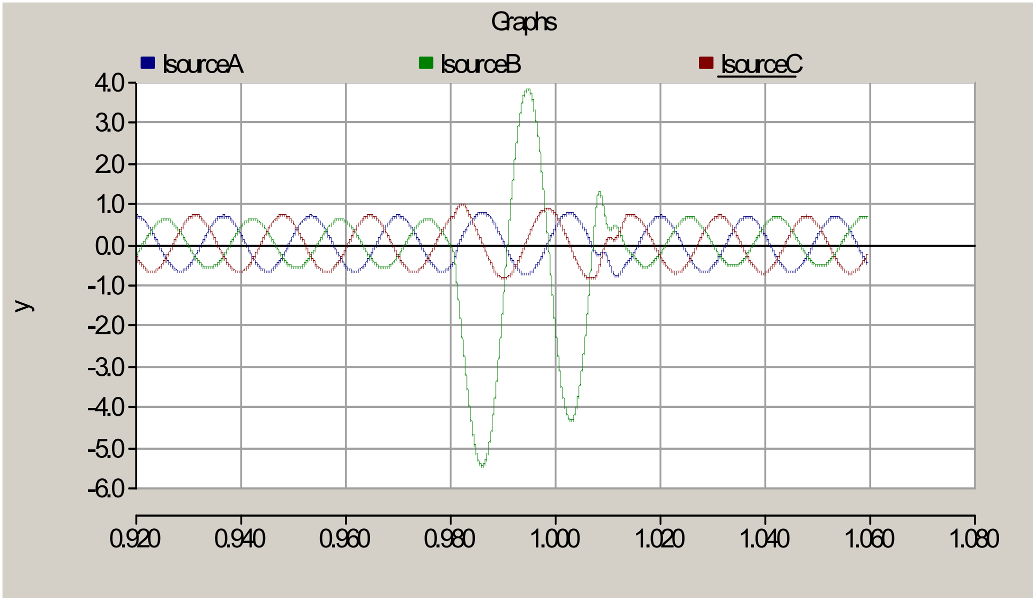


Figure A.34 Source currents.
Now moving the fault location to 633.
The fault current and voltage are shown in figure 31.

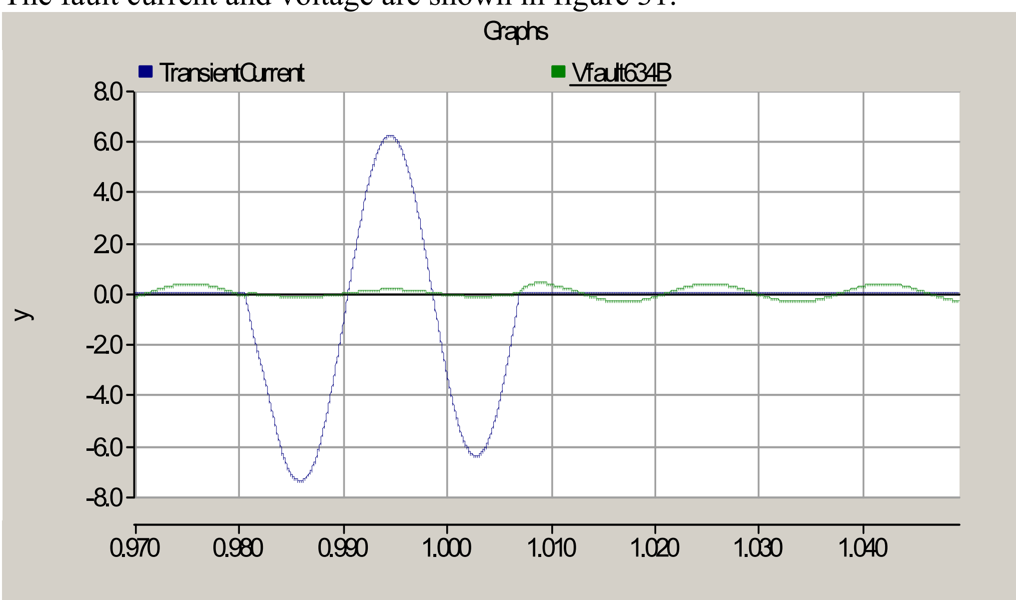


Figure A.35   Fault current at the fault location.

Source voltages are shown in figure A.36

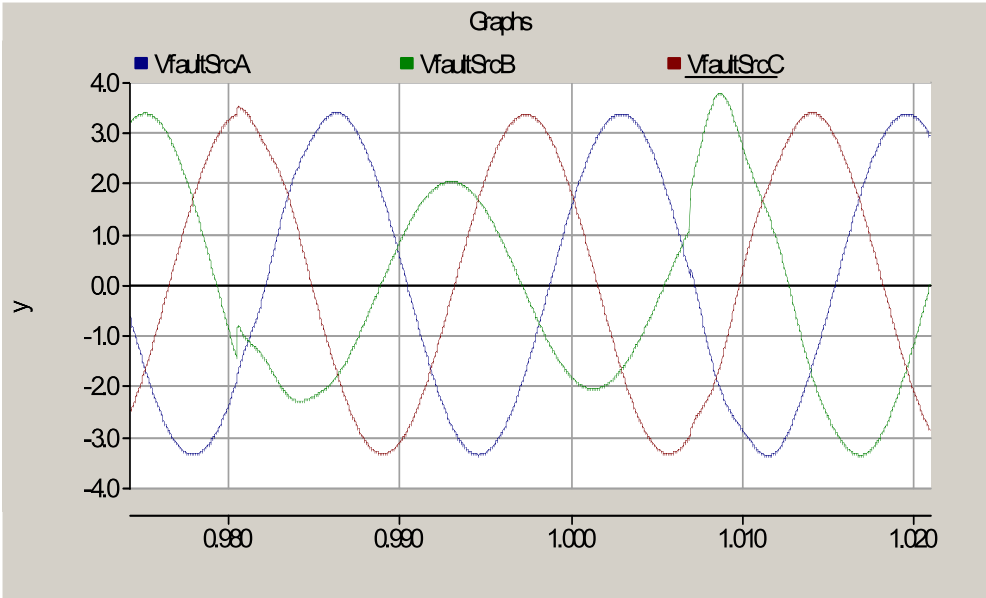


Figure A.36 Source Voltages

Voltages and currents at various other nodes are shown in figures to follow.

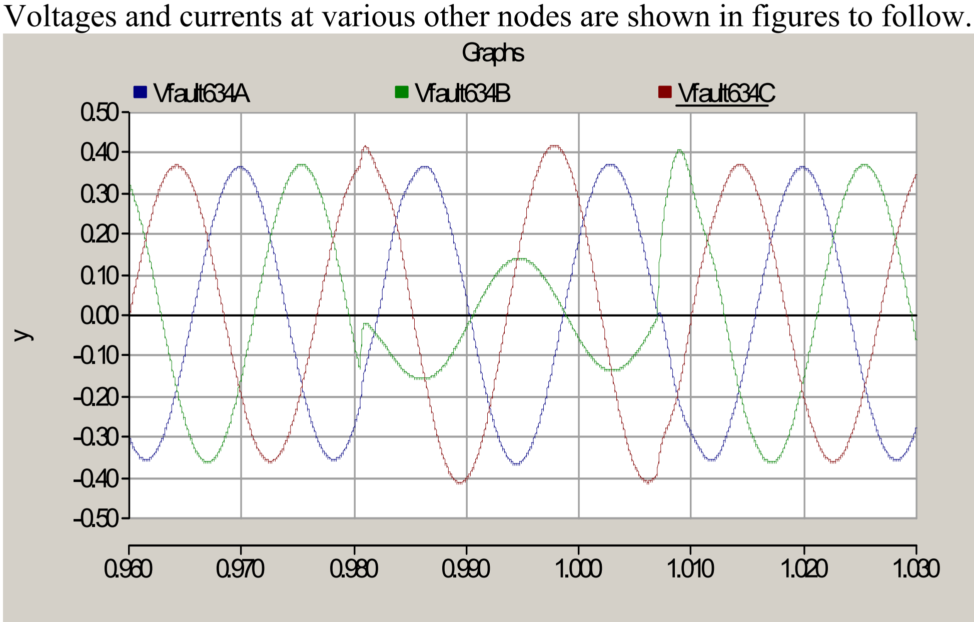


Figure A.37 Voltages and Currents at Node 634

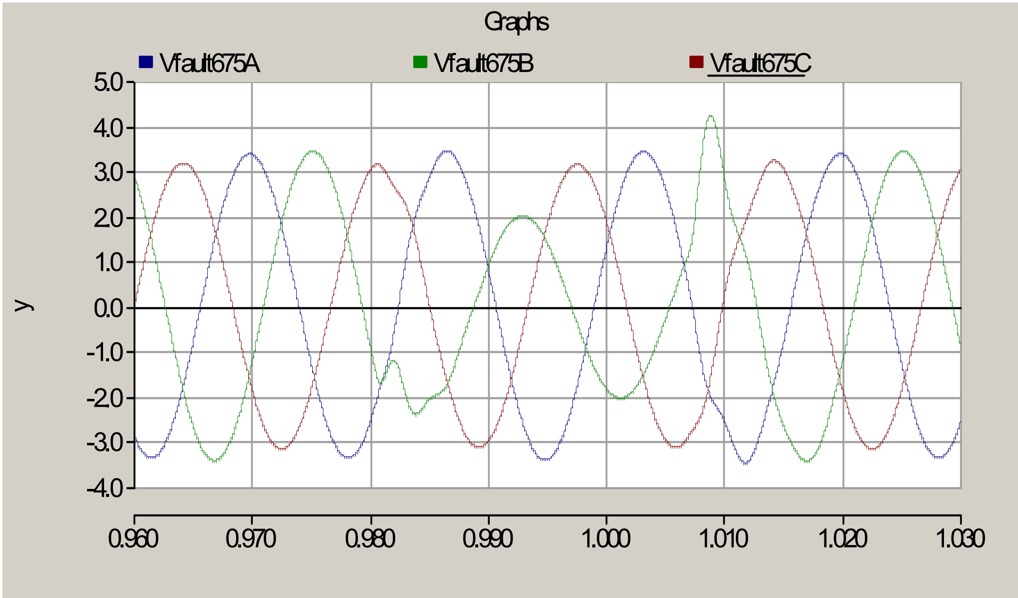


Figure A.38 Voltages at node 675

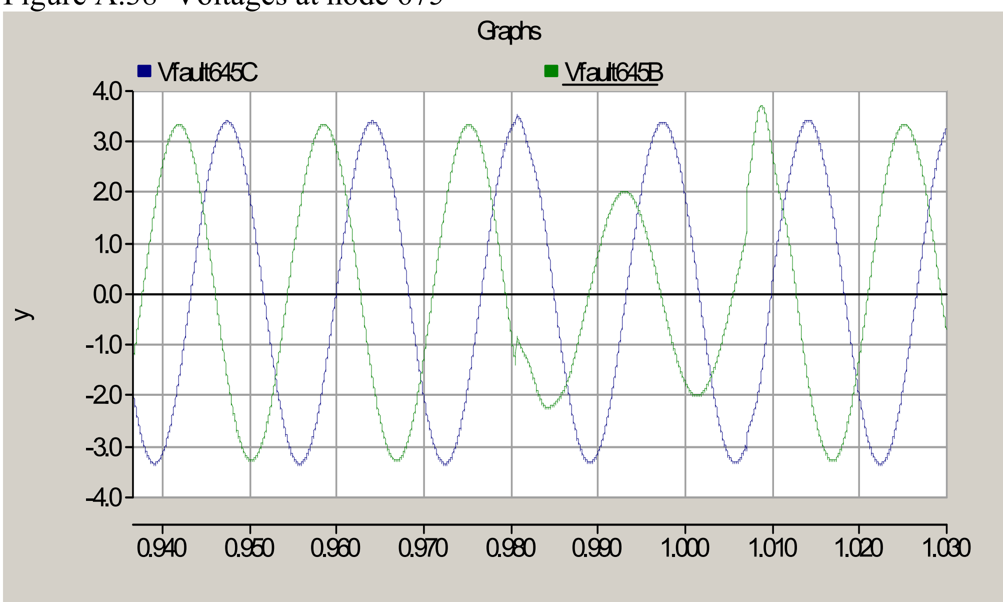


Figure A.39 Voltages at node 645.

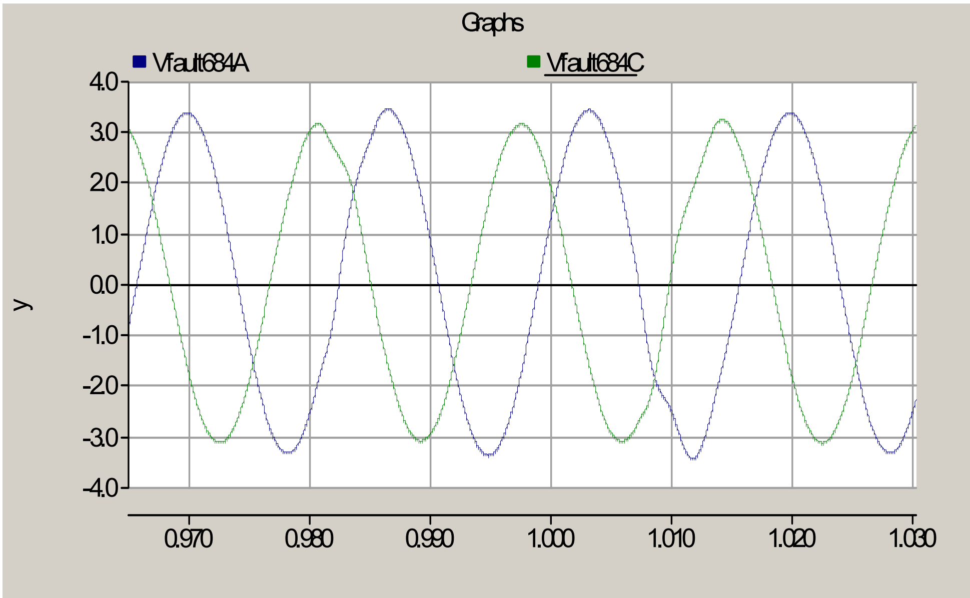


Figure A.40 Voltages at node 645.

Currents at various nodes are shown in figures to follow.

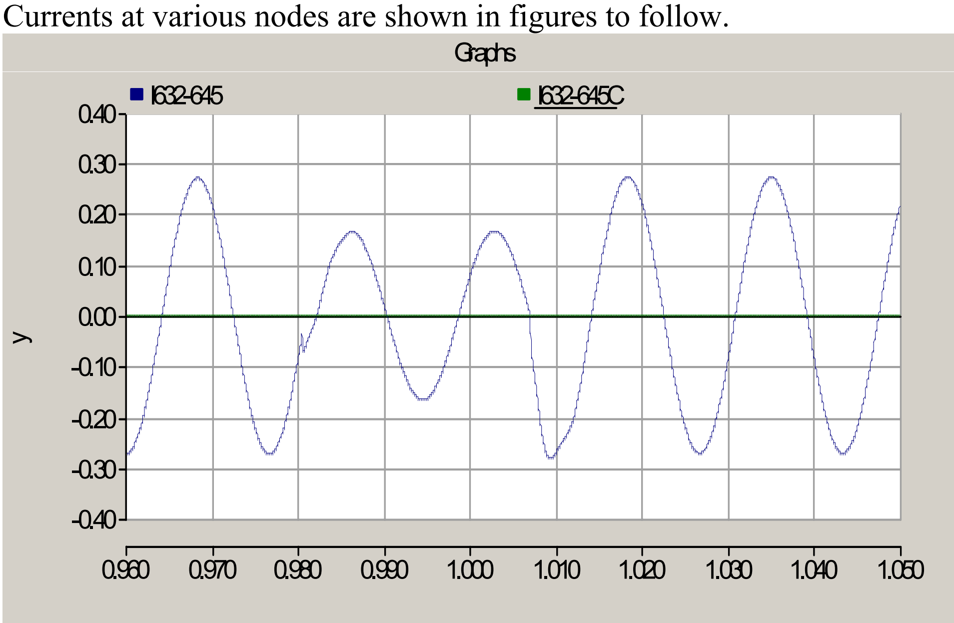


Figure A.41 Currents at Node 632-645.

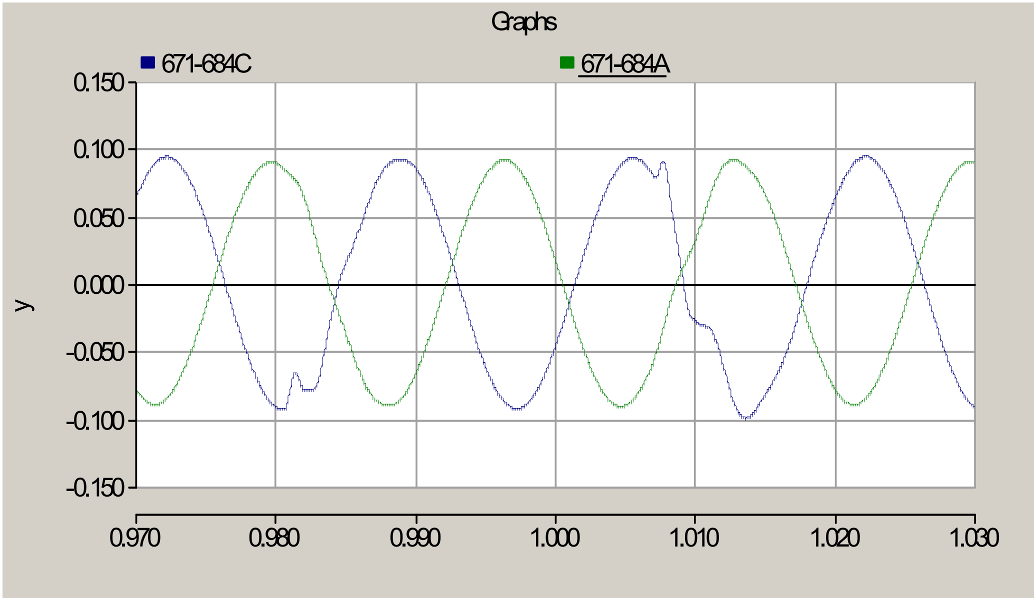


Figure A.42 Currents at Node 671-684

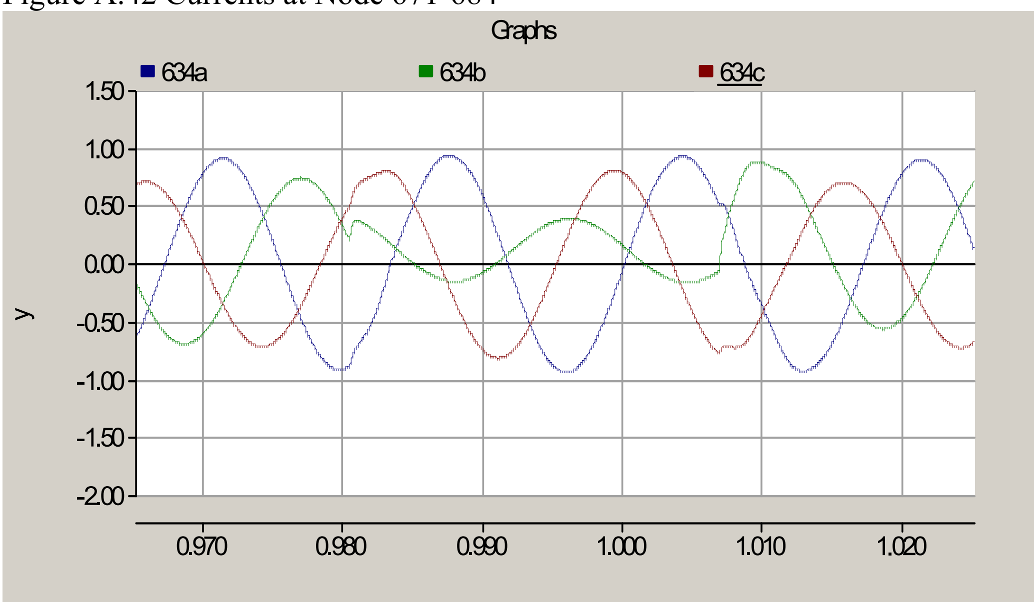


Figure A.43 Currents into Node 634

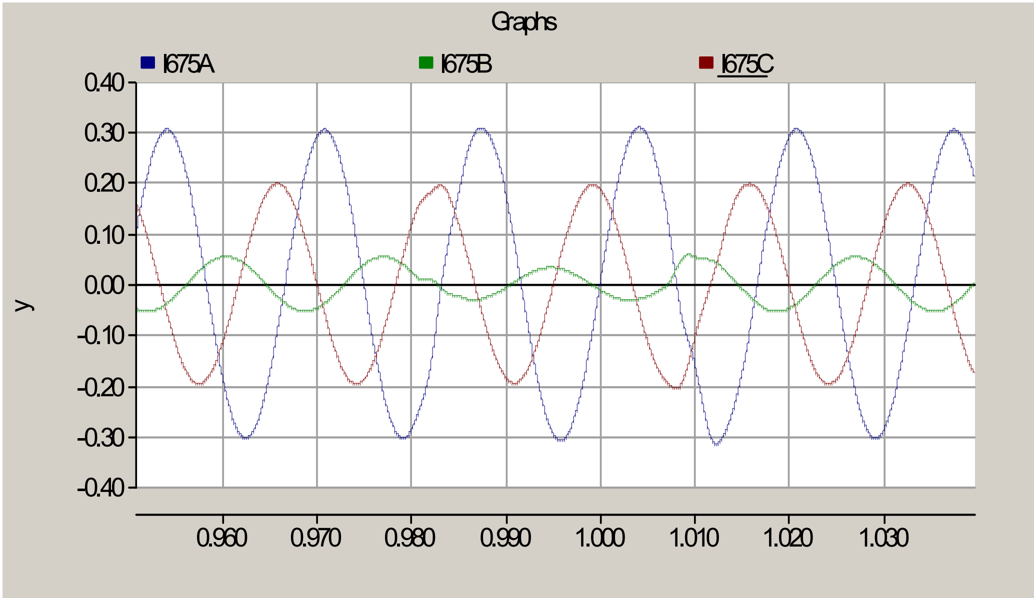


Figure A.44 Currents into Node 675

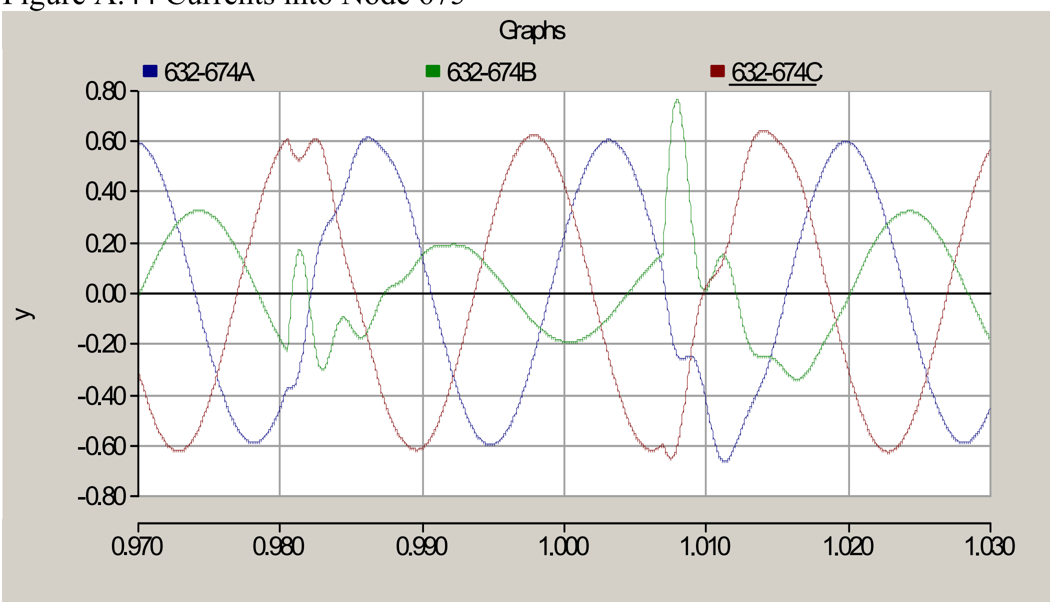


Figure A.46 Currents into the Node 632-647

Now we have the fault at node 645 and a DG source is at node 675. The various currents and voltages at different nodes are as shown in the figures below. Fault current and voltage are shown in figure A.47

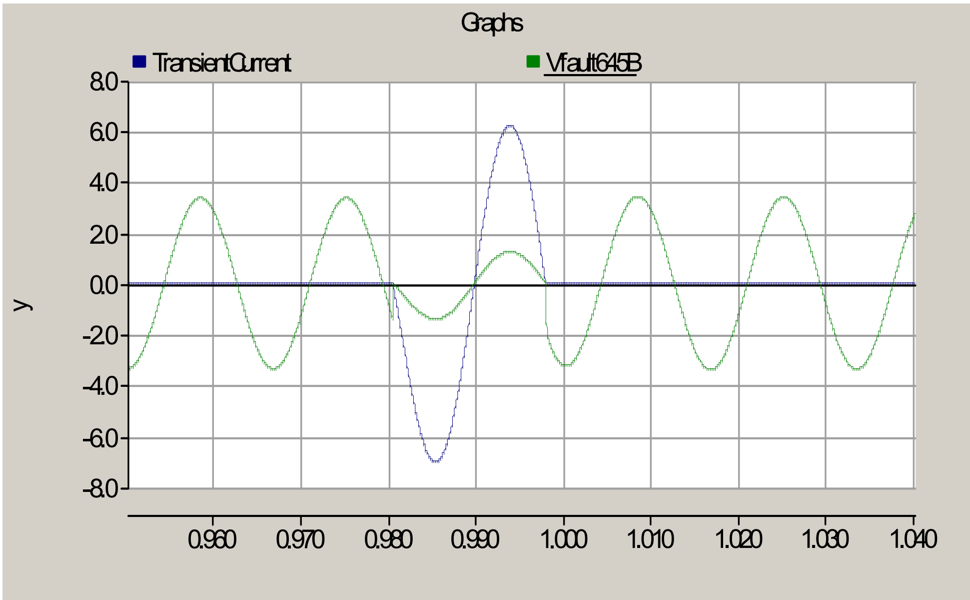


Figure A.47 Fault voltage and current.

