Digital Fault Detection Algorithm for Micro-Grids

A Project Report

Submitted by

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(EE08B041)

in partial fulfillment of the requirements

for the award of the degree of

BACHELOR OF TECHNOLOGY IN ELECTRICAL ENGINEERING

AND

MASTER OF TECHNOLOGY IN MICRO ELECTRONICS AND VLSI

(DUAL DEGREE)

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY MADRAS

MAY 2013

THESIS CERTIFICATE

This is to certify that the thesis titled **Digital Fault Detection Algorithm for Micro-Grids** submitted by **Majarikar Vikrant Jiwanrao**, to the Indian Institute of Technology, Madras, for the award of the degree of **Bachelor of Technology in Electrical Engg. And Master of Technology in Microelectronics in VLSI** , is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ACKNOWLEDGEMENTS

I am grateful to my guide**, Prof. K.S.Swarup,** for his encouragement and guidance throughout my project. I thank him for giving me the freedom of working in my own way, which was crucial in getting a lot more interested in this area of than I was when I began working on the project. His comments and useful inputs were instrumental in making significant progress.

I am indebted to all the teachers of Electrical Engineering Department, especially professor Shanti Swarup K, for the timely direction that provided to every step during my coursework, with their suggestions and purposeful inputs.

I wish to thank also the students of the IIT Madras class of 2013 whose company has been an experience worth remembering. My special thanks to Dilraj, Rohit, Amit, Venkatesh, Chaitanya, Devika and Yashwant for providing me encouragement and motivation and help they rendered during my project and well as during stay in power system computational lab.

This work has been carried out at the Department of Electrical Engineering, Indian Institute of Technology, Madras

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Abstract

Microgrids includes low voltage distribution systems with distributed energy resources (DER) and controllable loads which can operate in medium voltage grid connected mode or in islanded mode. Microgrid provides environmental and economic benefits for end-user, customers, utilities and society. However, their implementation creates great technical challenges, such as a protection of microgrid.

In traditional protection systems associated with medium and low voltage networks, fault detection design is based on the assumption of unidirectional power flows as it is a radial system, having the use of time coordinated over-current relays makes an efficient and reliable way of protecting against several transient disturbances. Microgrid system has bidirectional power flows which makes traditional fault detection insufficient.

This thesis proposes an implementation procedure and performance testing of an algorithm comprise of Cumulative sum algorithm and power flows for fault detection in micro-grid systems. The Cumulative sum algorithm is found to be better than the traditional methods in the presence of noise, system frequency deviation, and other uncertainties for radial system. By monitoring the power Flows between buses along with cumulative sum algorithm, detection of faults in micro-grid system is carried out. The proposed digital Fault detection is implemented experimentally for performance testing on a test micro-grid system. Several transient disturbances viz. grid connection, single-phase to ground fault, 2phase fault, 3phase to ground faults, etc. occurring in different parts of the test micro-grid system are investigated experimentally.

KEYWORDS: Microgrid, Fault Detection, Cumulative Sum algorithm, Power Flows, Digital Protection, Faults, etc.

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Chapter 1

INTRODUCTION

1.1 Role of protection in power system

Power system protection is a branch of electrical power engineering that deals with the protection of electrical power system from faults through the disconnection of faulted parts from the rest of the electrical network. The main objective of a protection system is to maintain the power system stable by isolating only the parts/components which is defected, while leaving as much of the network still in operation. Thus, protection schemes must apply a concerned with practical matters approach and by expecting the worst possible outcome approach for clearing system faults. For this reason, the technology and philosophies employed in protection strategies can frequently be old and well established because they must be very dependable. The fundamental objective of the protection system is to provide isolation of a defected area in the system as quick as possible, such that the rest of the system is left to continue.

A protection system defends the power system from the harmful effects of a sustained fault. A fault (meaning in most cases a short circuit, but more generally an abnormal system condition or transient disturbances in current or voltage signals) occurs as a haphazard manner. If some of the faulted power system elements like line, bus, transformer, etc. are not disconnected from the system quickly, it may tends to power system imbalance or even damage the system.

One of the most important instrumentation applied in the protection of power systems are protective relays which has main function of detecting faults. IEEE defines a protective relay as a relay whose purpose is to detect/find defective lines / apparatus / equipments / other power conditions of an unnatural / serious nature and to start appropriate control action for systems protection. The reliability and stability of a system counts very much on the efficiency and fastness of the protection systems. Therefore Fault detection plays a very important role in protection strategies.

1.1.1 Basic objectives of system protection

The protective relay acts only after an unnatural or unbearable condition that has occurred in the system, with enough indication to allow their procedures. Thus protection in the system does not mean prevention of it but instead, reducing the length (time required) of the problem and reducing the damage caused, equipment failure time, and related problems that may result.