Contribution of DG source and the main source is compared in figure A.48

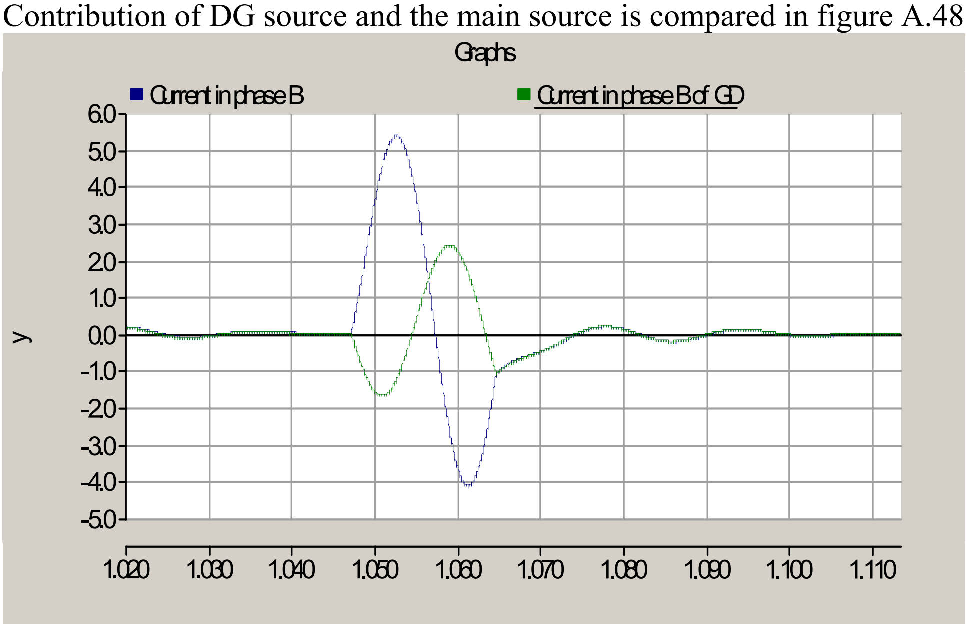


Figure A.48 Fault current contribution of Main source and the DG source.

Voltages near the DG source. It can be seen that the voltage at phase B improved when compared with the case without DG.

The source voltages are shown in figure A.49

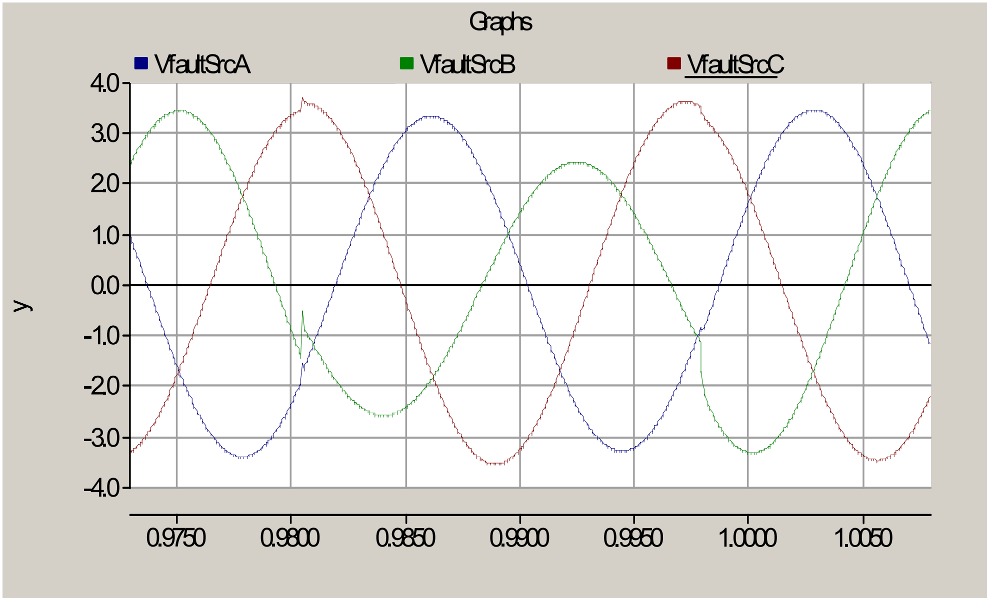


Figure A.49 Source voltage.

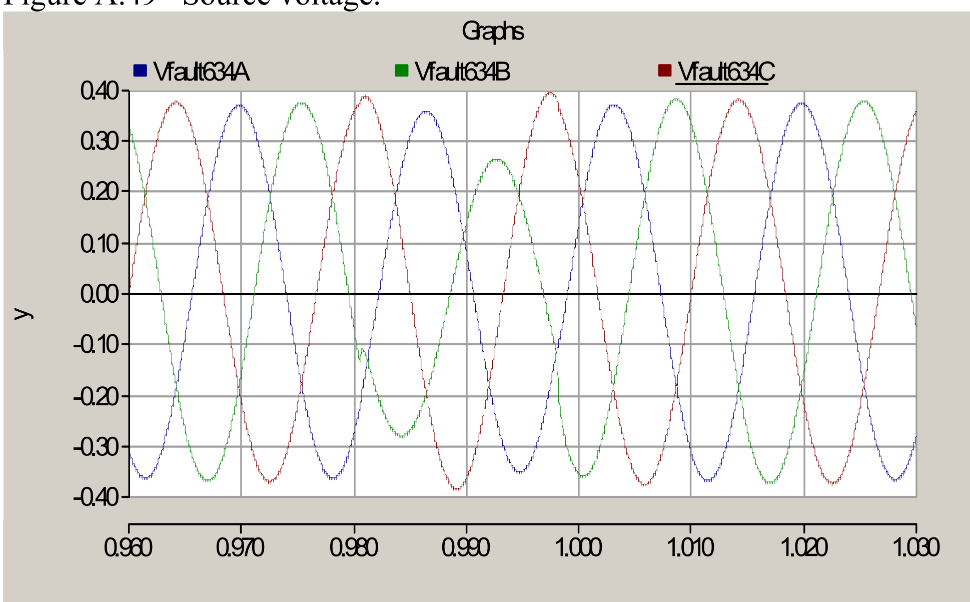


Figure A.50 Voltages at Node 634

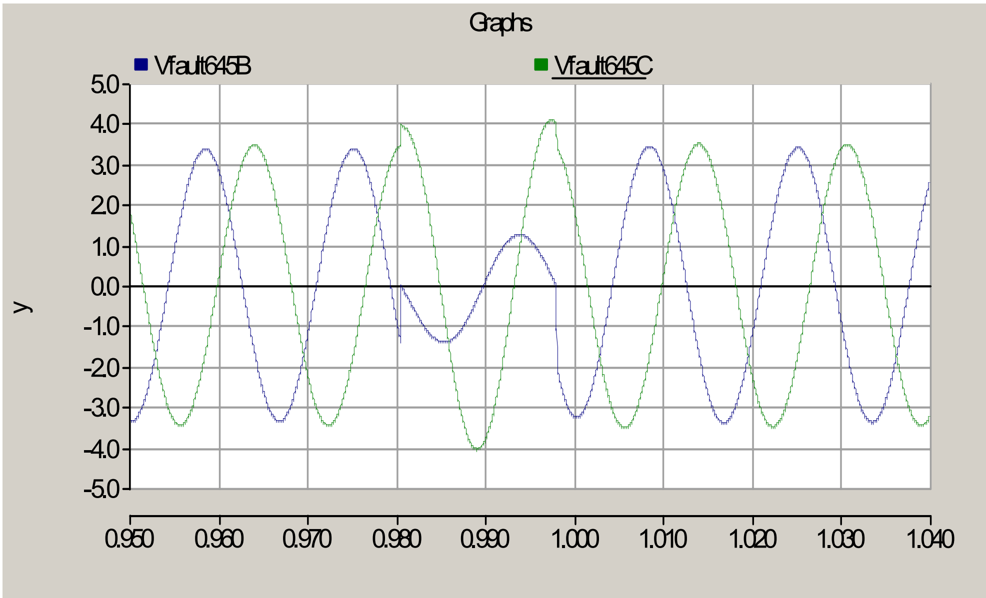


Figure A.51 Voltages at Node 645

Currents at various nodes are shown in figures to follow.

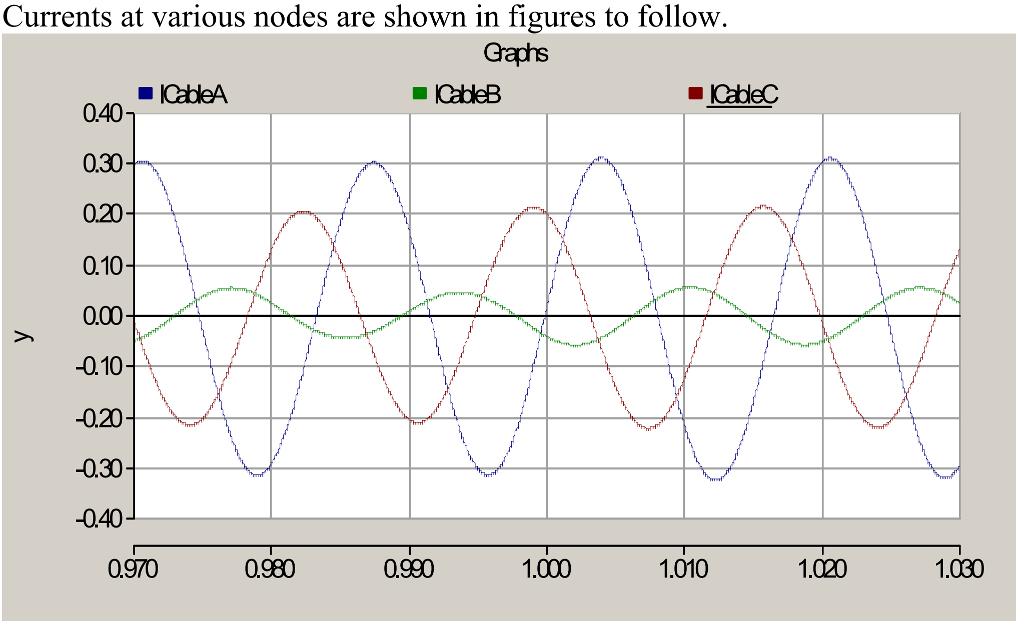


Figure A.52 Currents from node 692 to 675.

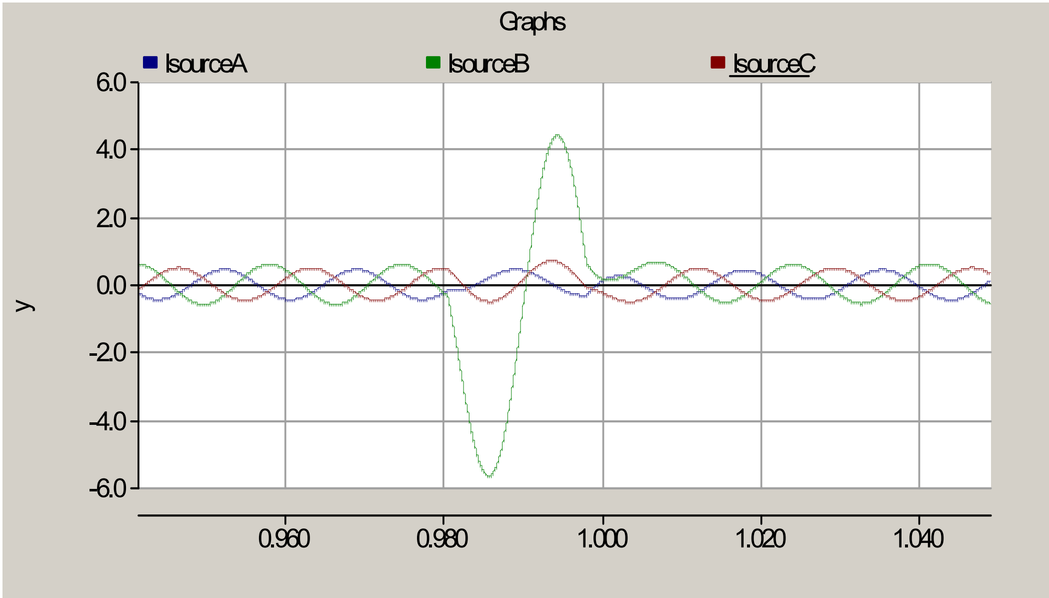


Figure A.53 Currents at the Source

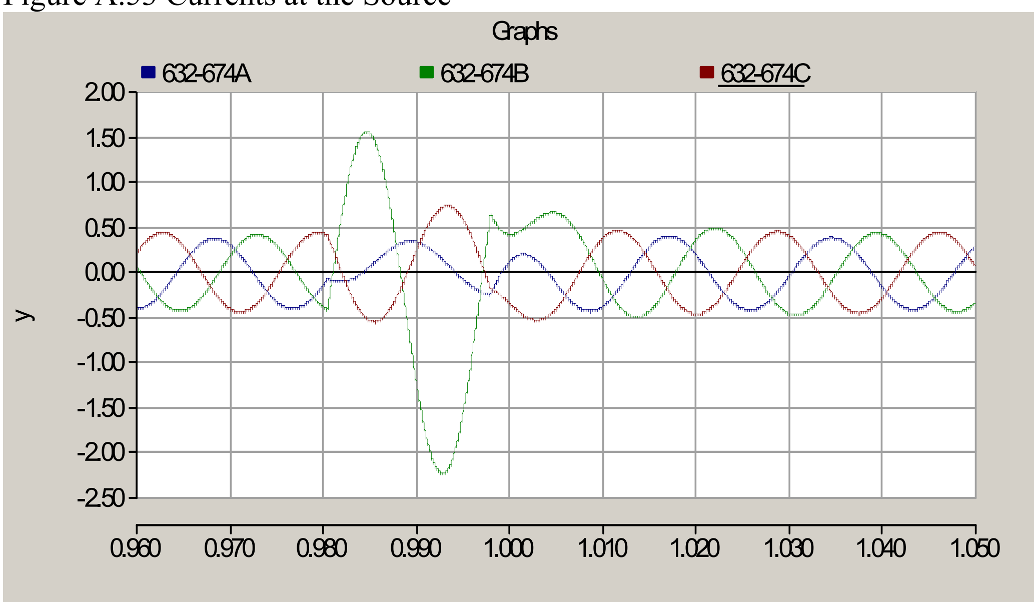


Figure A.54 Currents from Node 632 to 674.

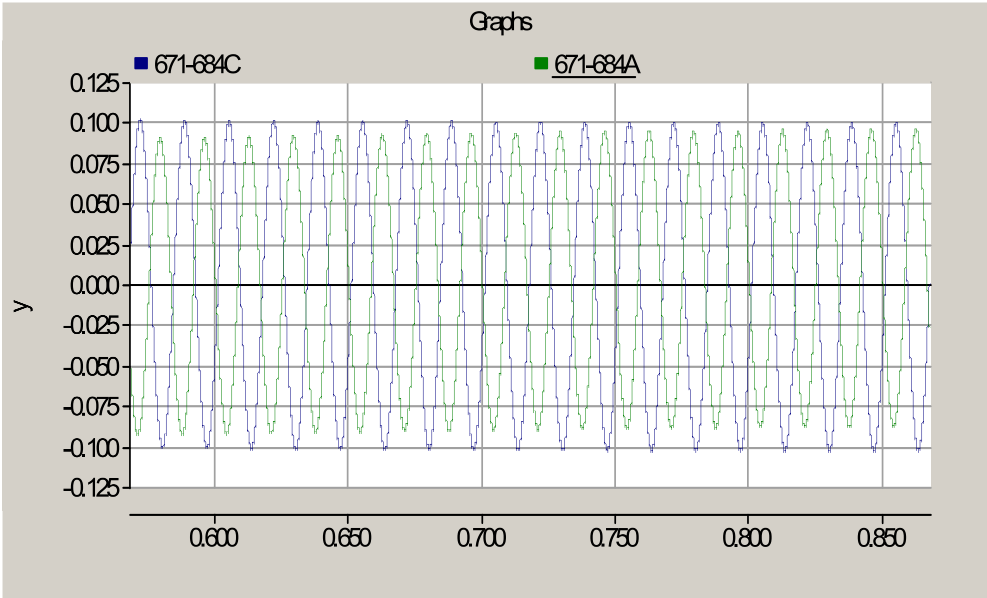


Figure A.55 Currents from Node 671-684

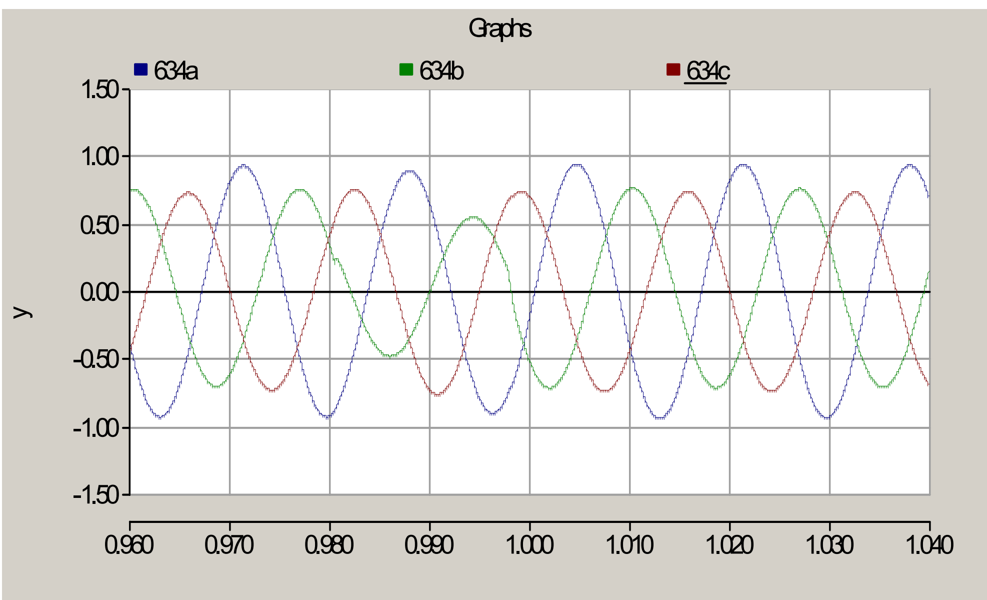


Figure A.56 Currents flowing into the Node 634

Changing the Fault location to node 611.

Fault current and voltage are shown in figure A.57

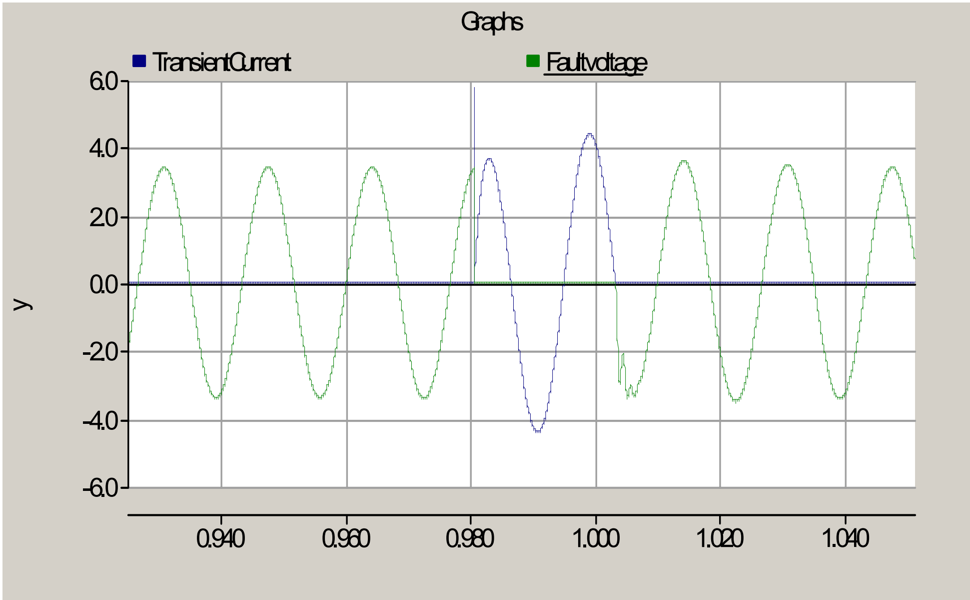


Figure A.57 Fault voltage and current for a fault at node 611.

The voltages and currents at various locations are shown in the figures that follow.

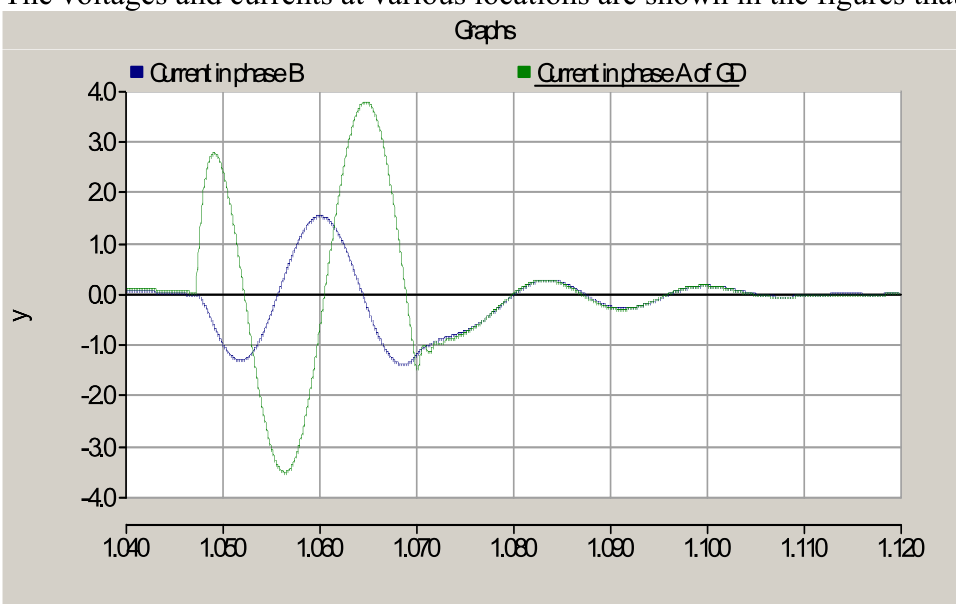


Figure A.58

Contribution to the fault current from the Voltage source and the DG source.

The source voltages are given in figure A.59

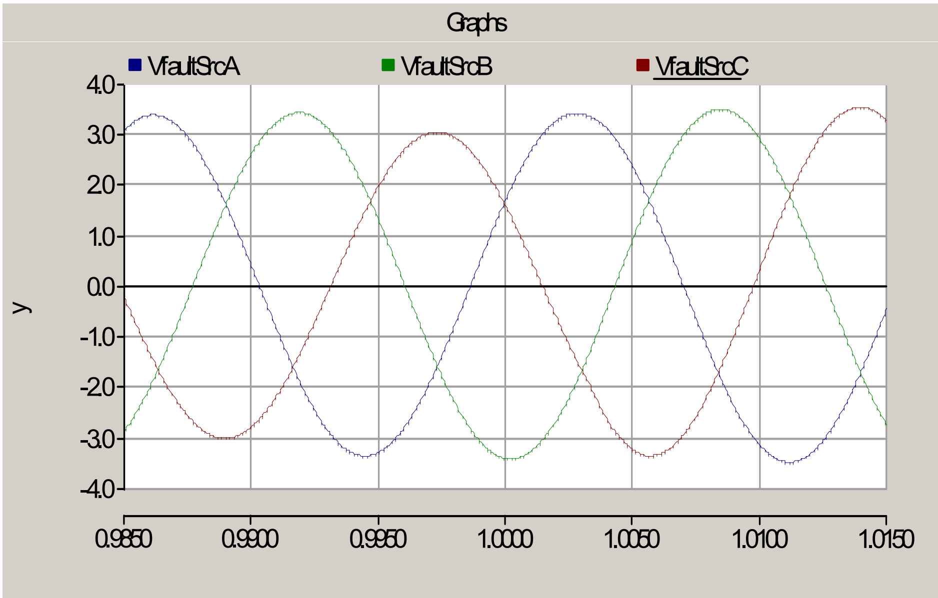


Figure A.59 Source Voltages.

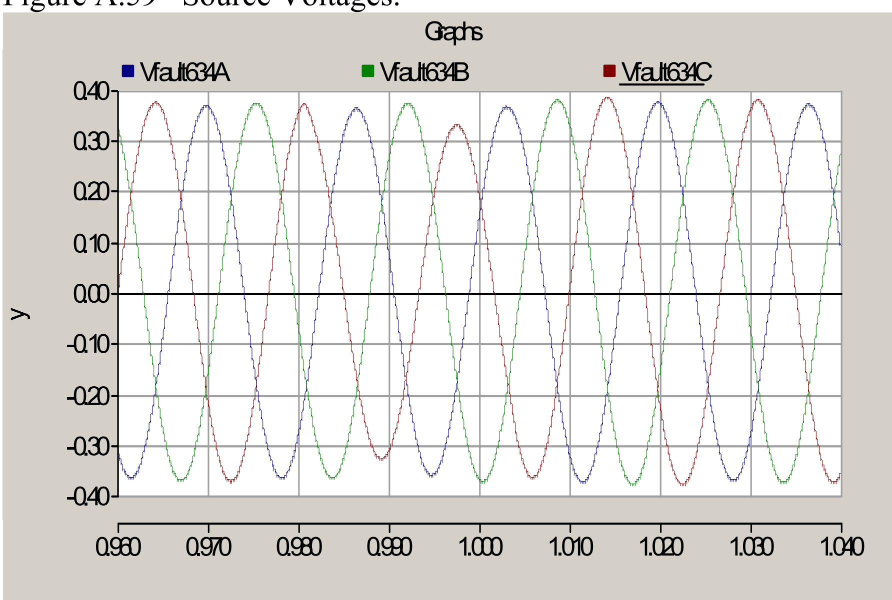


Figure A.60 Voltages at node 634.

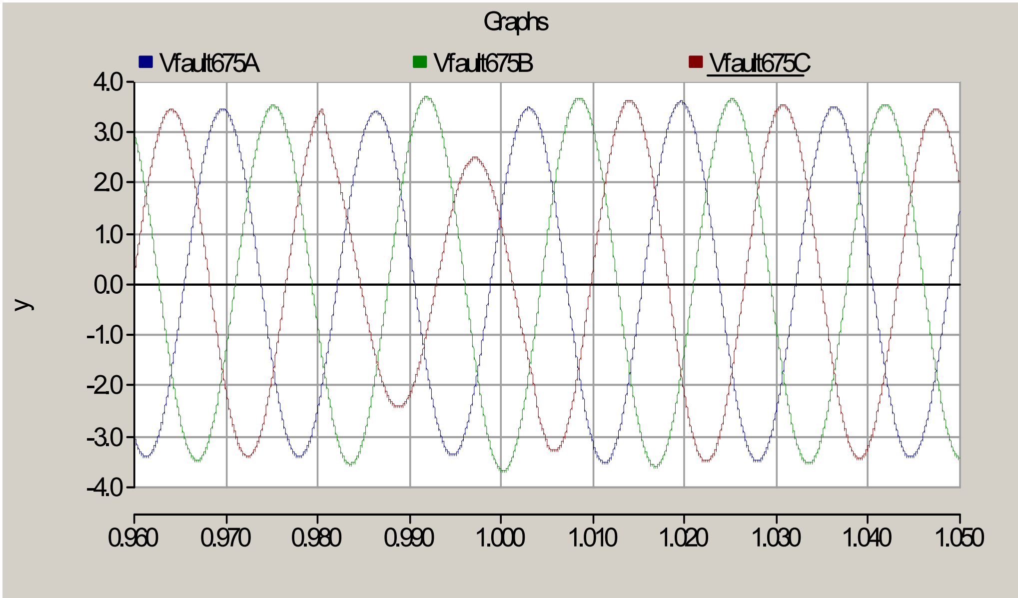


Figure A.61 Voltages at node 675

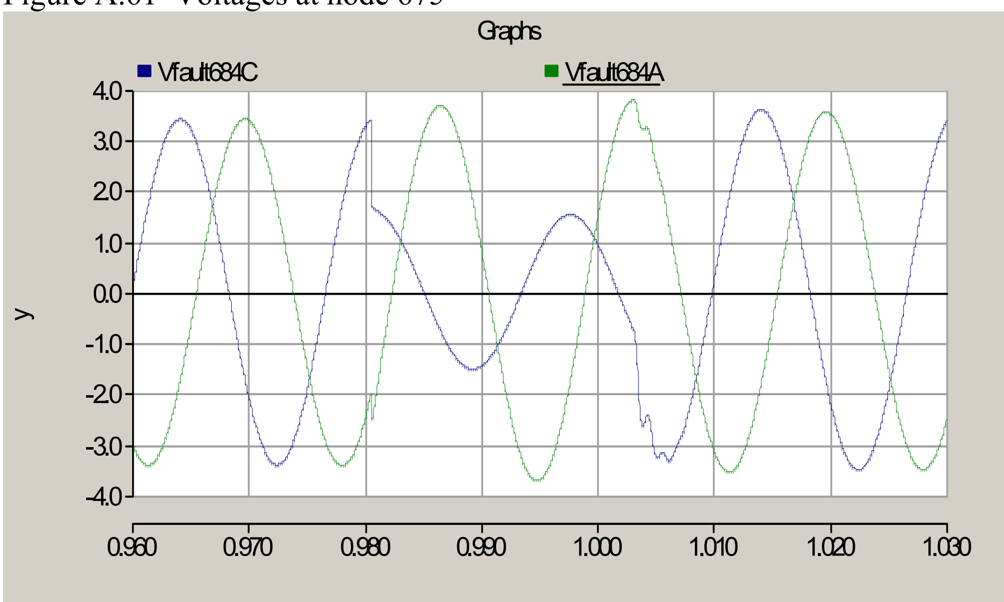


Figure A.62 Voltages at node 684.

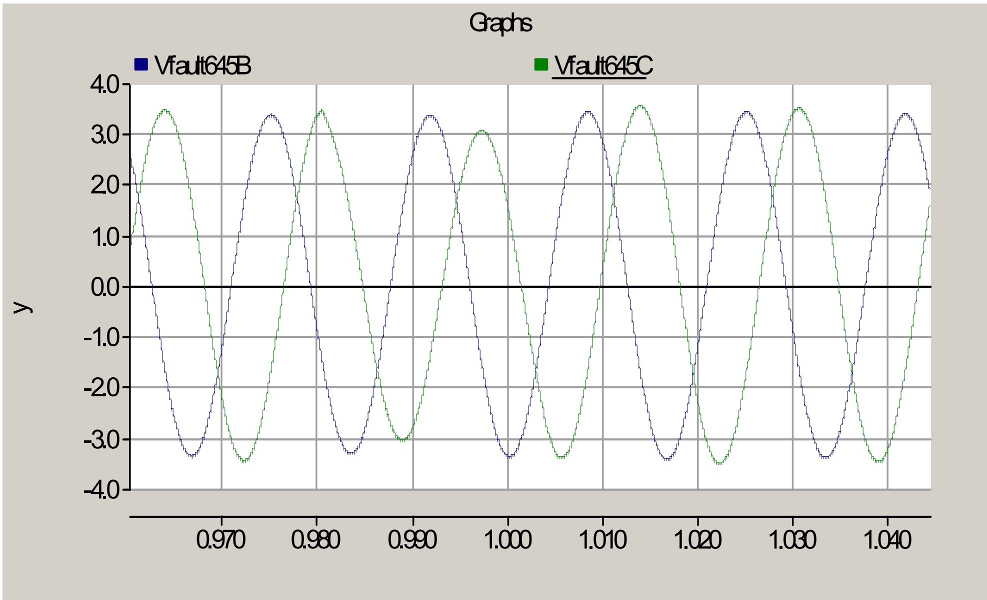


Figure A.63 Voltages at node 645.

Currents at various nodes are given in the figures that follow. Source currents are shown in figure A.64

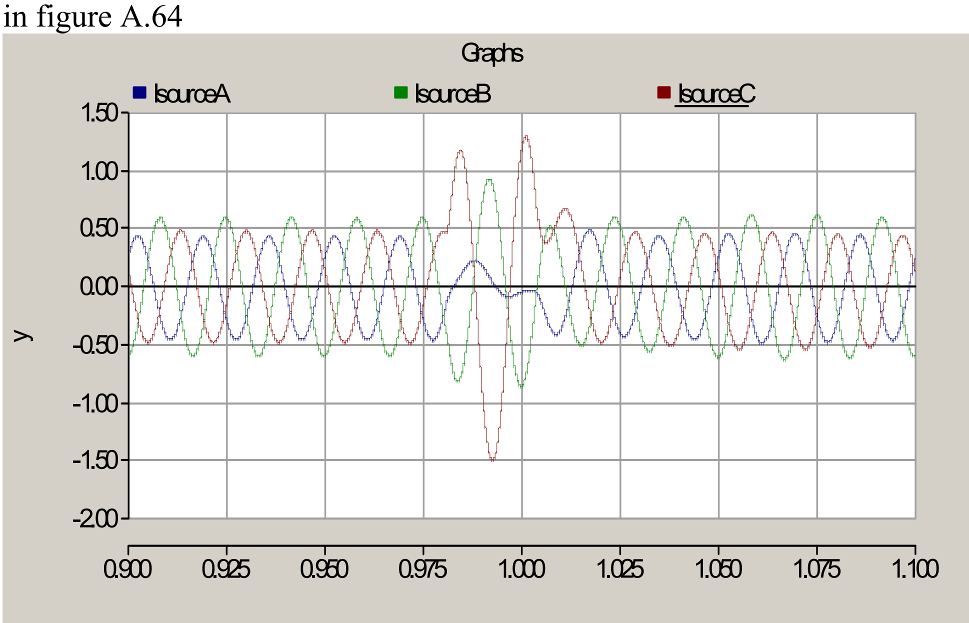


Figure A.64 Source currents.

Contribution of the capacitor to the fault current is shown in figure 60.

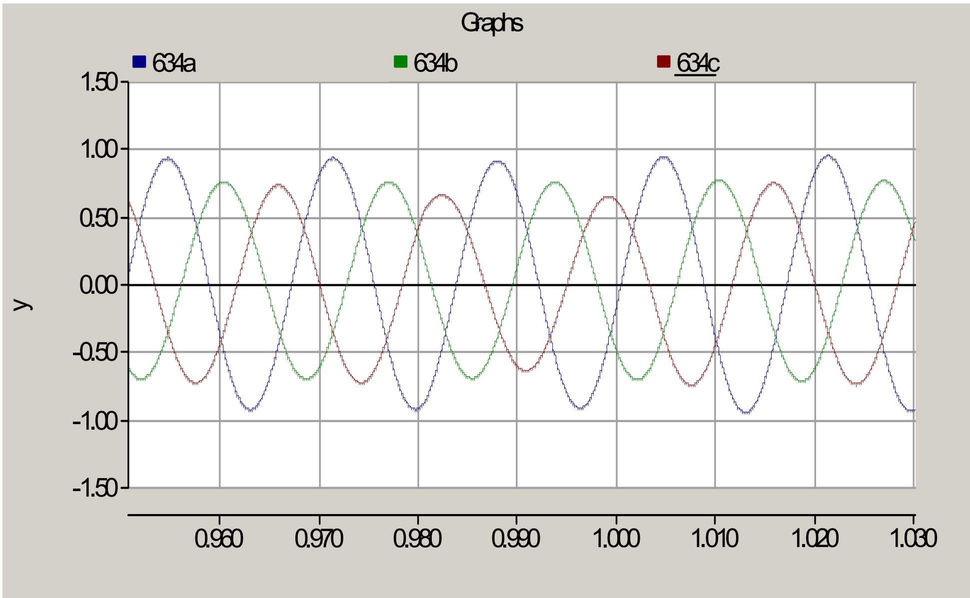


Figure A.65 Currents flowing into node 634.

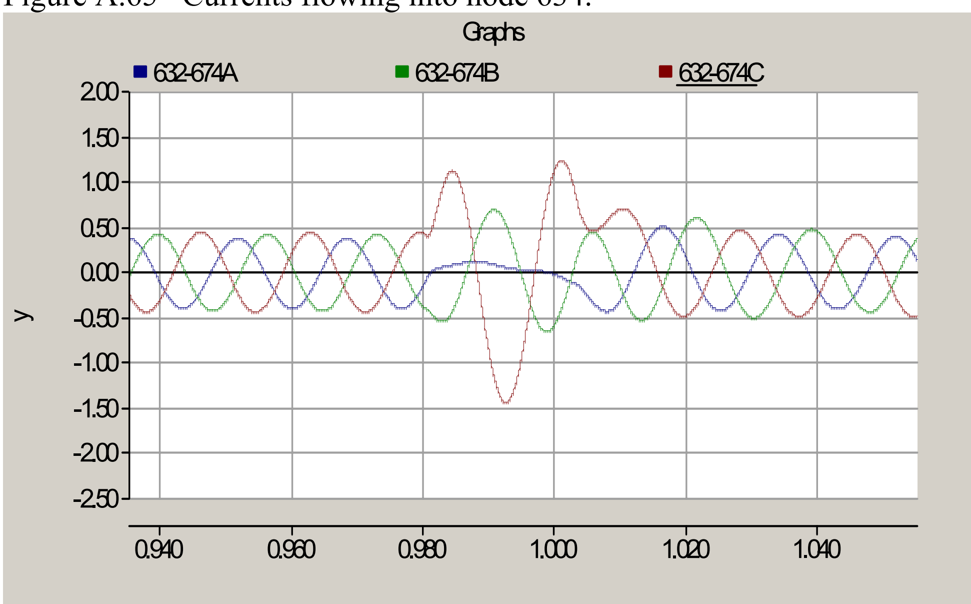


Figure A.66 Currents in the branch 632-674.

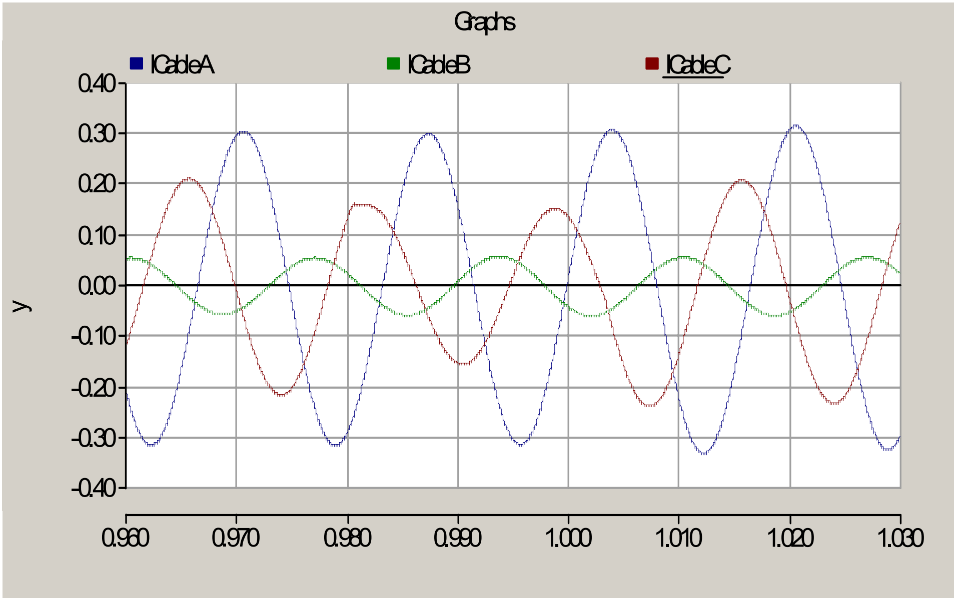


Figure A.67   Currents flowing in the branch 692-675.

Fault location node 634 phase B. The fault current and voltage are shown in figure A.68

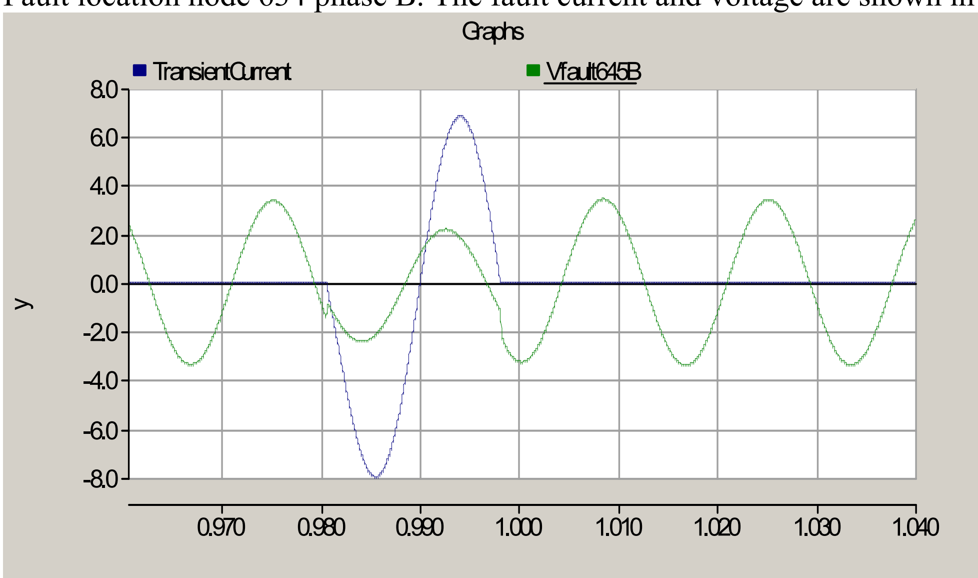


Figure A.68 Fault voltage and current at node 634.
The contribution from the source and DG are shown in figure A.69

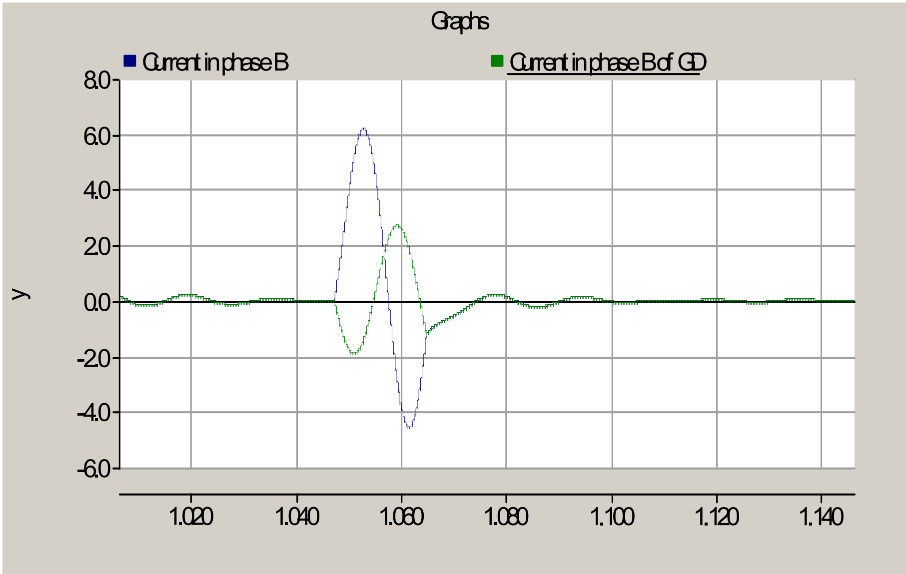


Figure A.69 Currents from source and the DG unit to the fault.

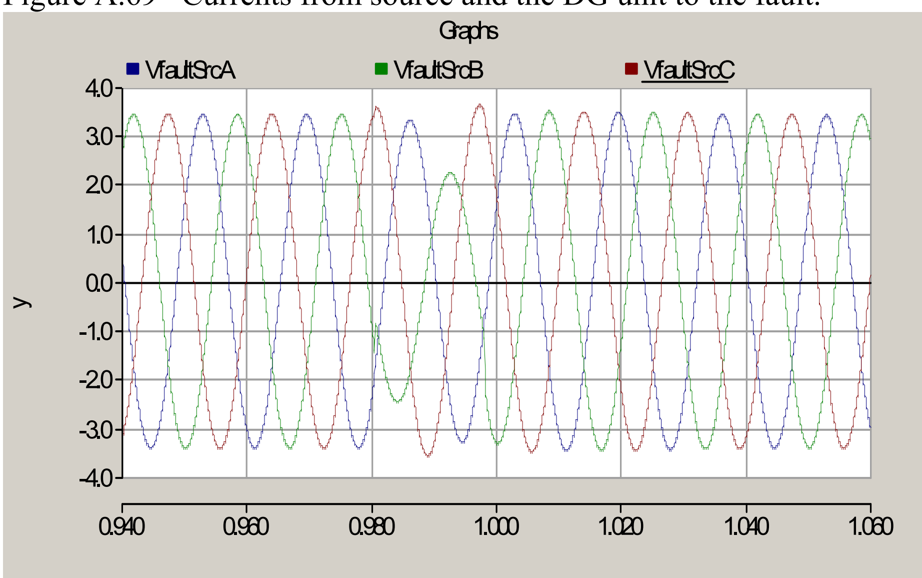


Figure A.70 Source voltages.