The five basic facets are:-

1. Reliability: Assurance that the protection will perform correctly.
2. Selectivity: Maintain persistence of service with minimum system disconnection.
3. Speed of operation: Minimum fault duration and equipment damage.
4. Simplicity: Minimum protective equipment used to accomplish the protection objectives.
5. Economics: Maximize protection at minimum cost.

Because these are the underlying foundation of all protection devices currently in use.

The most important aim of all the power systems is to keep a very high level of persistence of service, and when unnatural/abnormal conditions persist, to minimize the break down time. It is almost impossible to avoid effects of natural events, physical accidents, equipment failure or disorder which results in the deprivation of power, voltage dips on the power system. Natural consequences can cause short circuits i.e. faults which can be of any type viz, single phase to ground or phase to phase or phase to phase to ground or a three phase fault. Most faults in an electrical system occur in networks of overhead lines are single-phase to ground (SPG) faults occurs due to connecting foreign objects which induced transient high voltage like falling of a tree. In the overhead hanging transmission lines, tree contact due by wind is a major cause for faults. The appropriate percentages of occurrents various faults are listed below:

Single line to ground fault – 70-80%

Line-Line to ground fault - 10-17%

Line-Line fault – 8-10%

Three phase – 2-3%

When faults take place in the power system, they usually provide substantial variations in the system parameters like over-current, over or under-power, power factor, frequency and direction of power or current flows. The most common changeable parameter and also the one used in this thesis is the over-current which is widely used for fault detection.

Power system protection has main aim to provide maximum sensibility to faults and unnatural conditions and to restrict false alerts during normal state of operations. The protective relays are more of a preventive device which comes in to picture only after a fault has occurred which tries to help in reducing the duration of fault and limiting the damage, outage time and related problems. For the fault detection to work properly, it is essential to isolate the defected area immediately with a minimum number of system disturbances. Both false operation and failure to operate can result in major system disturbs that involves more instrumentation damage, more personnel hazards and possibly long disruption of service.

In general, the first step in the power system relaying algorithms is to detect the faults and the next step is to isolate defected part from the healthy system.

1.2 Technical challenges/problems in micro-grid protection

The microgrid concept has to face a number of disputes in several fields, not only from the protection perspective, but also from the control and dispatch point of view [1],[2]. However, due to their specific features and operation, microgrid protection systems have to deal with new technical challenges:

- Due to generation in both low voltage (LV) and medium voltage (MV), power flows bidirectional in the system;
- Two functional modes: grid connected mode and islanded/stand-alone mode;
- Topological variations in low voltage network due to connection/disconnection of grid and generators, storage systems and loads;
- Irregularity in the generation of several micro-generators connected in the microgrid;
- Increasing use of rotating machines in microgrid, which may cause fault currents to go beyond equipment ratings.
- Deficient level of short-circuit current in the islanding operation mode, due to power-electronics interfaced distributed generation (DG);
- Decreased in the allowable triggering time when faults occur in medium voltage and low voltage systems, in order to keep the stability of the microgrid;
- Substantially decrease fault current signal level when switched from grid-connected mode to islanded mode of operation.

The last point especially is one of the improtant aspects which have been under research for the past decade. The features of most protective devices used in microgrids are usually same as to those used in the protection of conventional distribution networks and in distribution networks are grounded on large fault currents. Nevertheless, under islanded-operation, the utility grid cannot lend to the fault and therefore its magnitude is limited to what the micro-generators can provide in microgrid. Consequently, conventional over-current protection strategies may no longer be useful in microgrid protection due to the current limitations of most inverters used in it.

1.3 Motivation

Power generation from renewable energy resources, including solar, geothermal, wind, ocean, and fuel cells, is anticipated to go beyond 20% of the total electric energy generation in the coming years. The diverse power generations, along with later shifts in operation veers of grid utilities, have prompted proposing the micro-grid as economical, simple, and effective means for development of distributed generation units (DGUs). Micro-grids have offered a workable option to encounter increase in power demands by certain load centres through connecting DGUs to distribution feeders, rather than flourishing existing distribution networks.

A micro-grid system is a flexible bi-directional power flow distribution network that is able to suit combination of loads, distributed generation units DGUs, storage systems like batteries and power conditioning units. This structural characteristic of micro-grid system allows it to function as a single controllable system within its service domain, which generates and distributes electric power to its loads.

The developing integration of micro-grids amongst utility grids has varied the classical structures of power systems, where micro-grids are often connected or disconnected from distribution networks and also from grid connection. Such changes have presented challenges for conventional protection systems, which are mostly established on unidirectional power flow and radial network structures.