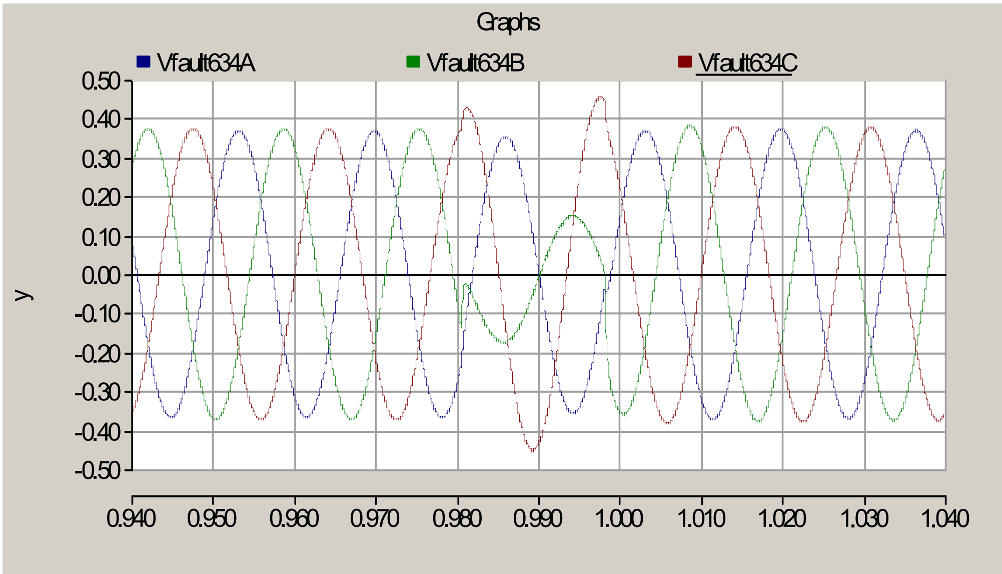


Figure A.71 Voltages at node 634.

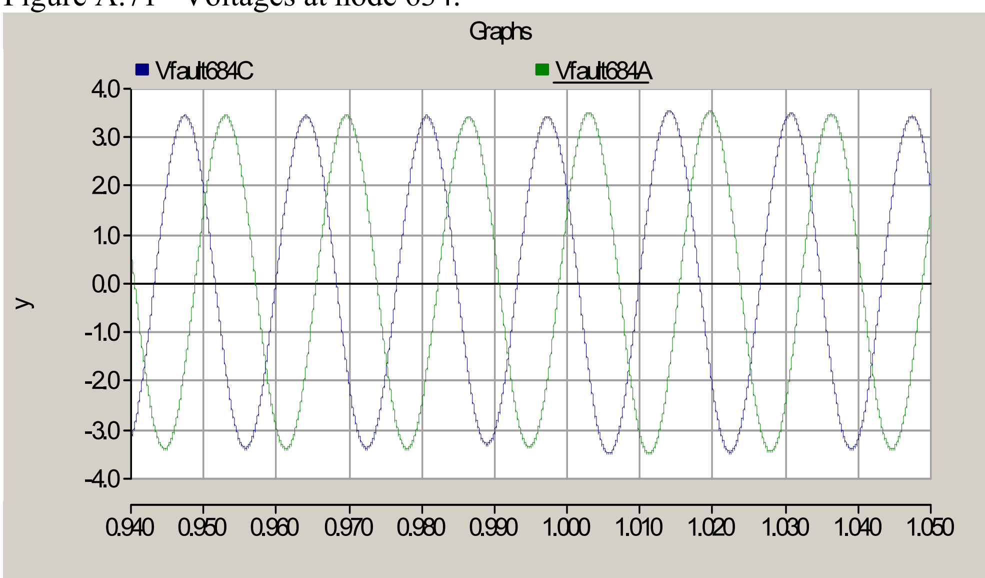


Figure A.72 Voltages at node 684.

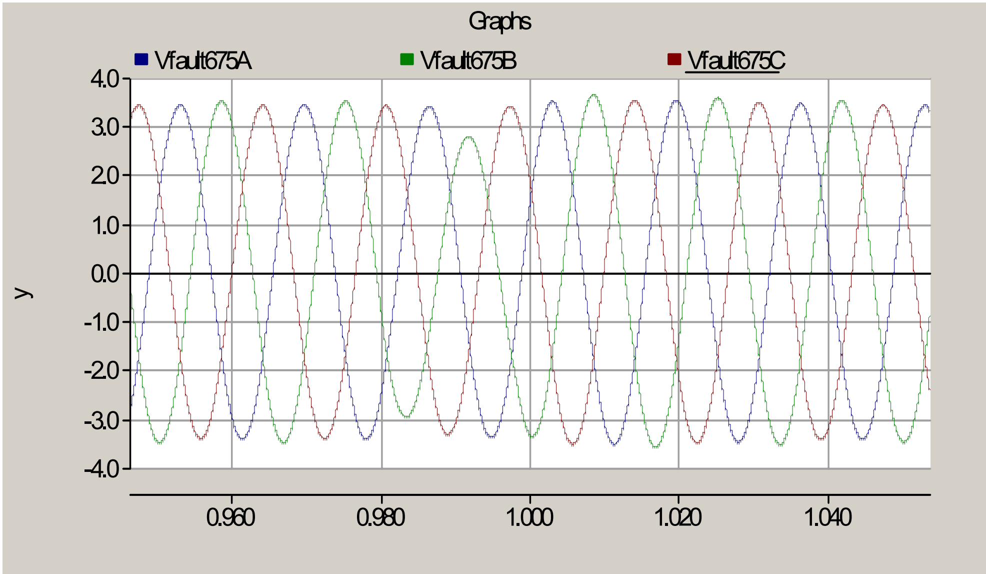


Figure A.73 Voltages at node 675.

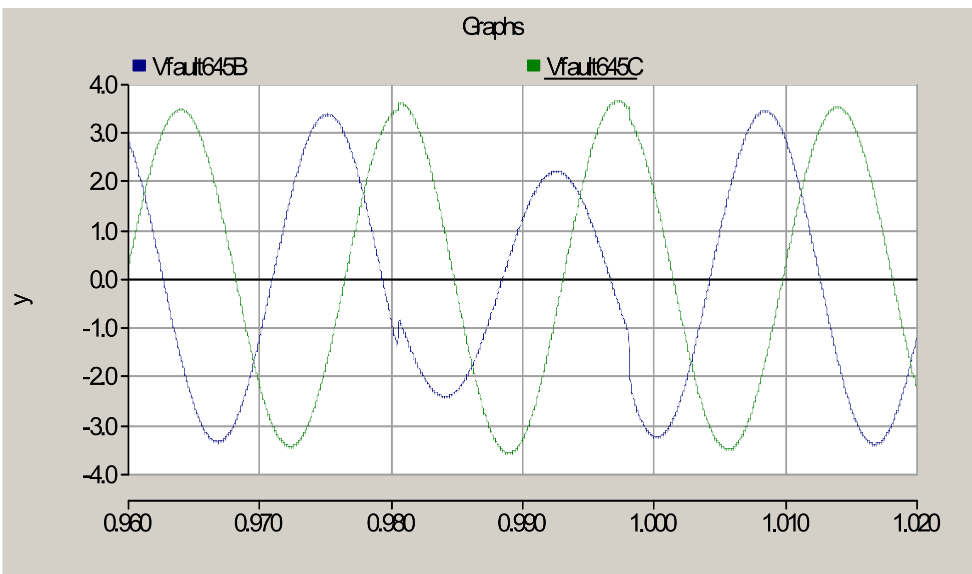


Figure A.74 Voltages at Node 645

Currents at various nodes are shown in the following figures.

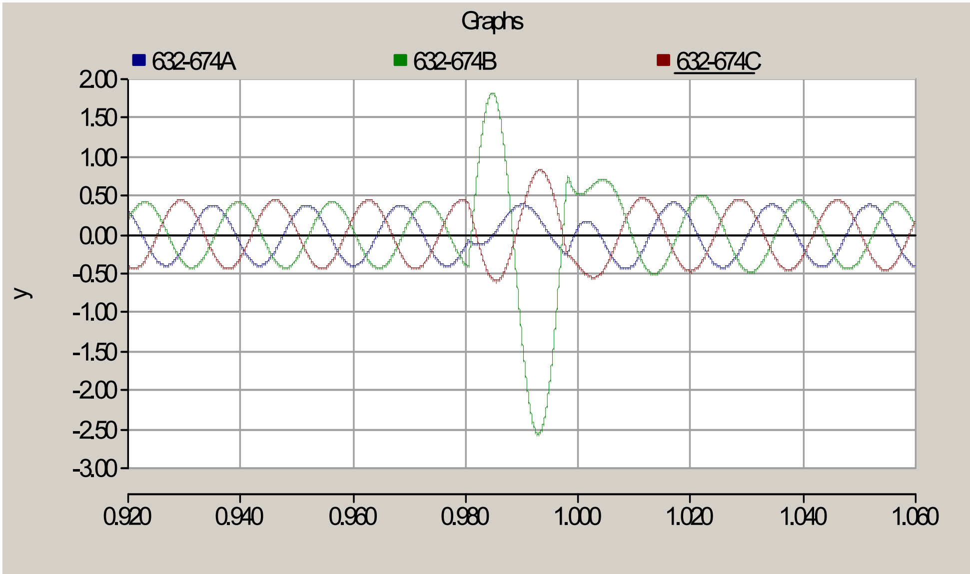


Figure A.75 Currents into the Nodes 632-647

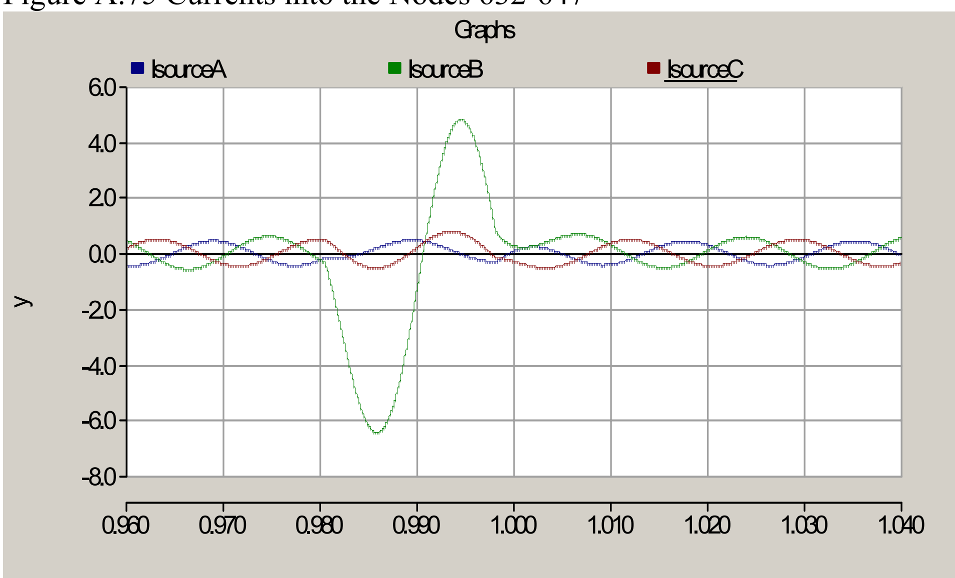


Figure A.76 Source currents.

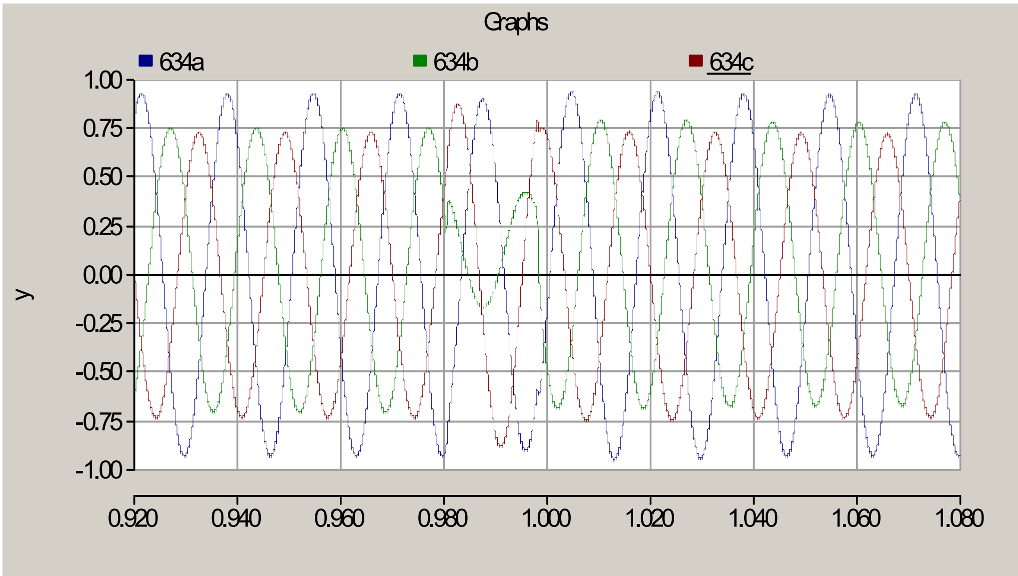


Figure A.77 Currents flowing into nodes 634.

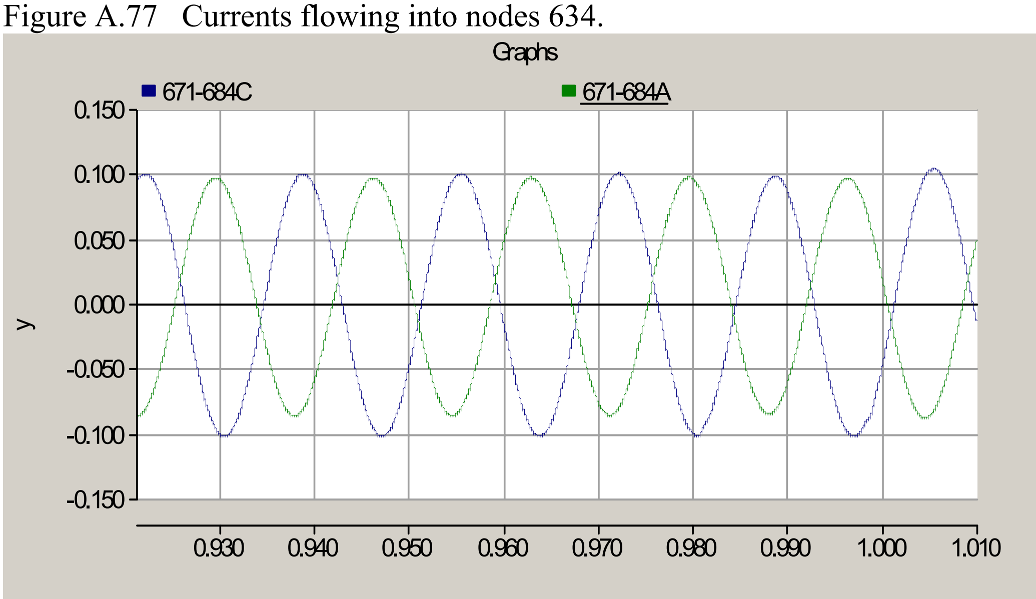


Figure A.78 Currents flowing into the Nodes 671-684.

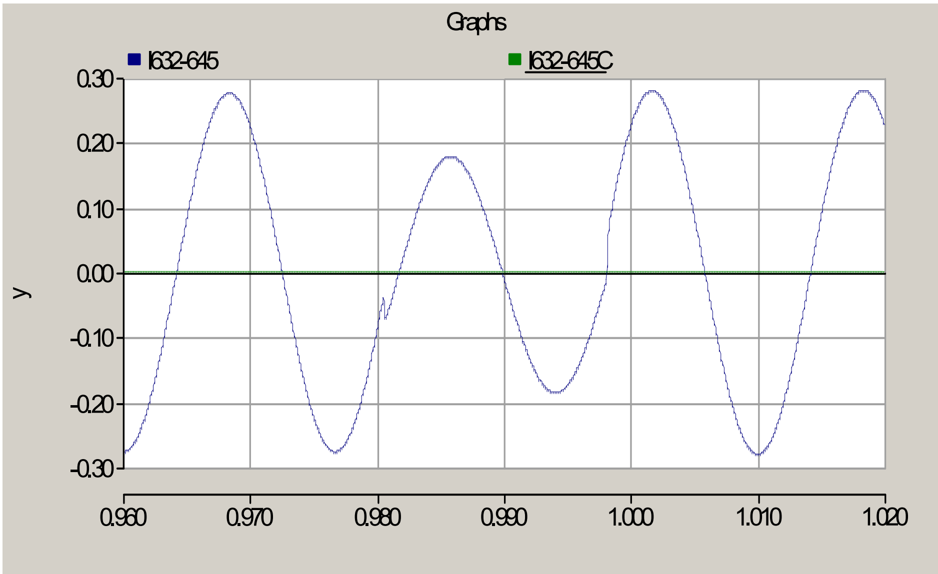


Figure A.79 Currents flowing into the Nodes 632-645

The DG is shifted to node 633. Fault is at node 645.
The fault current and voltage are shown in figure A.80

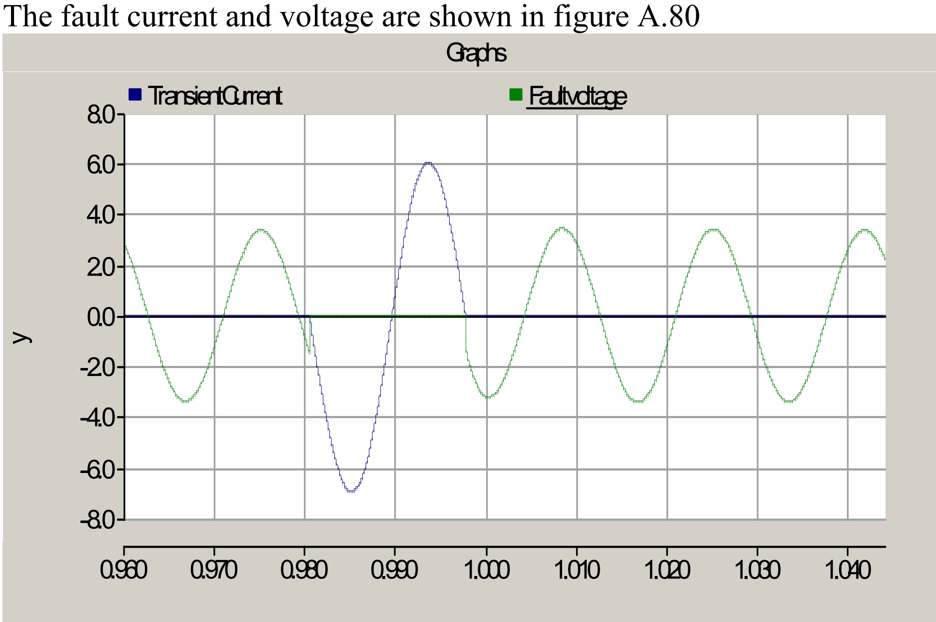


Figure A.80 Fault current and voltage.

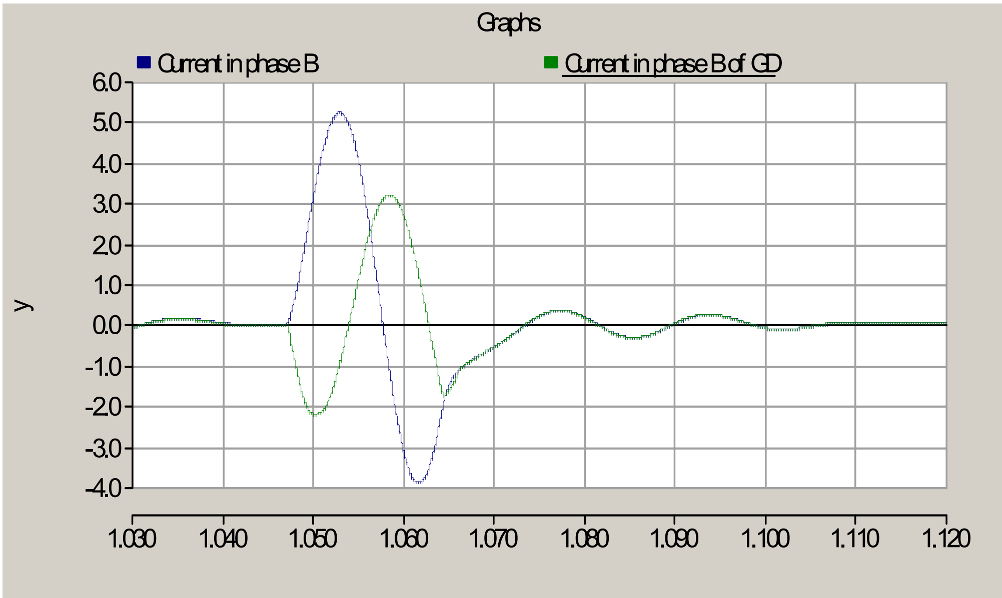


Figure A.81 Contributions of source and the DG unit to the fault.

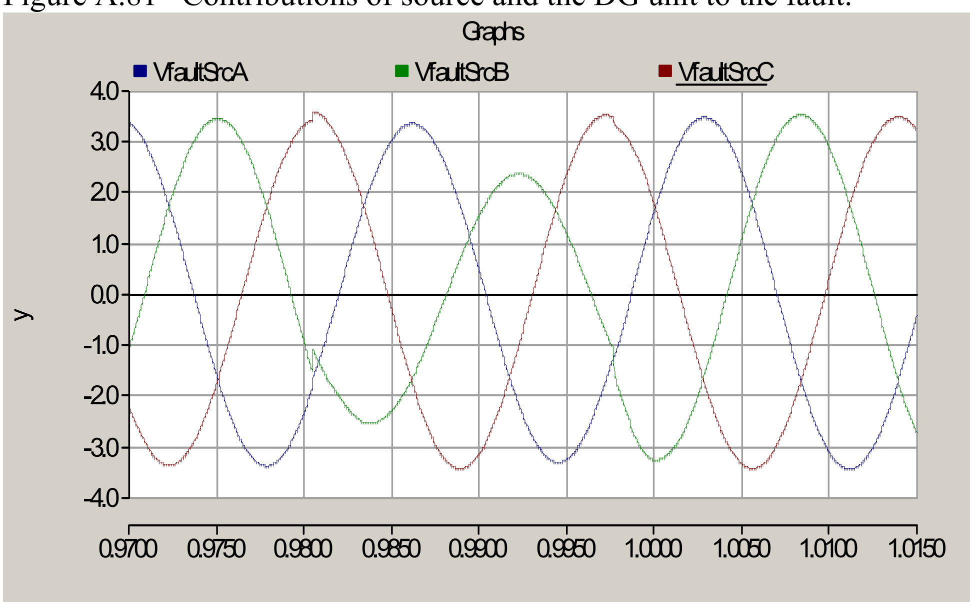


Figure A.82 Source voltages.

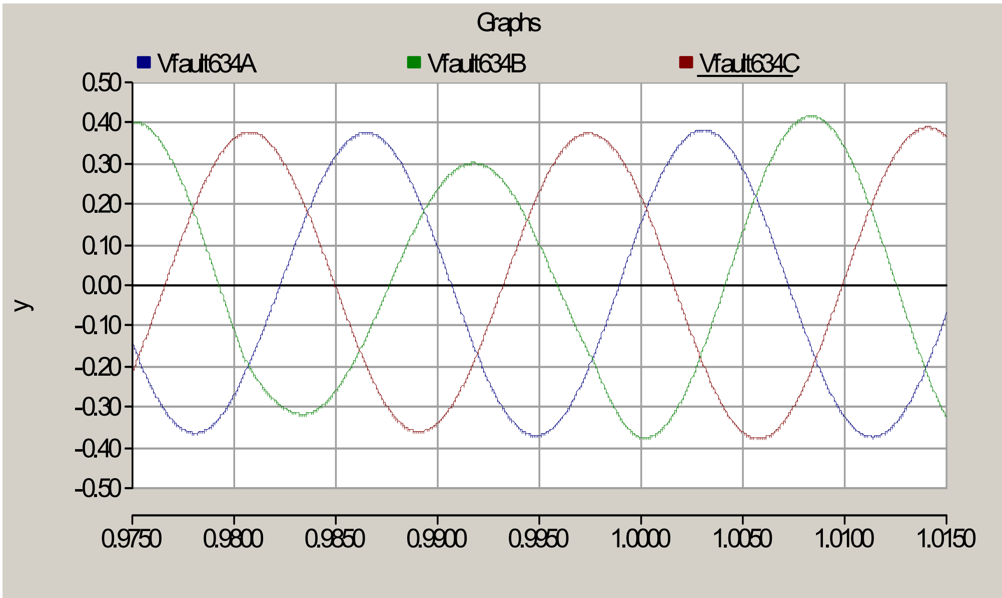


Figure A.83 Fault voltages at node 634.

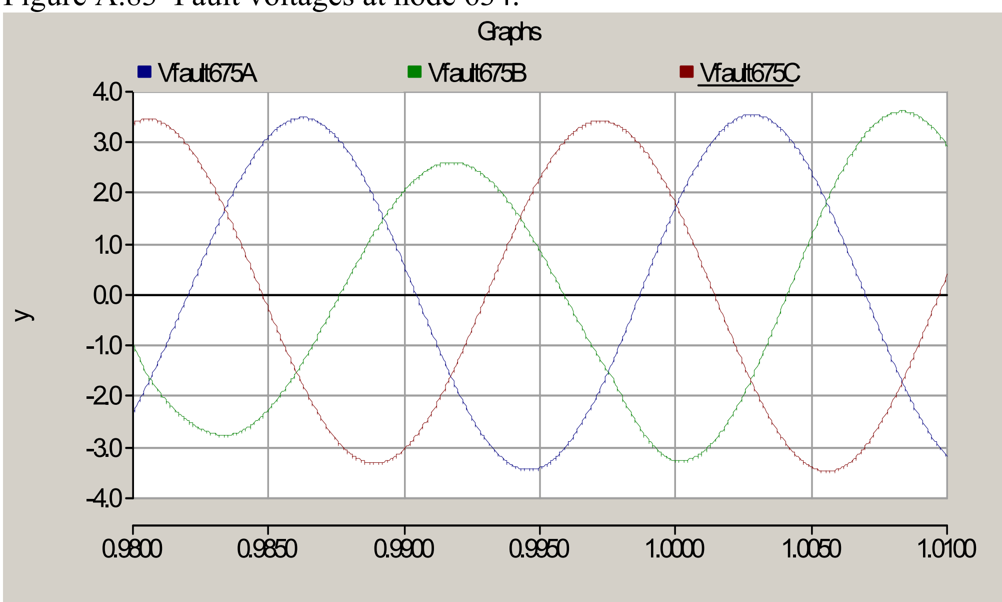


Figure A.84 Voltages at the Node 675

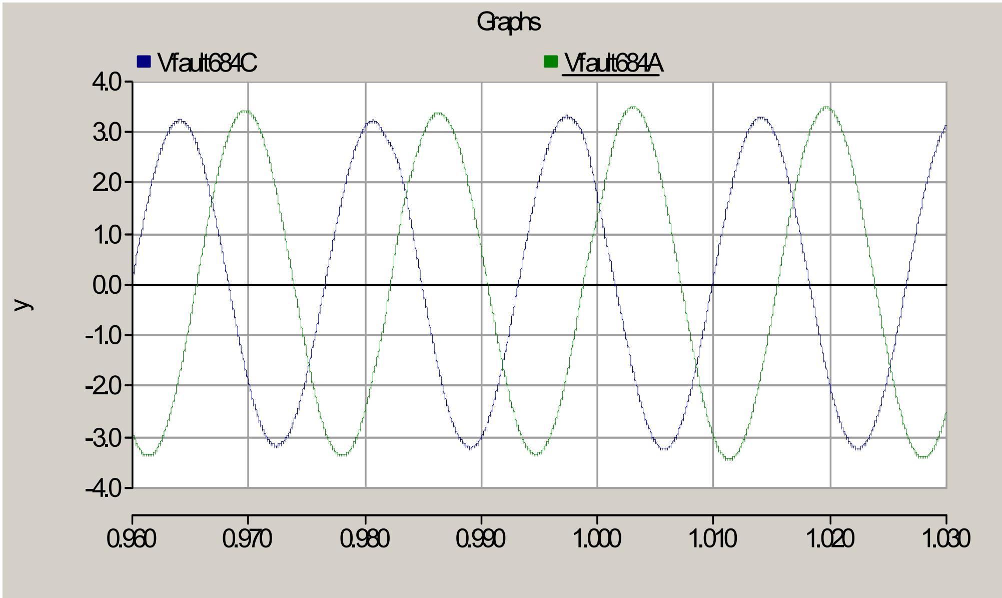


Figure A.85 Voltages at the Node 684

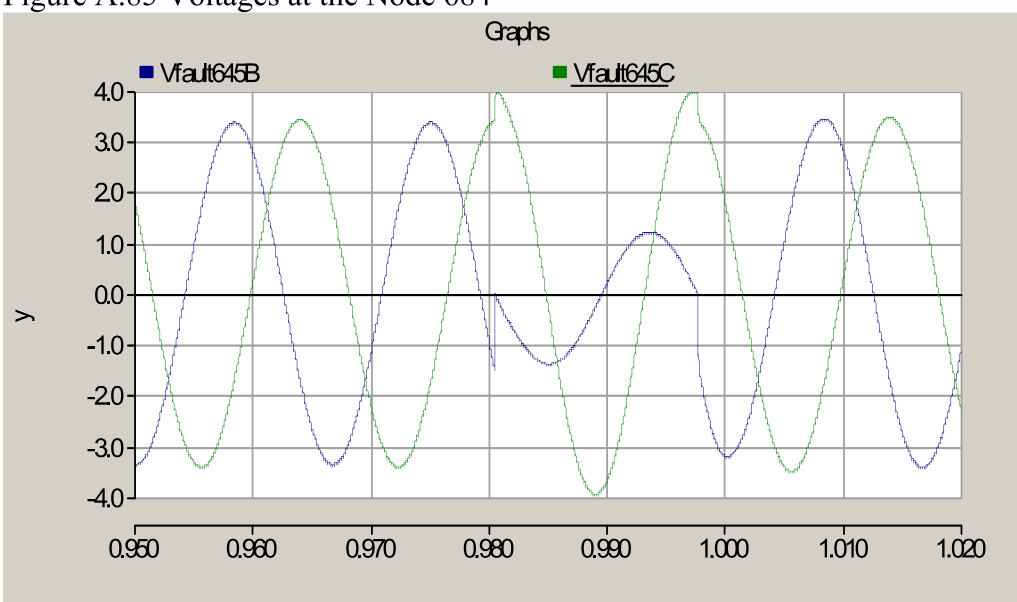


Figure A.86 Voltages at the Node 645

Currents at different nodes are shown in the following figures.

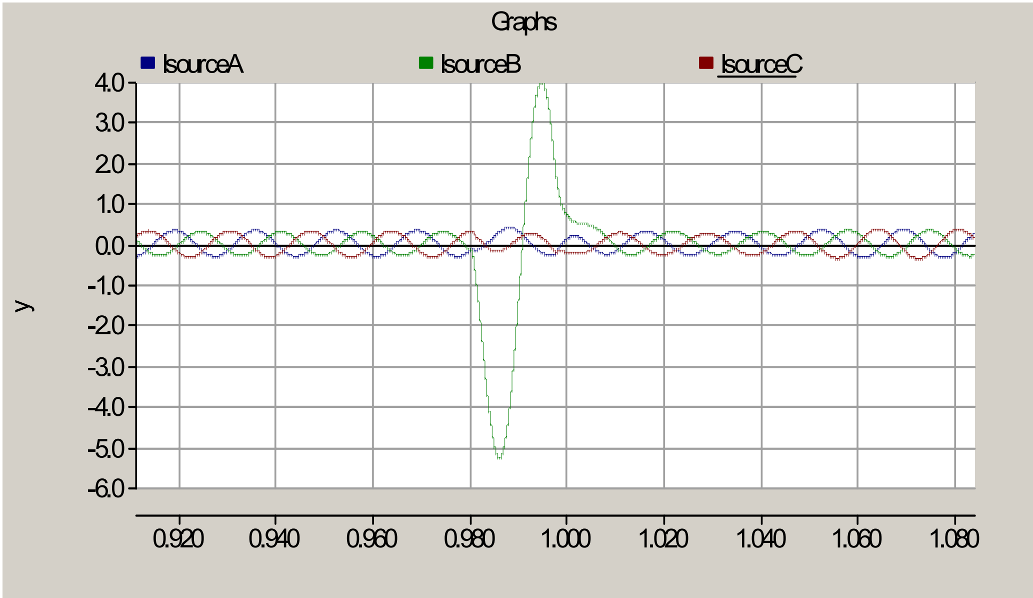


Figure A.87 Source currents.

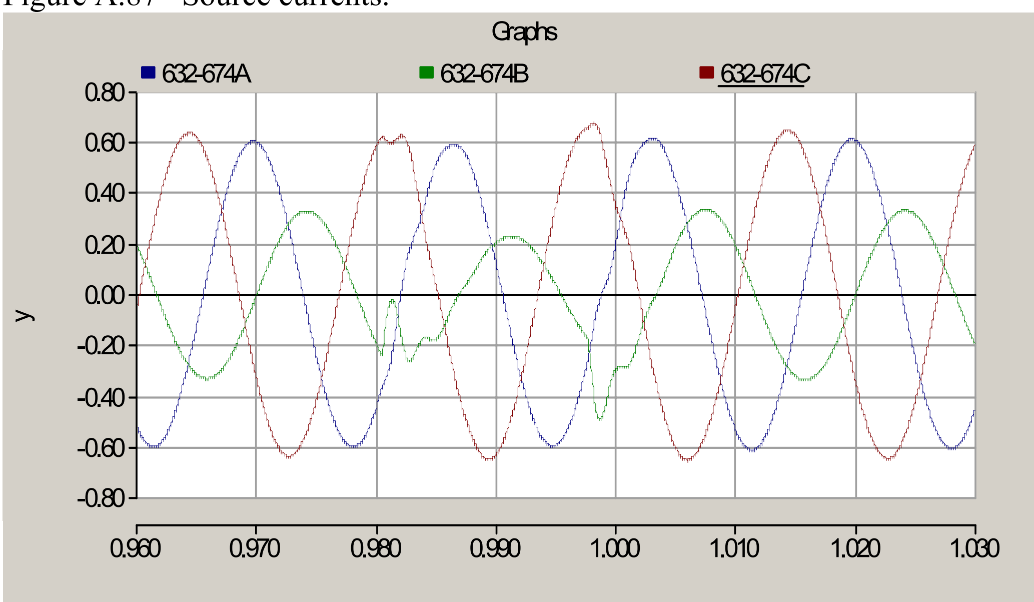


Figure A.88 Currents in the branch 632-674.

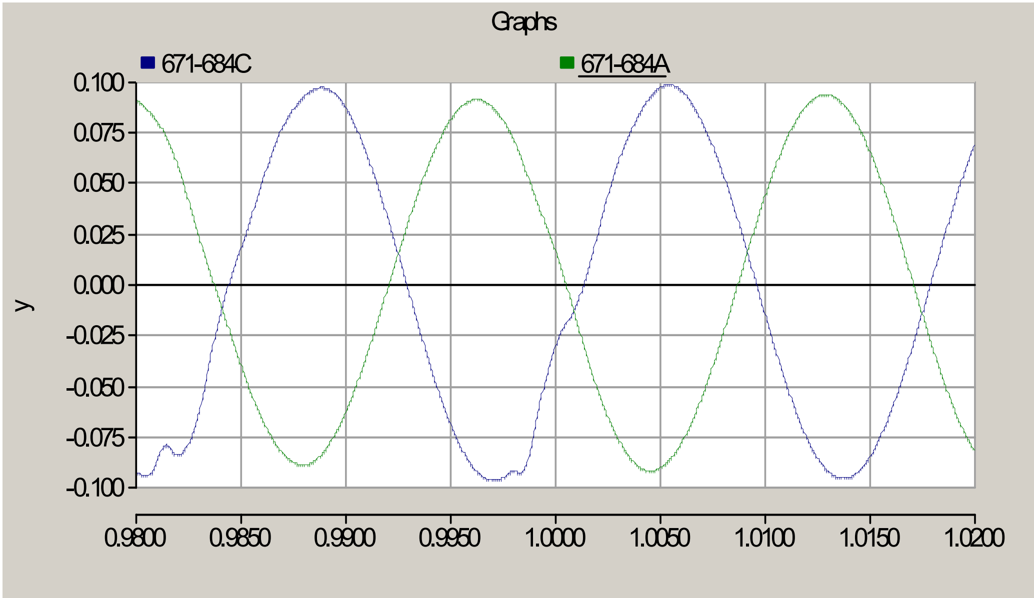


Figure A.89 Currents in branch 671-684.

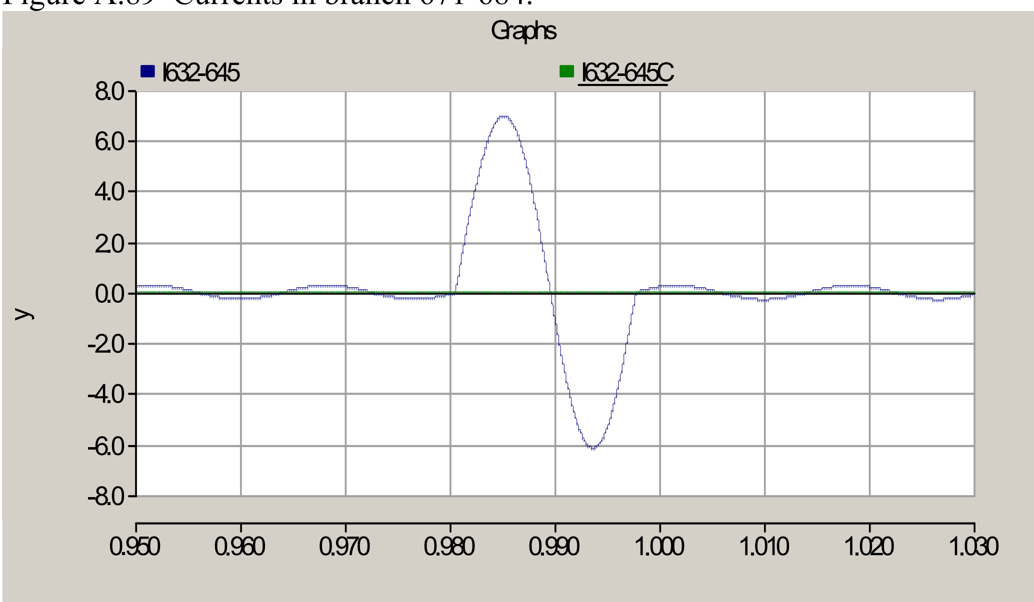


Figure A.90 Currents in branch 632-645.

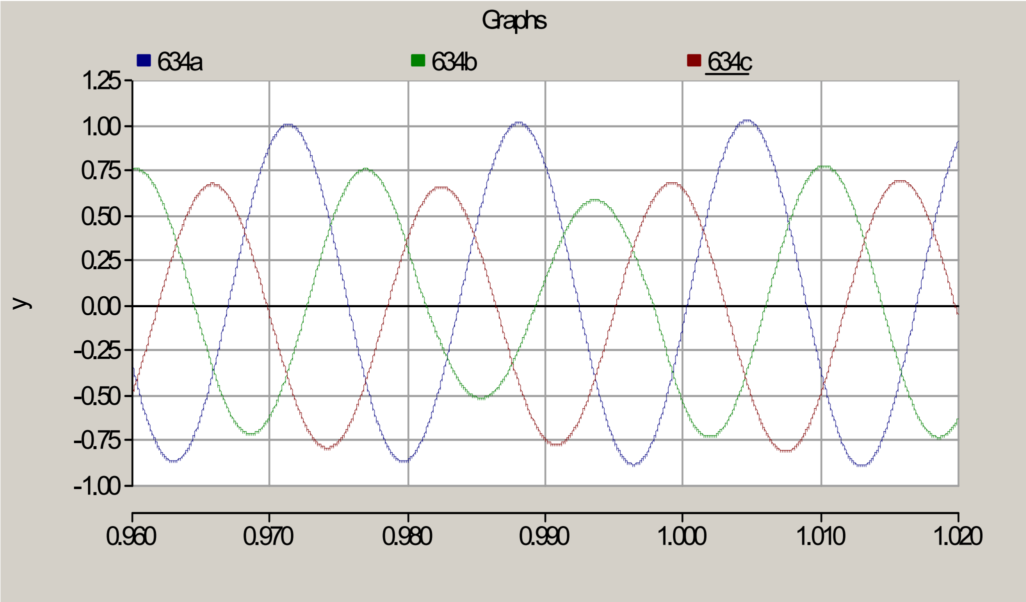


Figure A.91 Currents flowing into node 634.
Moving the fault location to node
The fault current and voltage are shown in figure A.92

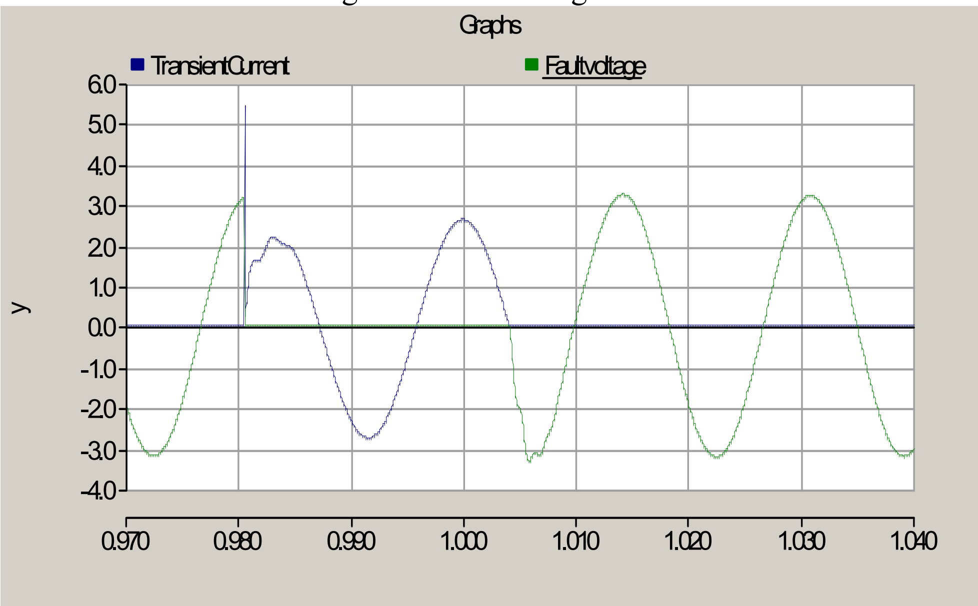


Figure A.92 Fault current and voltage.
The contribution of main source and the DG unit are shown in figure A.93

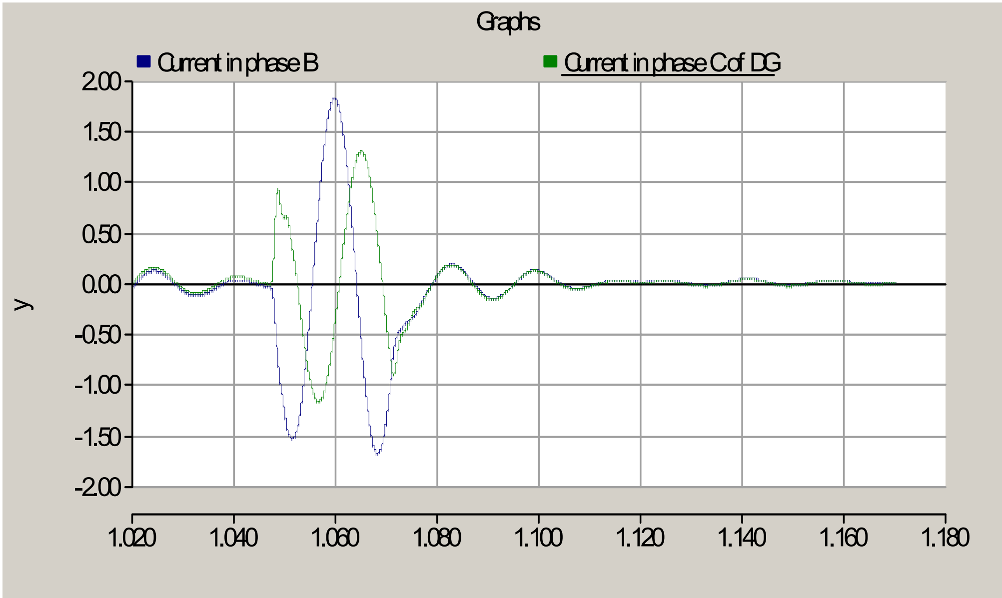


Figure A.93 Currents in the Source and the DG unit.

The contribution of the capacitor bank is shown in figure A.94

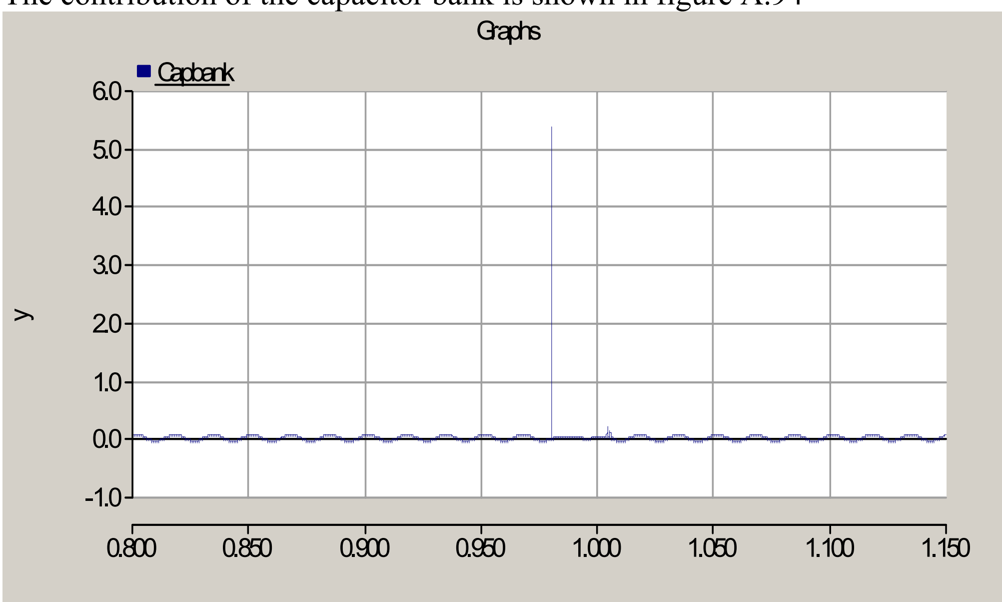


Figure A.94 Contribution of the capacitor bank to the fault.

Source voltage and currents are shown in figure A.95

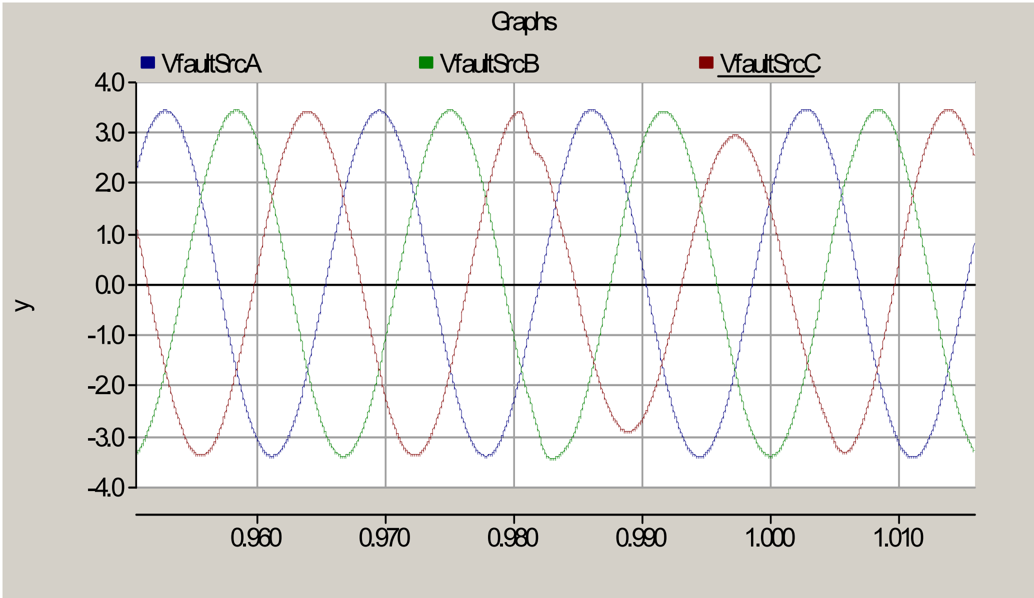


Figure A.95 Source voltages.

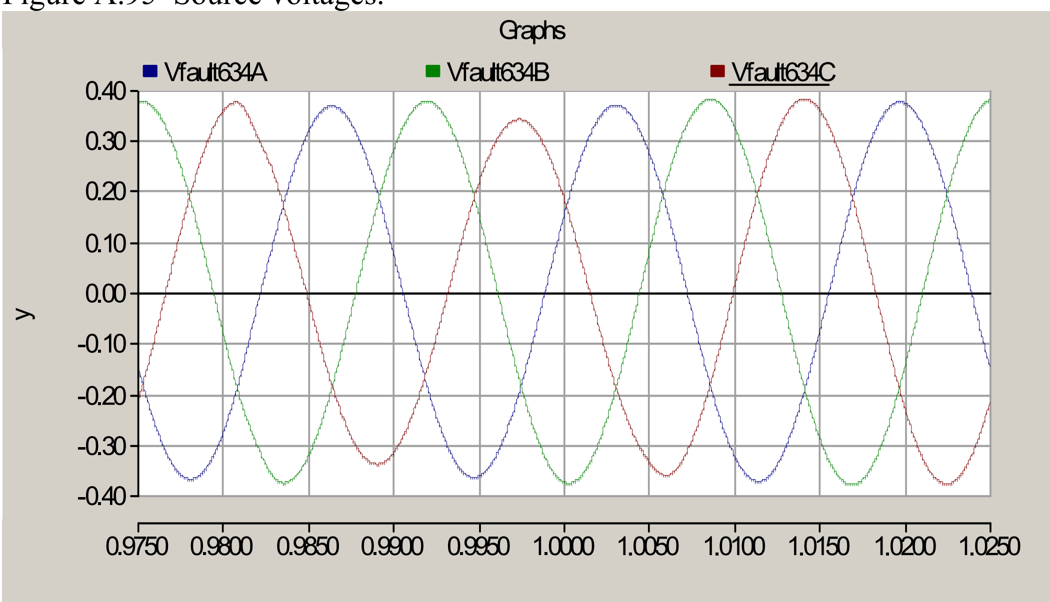


Figure A.96 Voltages at the Node 634

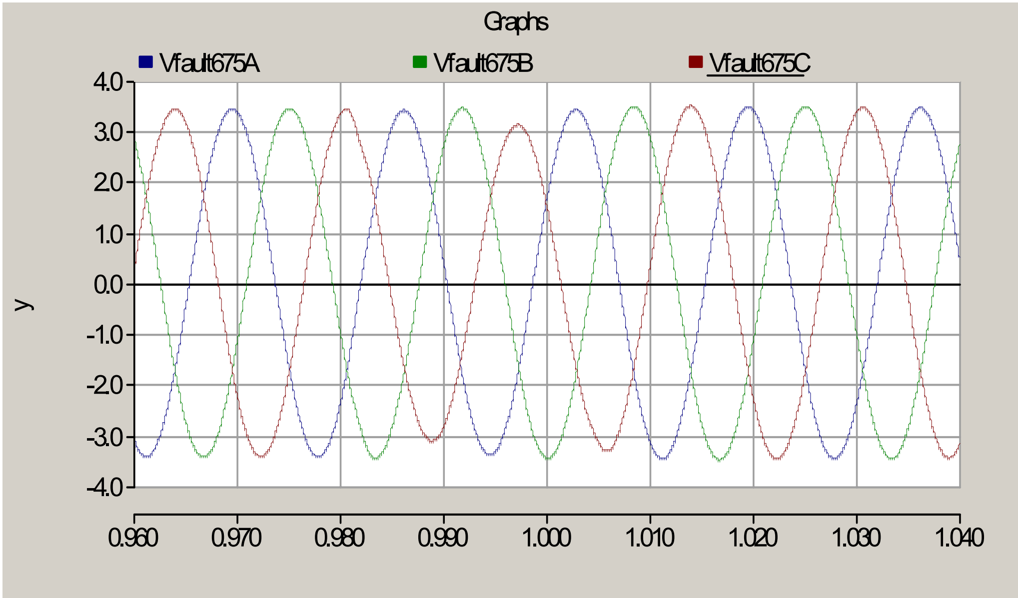


Figure A.97 Voltages at the Node 675

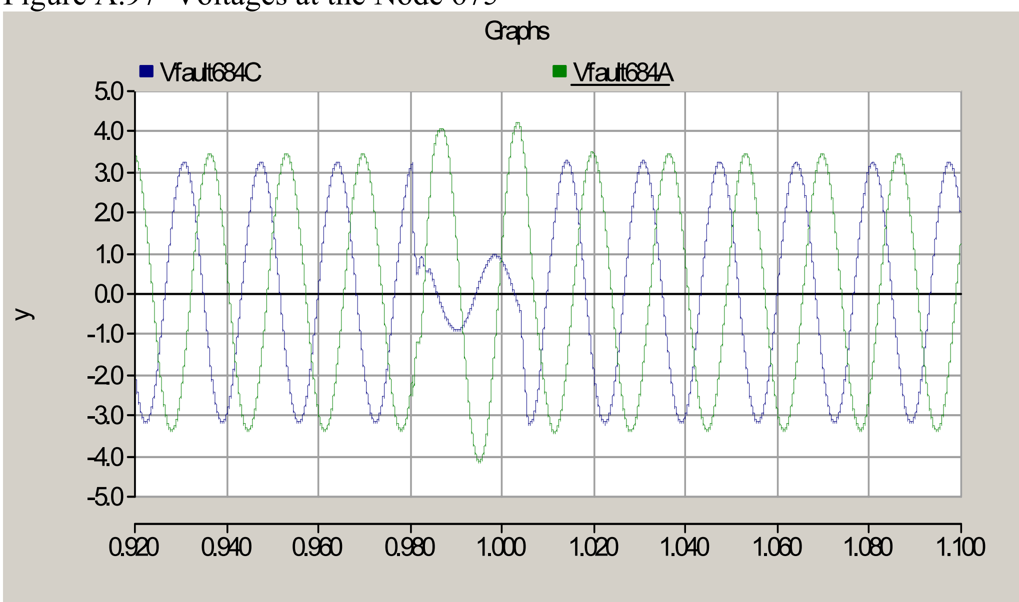


Figure A.98 Voltages at the Node 684

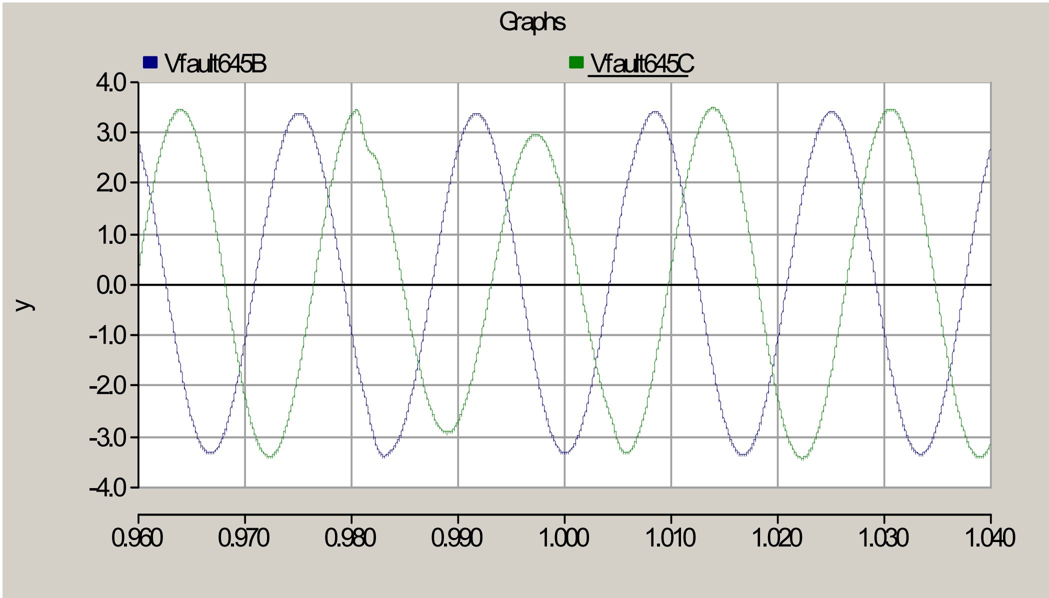


Figure A.99 Voltages at the Node 645

Currents at various nodes are shown in figures that follow.

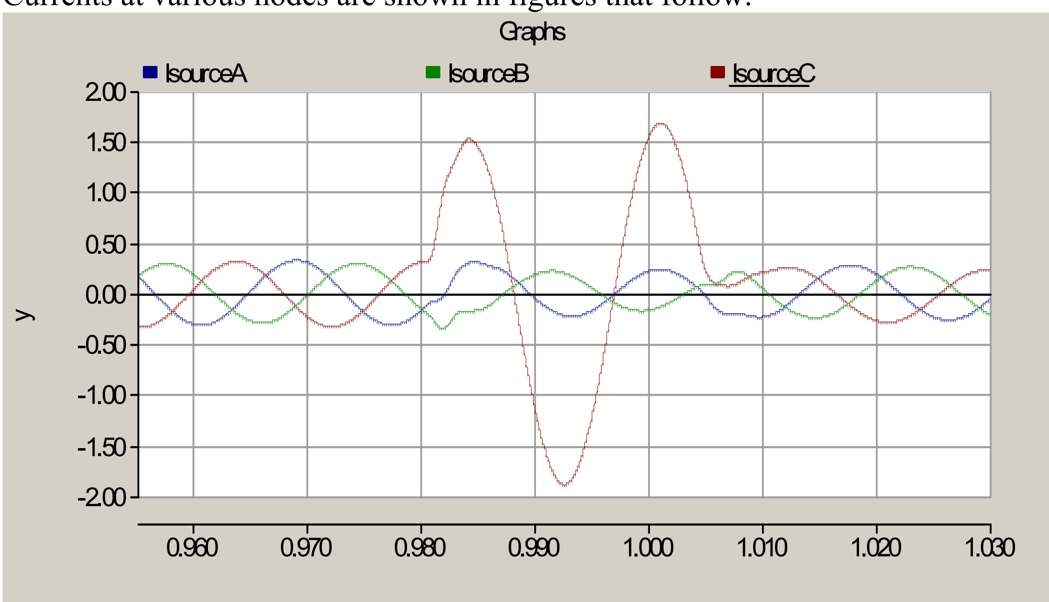


Figure A.100 Source currents.

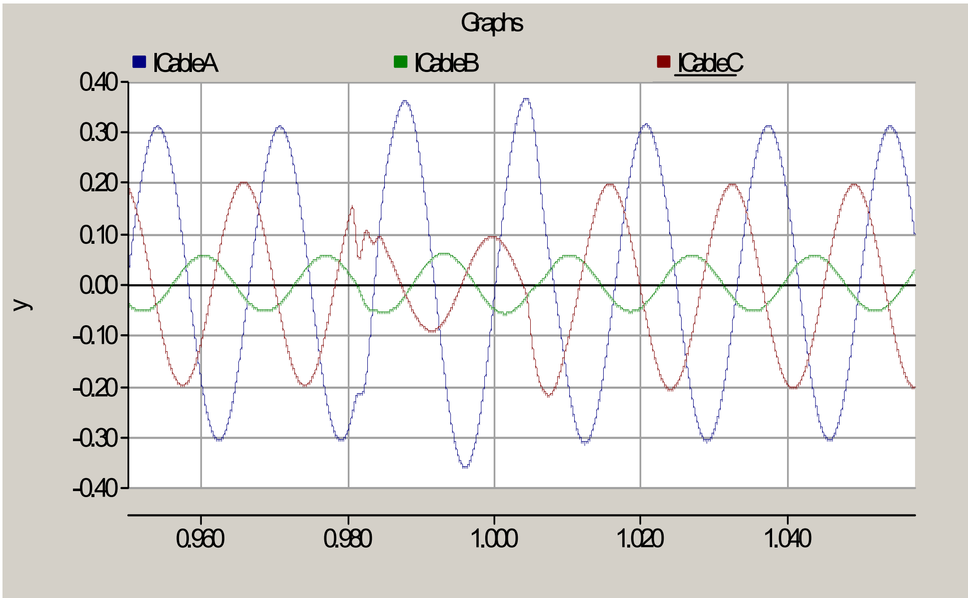


Figure A.101 Currents during the fault

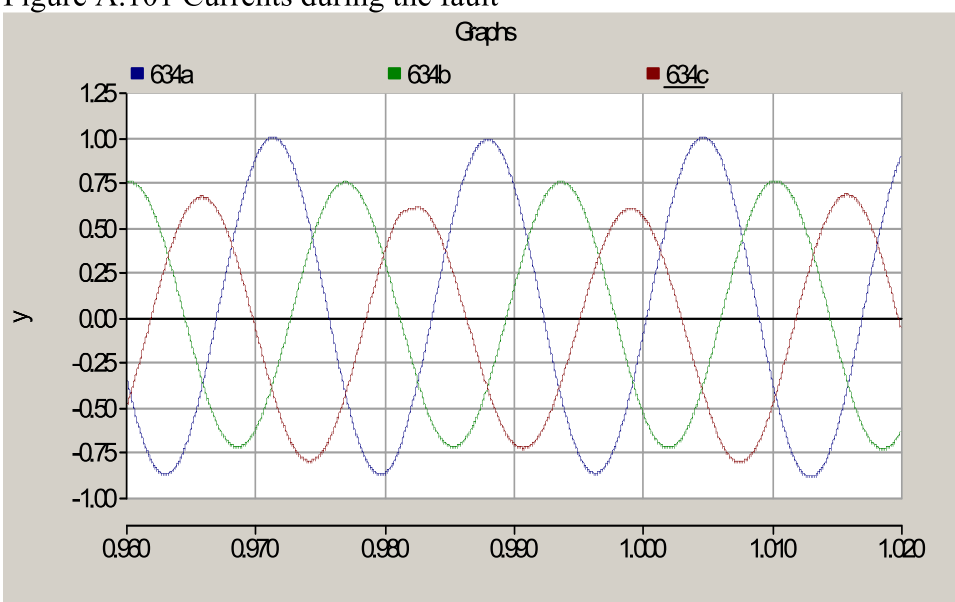


Figure A.102 Currents into the Node 634.

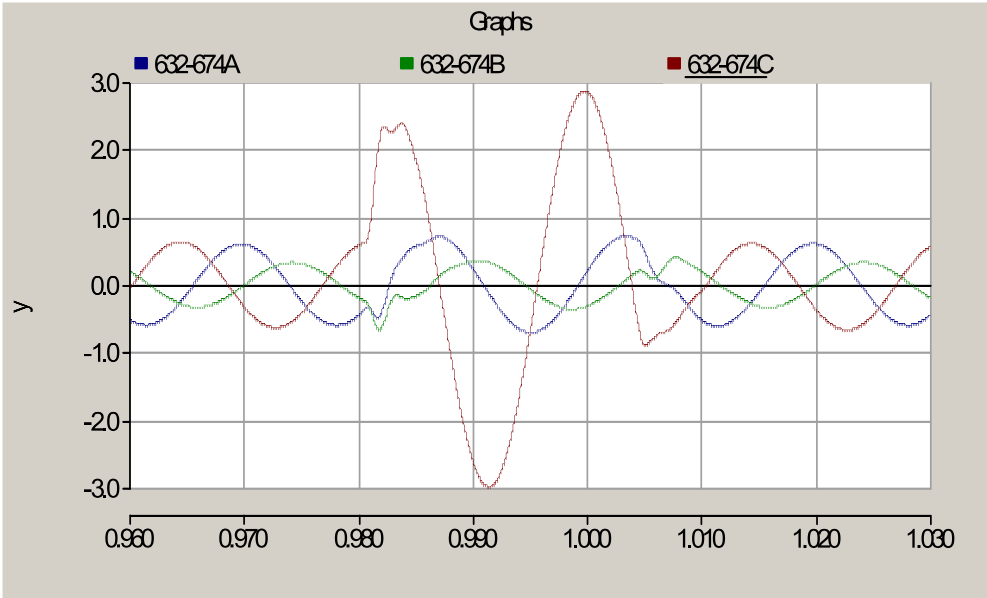


Figure A.103 Currents into the Nodes 632-674

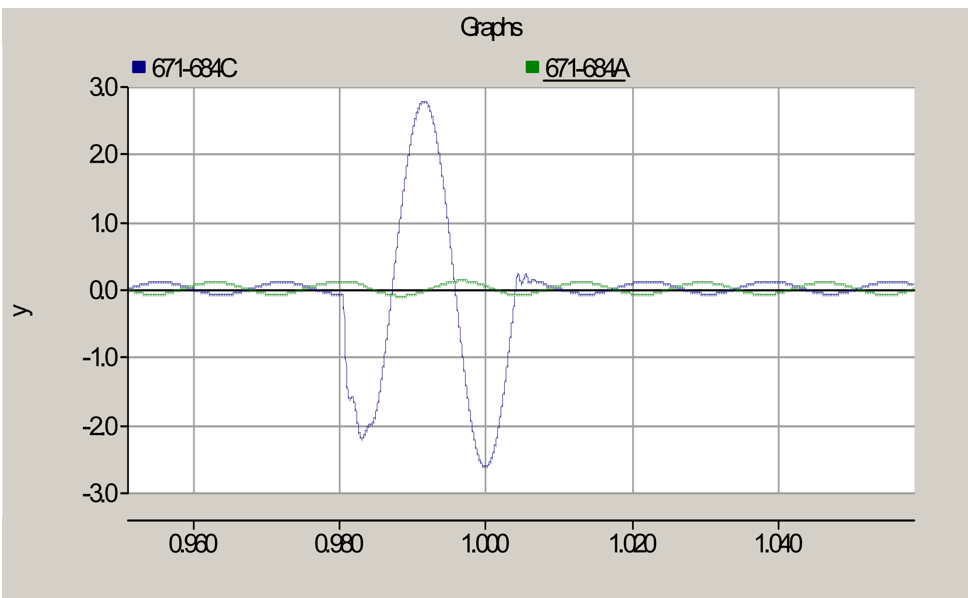


Figure A.104 Currents flowing into the Nodes 671-684

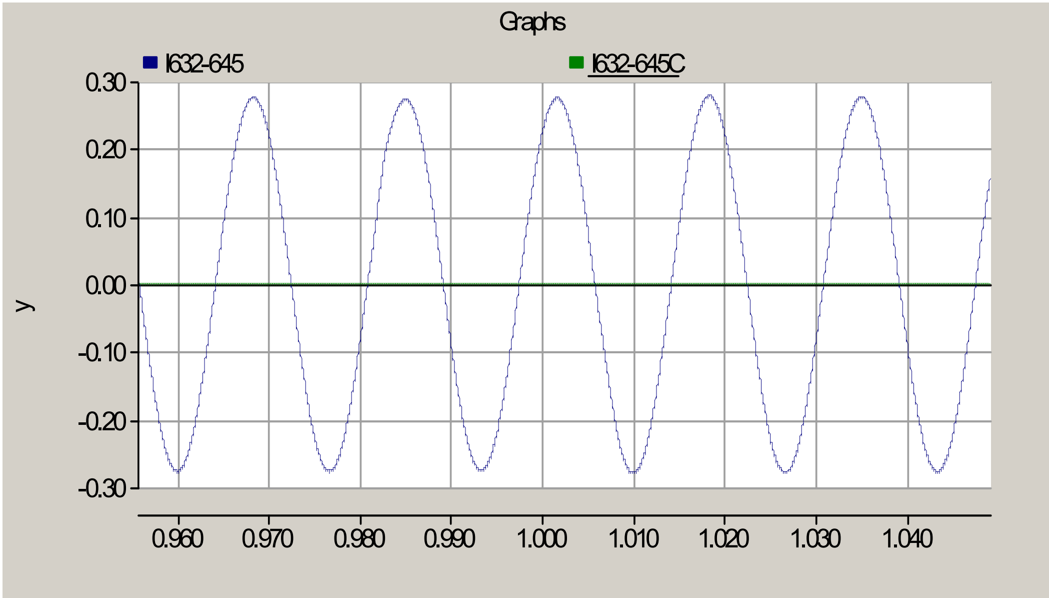


Figure A.105 Currents flowing into the Nodes 632-645

Changing the fault location to 675. The fault voltage and current are shown in figure A.106

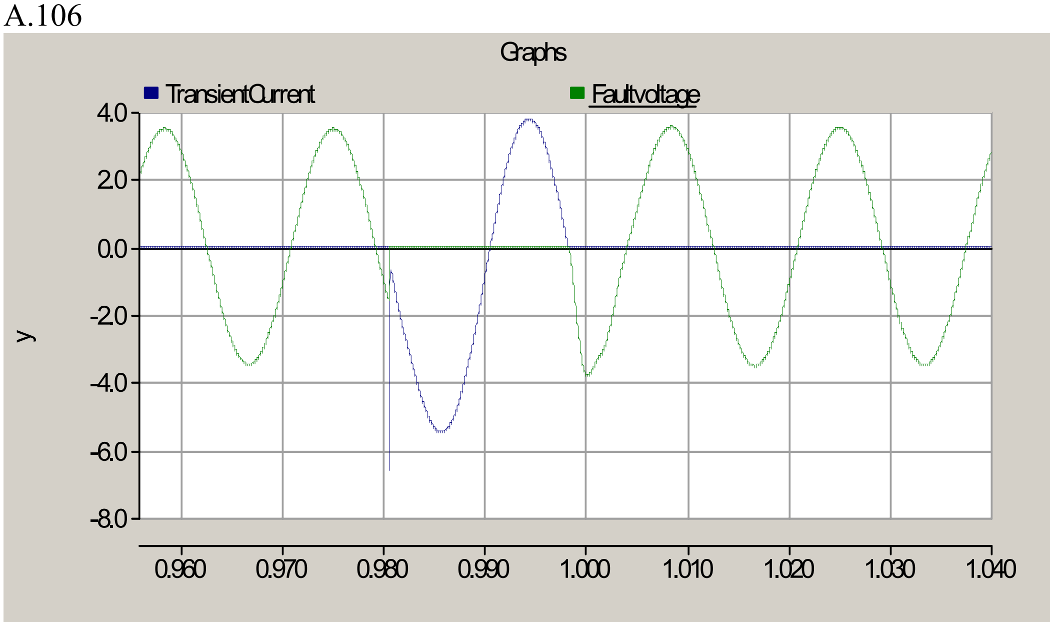


Figure A.106 Fault current and voltage.

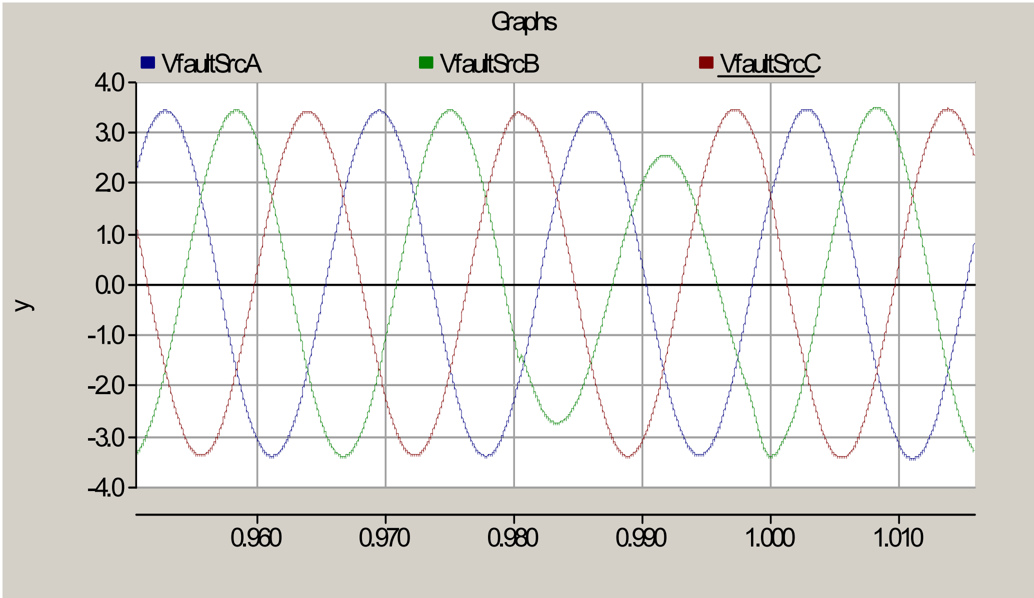


Figure A.107   Voltages at the source.

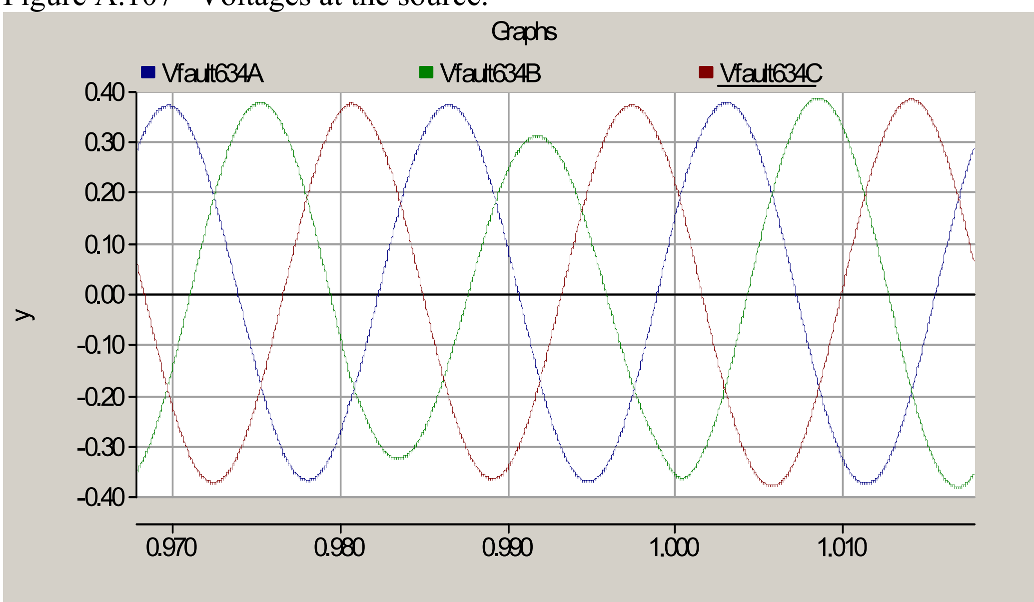


Figure A.108 Voltages at the Node 634.

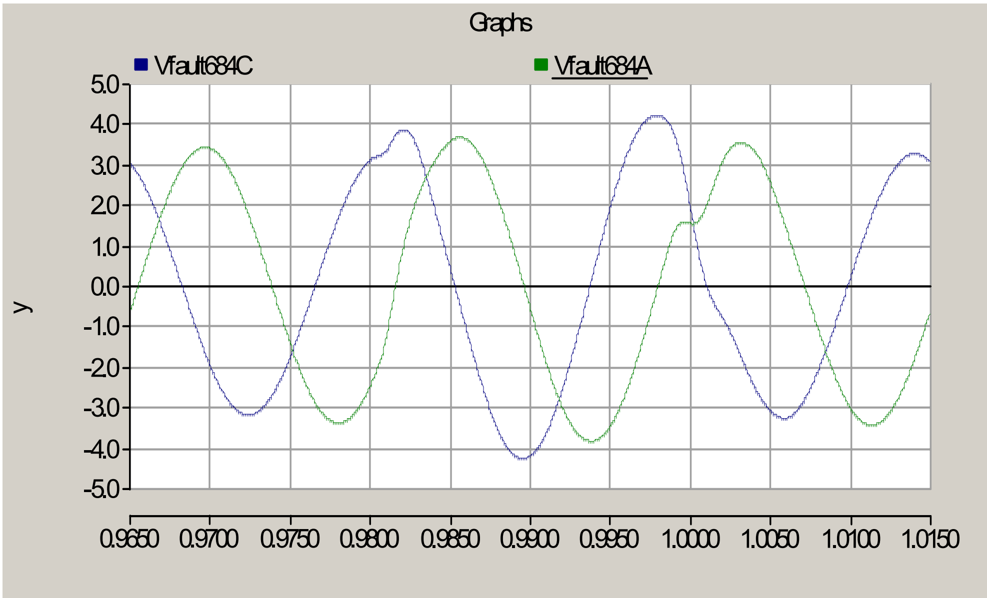


Figure A.109 Voltages at the Node 684.

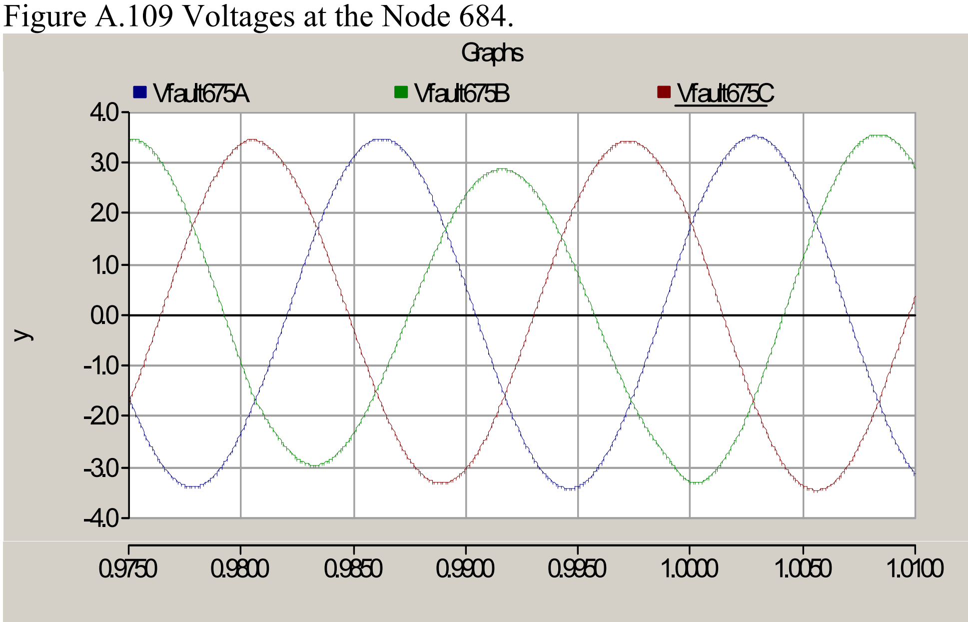


Figure A.110 Voltages at the Node 675.

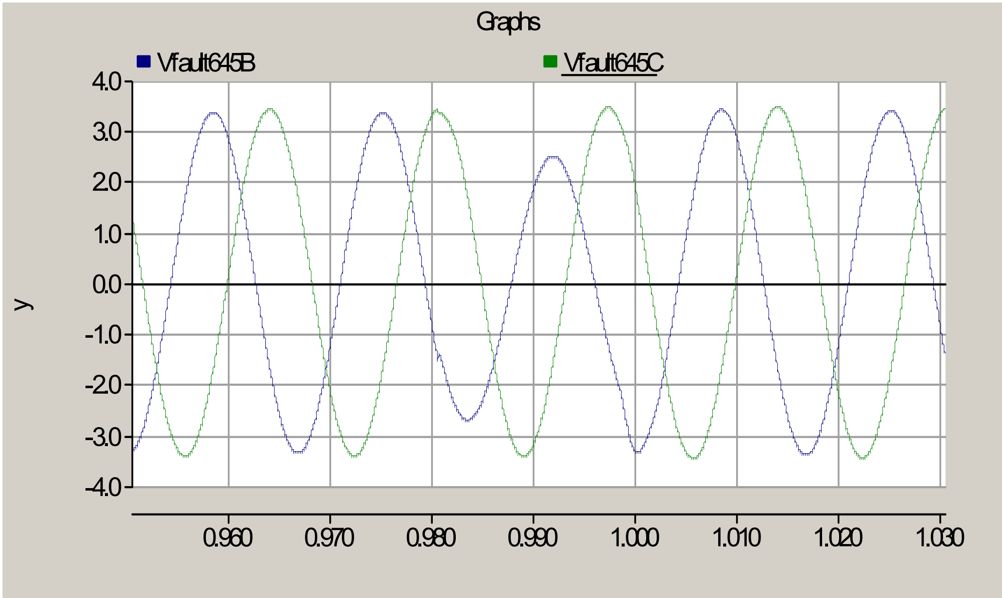


Figure A.111 Voltages at the Node 645.

The currents at various nodes are shown in figures to follow.

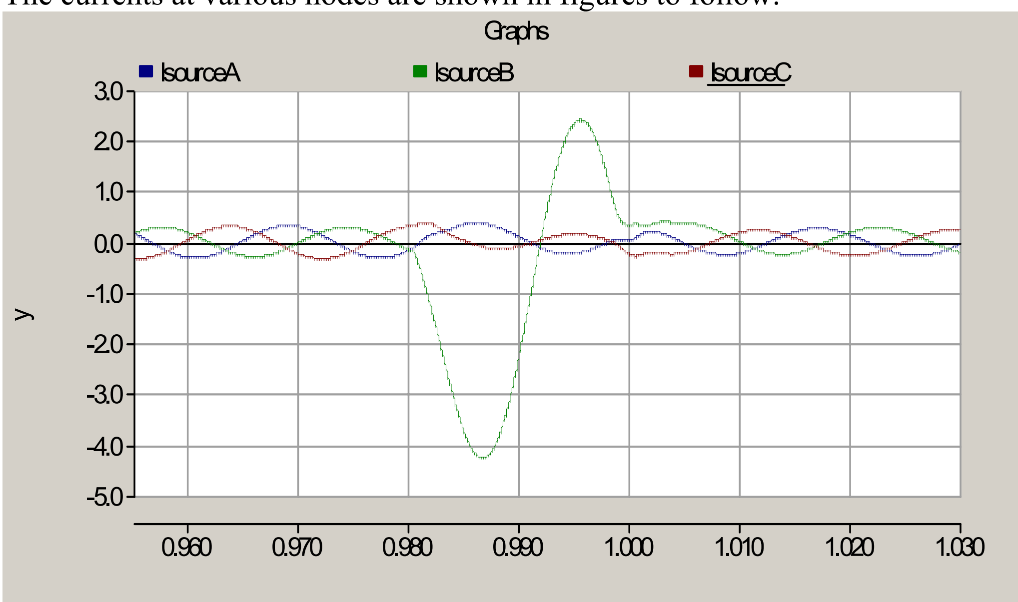


Figure A.112 Source currents.

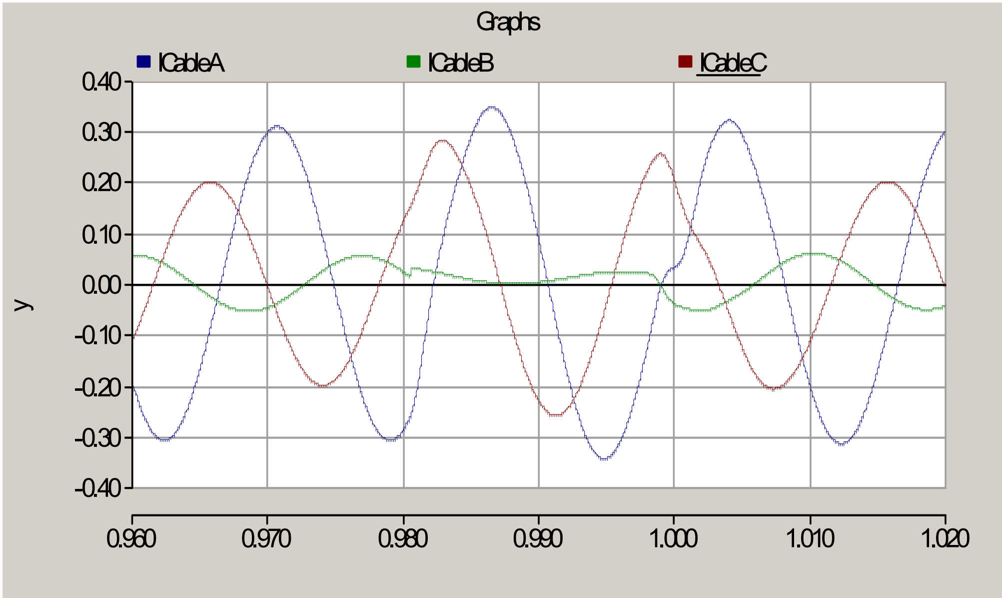


Figure A.113 Currents during faults.

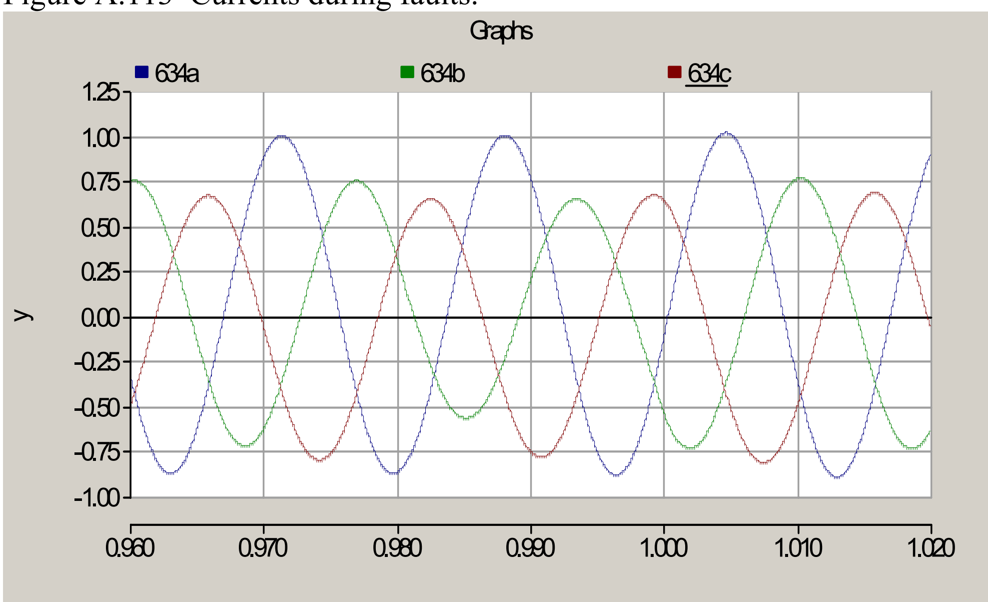


Figure A.114 Currents into the Node 634

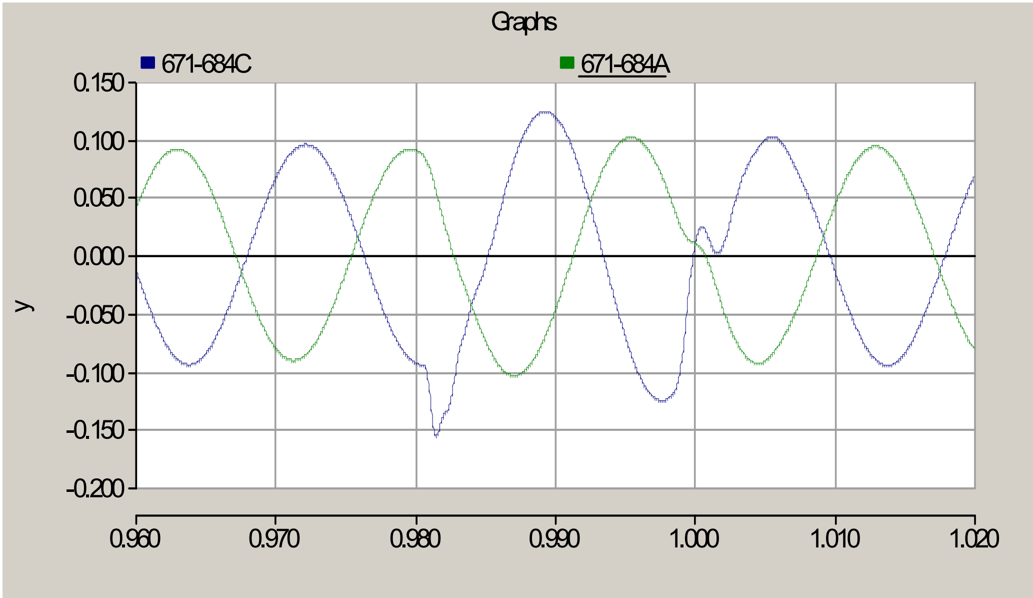


Figure A.115 Currents flowing into the Nodes 671-684

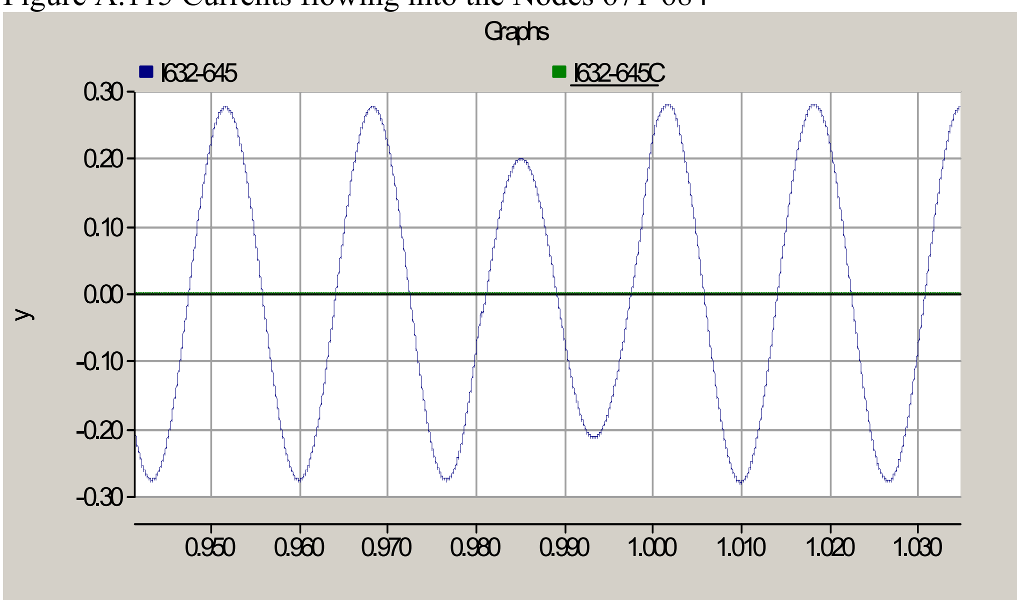


Figure A.116 Current flowing into the Nodes 632-645

Moving the fault location to node633. Fault current and voltage are shown in figure A.117

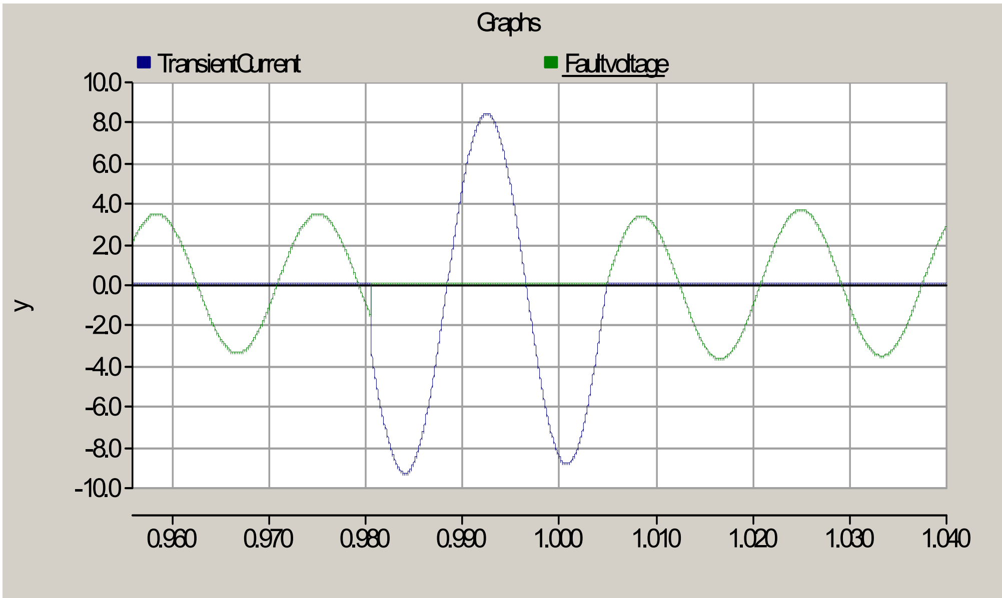


Figure A.118 Fault voltage and current.

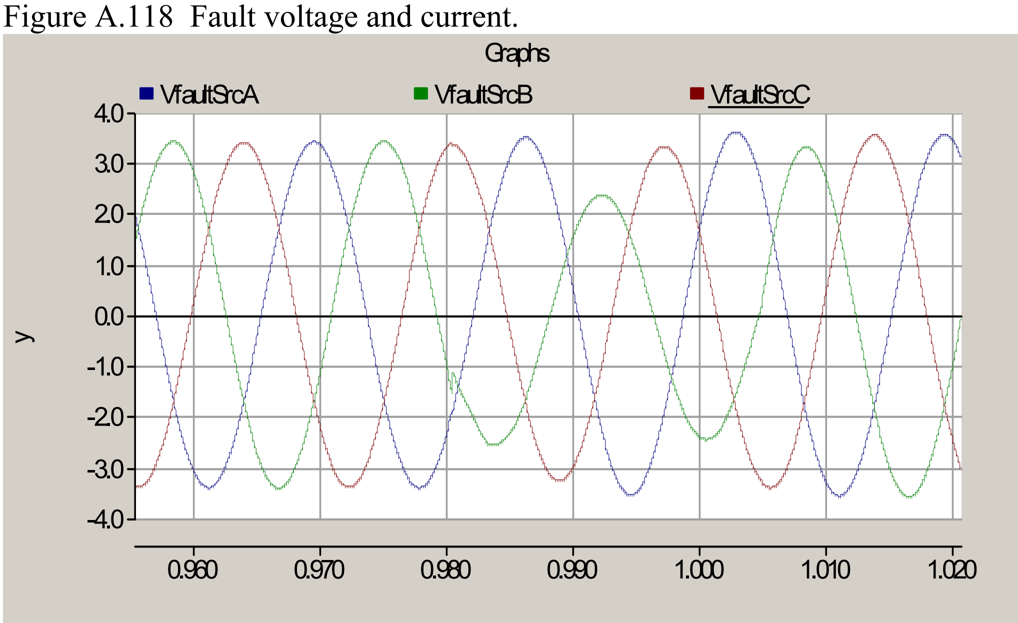


Figure A.119 Source voltages.

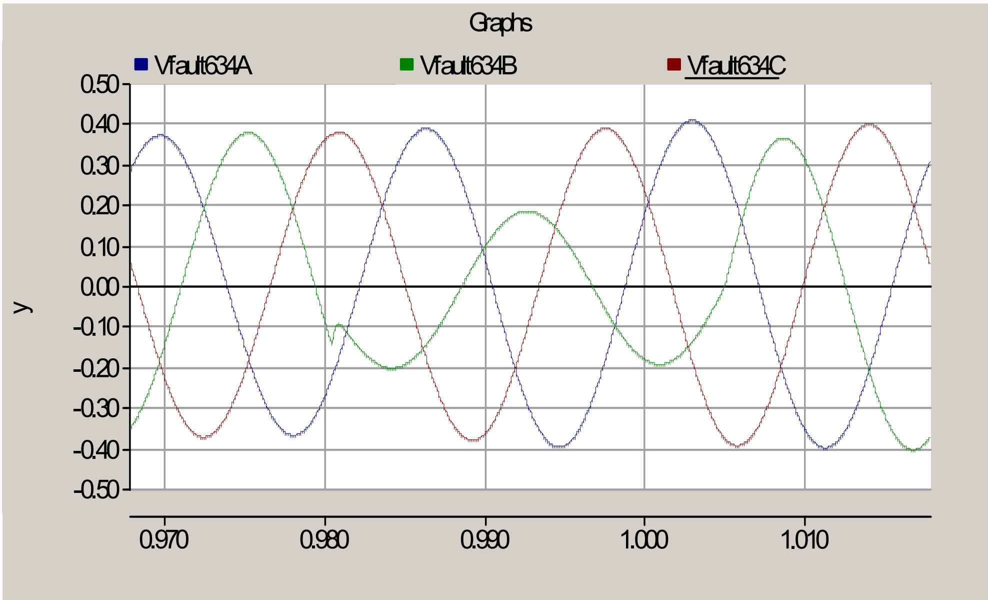


Figure A.120 Voltages at the Node 634

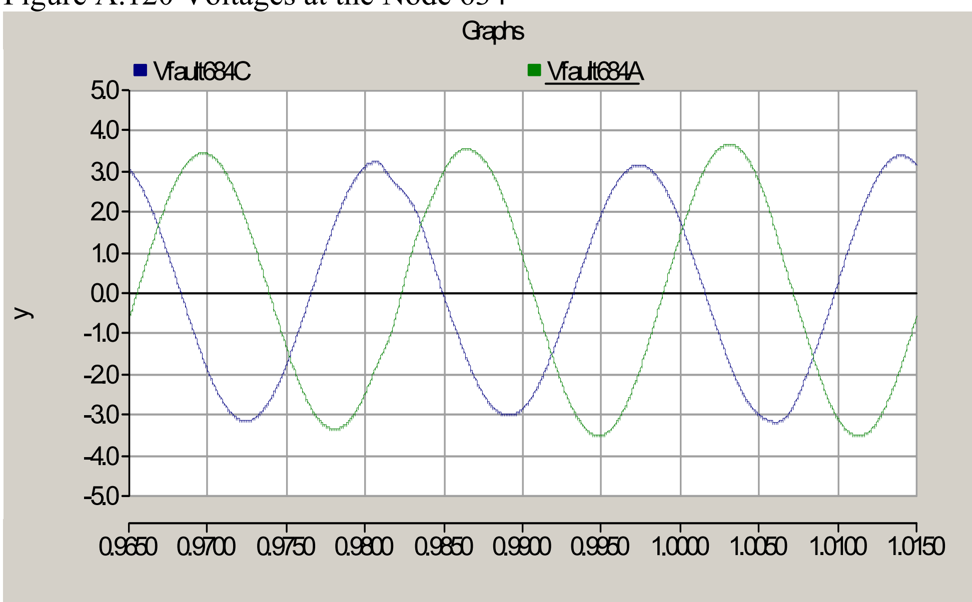


Figure A.121 Voltages at the Node 684

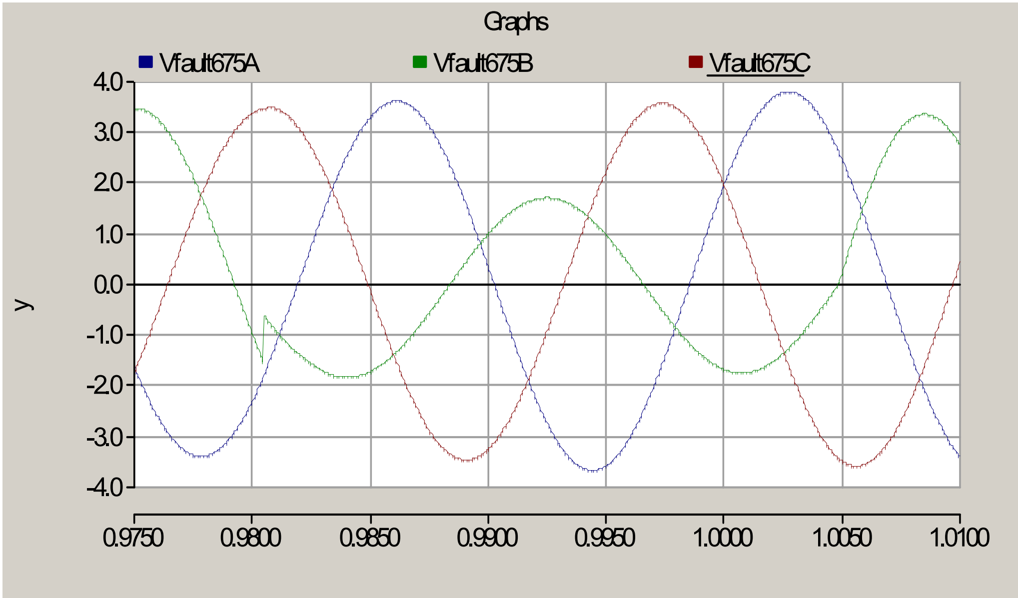


Figure A.122 Voltages at the Node 675

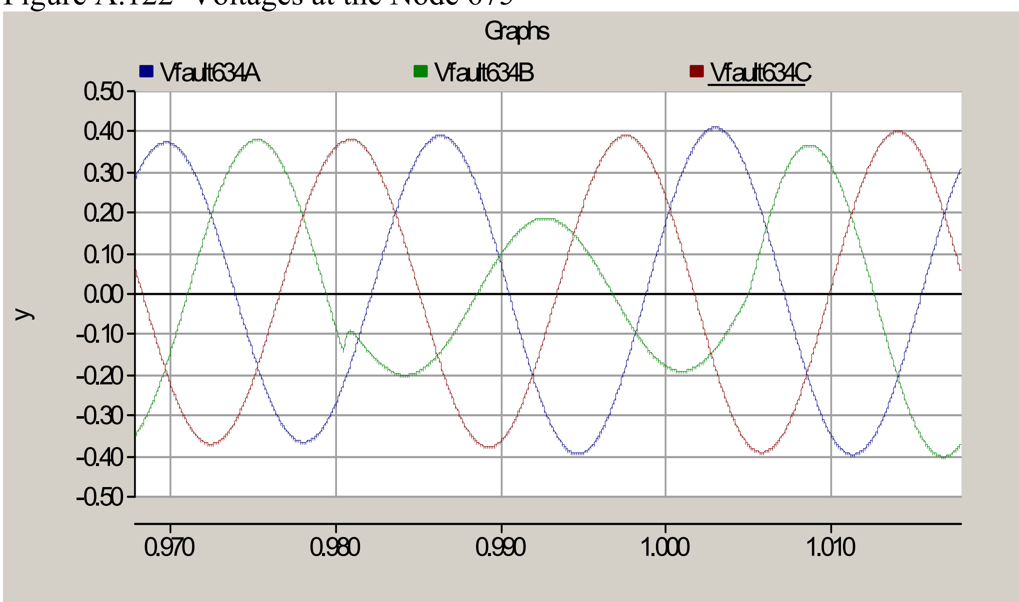


Figure A.123 Voltages at the Node 634

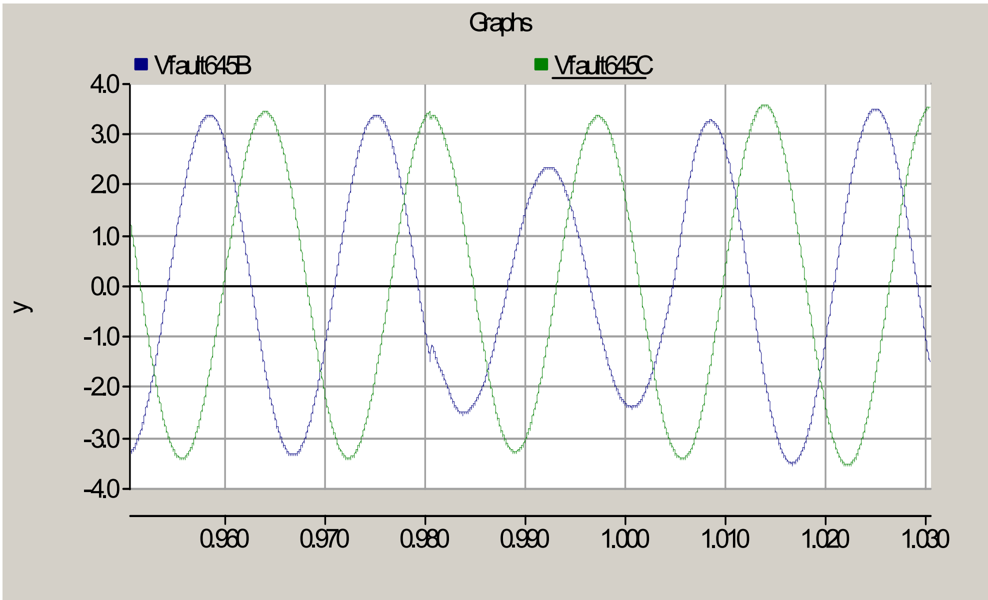


Figure A.124 Voltages at the Node 645

Currents at various figures are shown in figures to follow.

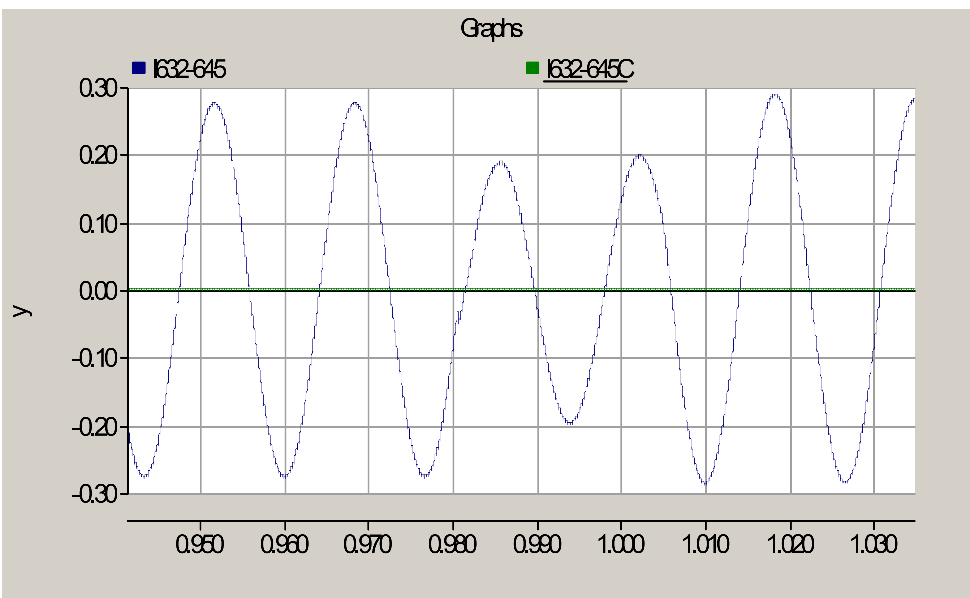


Figure A.125 Currents flowing into the Nodes 632-645.

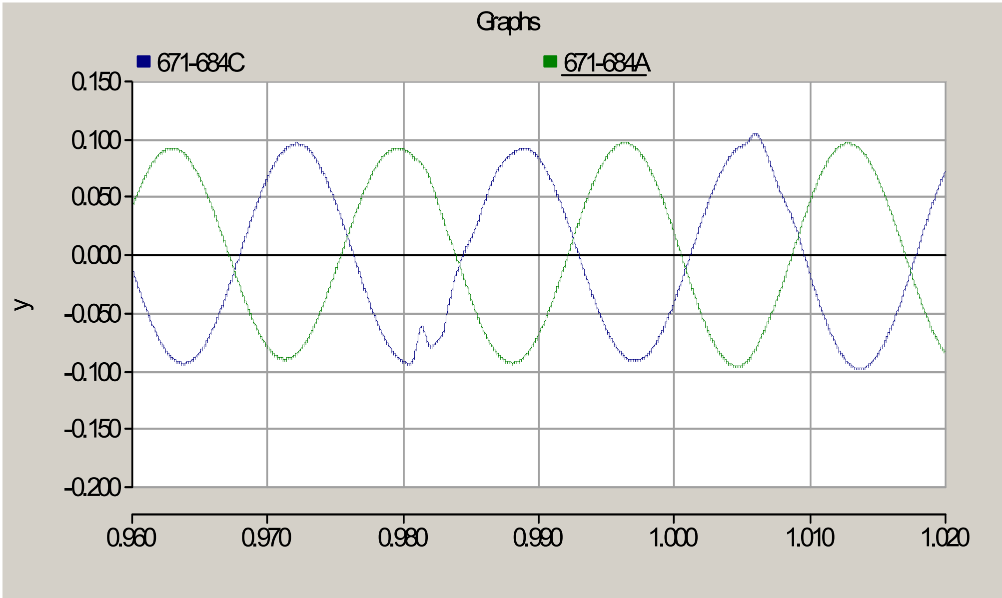


Figure A.126 Currents flowing into the Nodes 671-684.

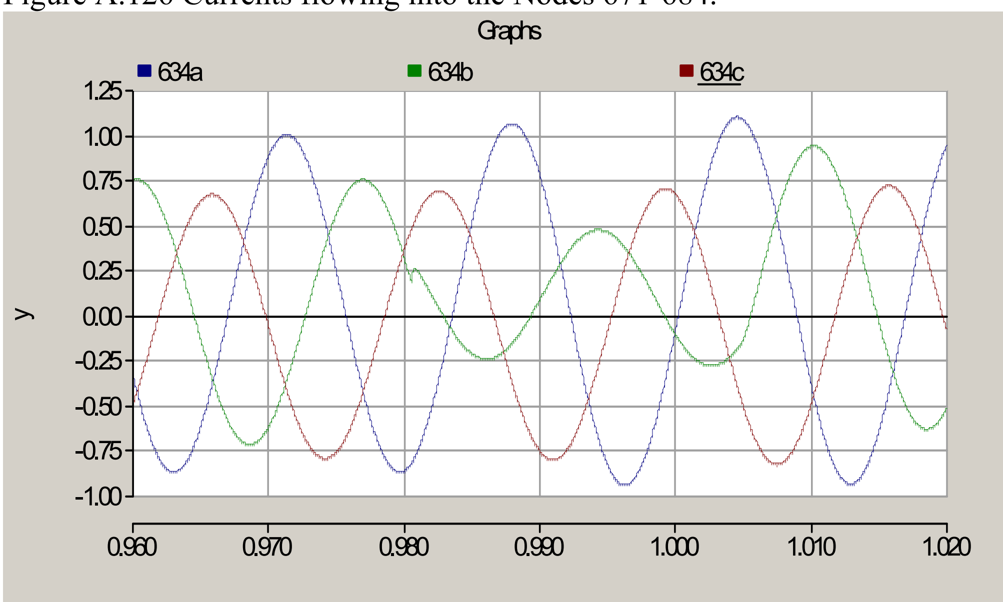


Figure A.127 Currents into the Node 634

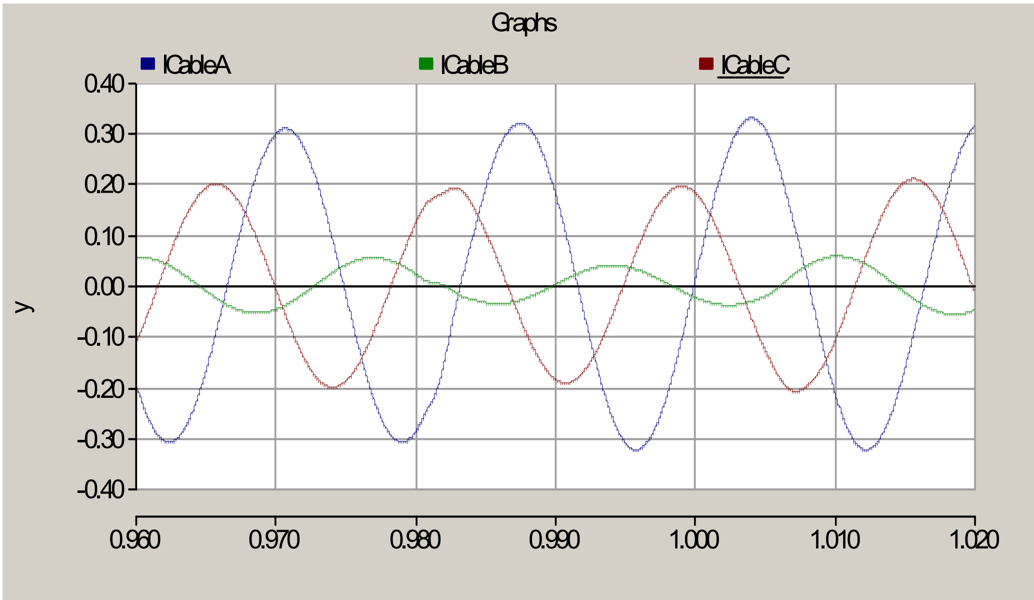


Figure A.128 Currents in the fault.

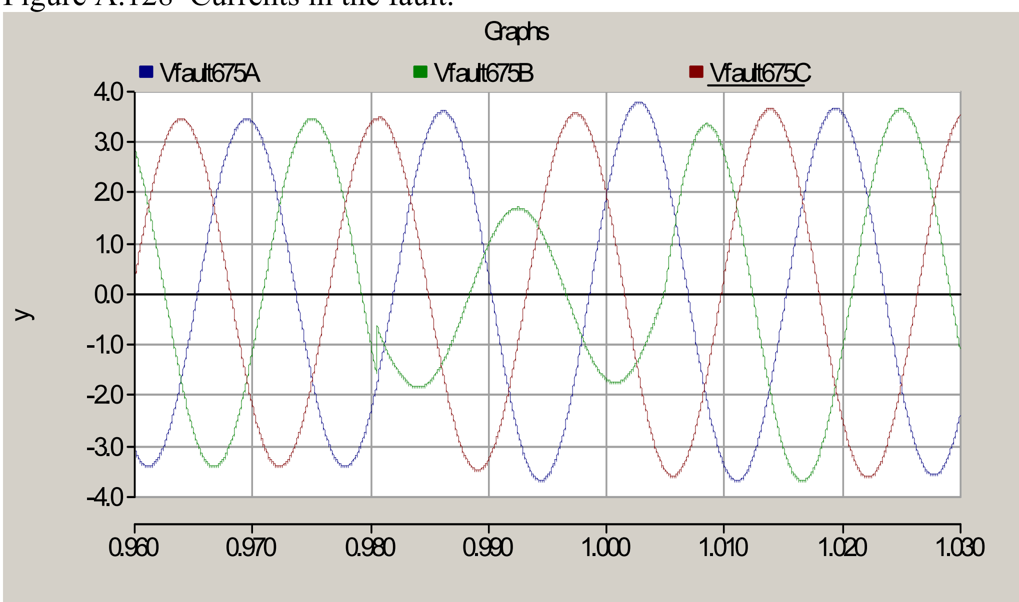


Figure A.129 Voltages at the Node 675

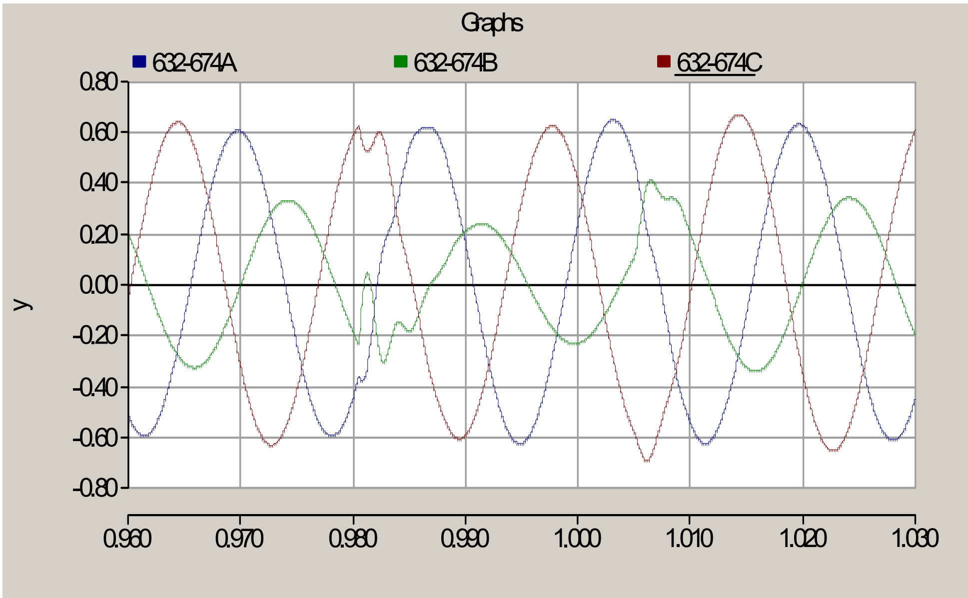


Figure A.130 Currents flowing into the Nodes 632-674.