The bi-directional power flow characteristics of micro-grid systems can be beneficial in providing benefits to utility grid operators and investors, distributed generation units DGU owners and customers. Such advantages may include exchanging active and reactive powers, reducing transmission system overloading and improving power transmission and distribution. However, along with these benefits, microgrids have also aroused an important challenge of micro-grid protection - the provision of rightly coordinated and authentic protection system so that it can reliably tripped in the event of a fault inside it to avoid damages to the loads.

1.4 Objectives

1. The objective of this thesis is to develop a fast and simple fault detection algorithm for detecting faults in a micro-grid system.

   Microgrid is a has a bidirectional power flow which has the ability to maintain stable and reliable function of the system. One of the main advantages of operating micro-grid systems for generating and distributing power is their potential of operating in both an islanded mode and in grid connection mode. Protection of microgrid is very important due to various advantages and it should be fast to trigger and simple algorithm to implement to detect faults so as to avoid damages to loads and system unstablility.

2. Implement an algorithm consist of Cumulative Sum algorithm and power flow for detecting faults in microgrids.

   Cumulative sum method alone is not sufficient to find out faults in micro-grid (looped) system therefore we use the concept of power flows to detect exact location of fault occurrences so that we can isolate the defected region to make the system stable. Implementation of an algorithm comprising of Cumulative Sum method and Power Flows is investigated and performances are evaluated for various types of fault detection in micro-grid systems.

1.5 Scope of work

The proposed algorithm for detecting faults in microgrid system comprises of Cumulative sum and power flow methods. Both these methods are implemented in Simulink. The various types of faults like single phase to ground, 2 phase fault, 2 phase to ground, etc. are tested in a test microgrid systems for verification of performance of the proposed algorithm.

1.6 Organization of the thesis

Chapter 1 gives a brief introduction about Power system protection problems in micro-grid system.

Chapter 2 deals with a detailed description of Micro-grid, its characteristics, advantages, protection issues in micro grids and its problems.

Chapter 3 gives an introduction about Cumulative sum fault detection algorithm in radial system, a comparison is done among 2 traditional and Cumulative sum algorithms for better fault detection algorithm.

Chapter 4 describes the implementation and Simulation of Cumulative sum fault detection algorithm in radial system and proposition of fault detection algorithm comprising of cumulative sum and power flows in micro-grid system for detecting various types of faults in it.

Chapter 5 discusses the inference and conclusion drawn from the protection of 4-bus and 5-bus Micro-grid system respectively.

Chapter 2

Microgrid

2.1 Introduction

Modern world of constructing and operating power systems show rising concerns in de-regulated operation. These trends have been started by installing numbers of distributed generating units (DGUs) in different locations with various capacities. The increased numbers of installed and operated DGUs are meant to achieve the following goals [3]:

i) Increasing generation capacity in host utility grids without substantial change in the infra-structure of the present grid;

ii) Possible power generation and delivery to meet demands of loads which are remotely supplying may impact the stability, economic and reliability of host utility grids.

The above mentioned goals for installing and operating distributed generating units have created interest among the people for introducing micro-grid systems. In general, a micro-grid system can be depicted as a power system with diverse combination of power generation (renewable or non-renewable power sources such as, such as wind, solar, geo-thermal, hydro, gas, diesel, thermal, etc.) to supply nearby loads locally, and can be operated in the islanded or utility grid- connected modes. Micro-grids has granted a viable option to achieve increase in power demands by certain load centres through connecting more installed DGUs to distribution feeders, rather than expanding present distribution networks [4]. Power generation from renewable or non-traditional energy resources, including wind, solar, geothermal, ocean, and fuel cells, is anticipated to exceed 20% of the total electric energy generation during the coming years. The various number of power generations specially renewable sources, along with later shifts in operation courses of grid utilities, have encourage proposing of the micro-grid as economical, simple, and effective means for development of distributed generating units.

Microgrids have much littler environmental affects than conventional big thermal and hydro power plants. Using of microgrids contributes reduction of gas emissions and it helps in extenuating the climate change. The most positive characteristics of microgrids are the comparatively short length between the generation and loads and low generation and distribution voltage level. Due to above mentioned factors, security and reliability of the systems increased, power losses in networks are minimized, costs on transmission and distribution decreased very much.

2.1.1 The Microgrid Concept

There is no universally consented standard definition for a microgrid, but certain features are common in the existing microgrids. A microgrid is compiled of interconnected distributed energy resources (renewable and non-renewable) which are able to provide sufficient and continuous energy to the most part of the microgrid inner load requirements. A microgrid must be able to operate both in grid connection mode and in autonomous mode from the utility grid seamlessly with little or no disturbances to the loads within the microgrid during a disruption [5].

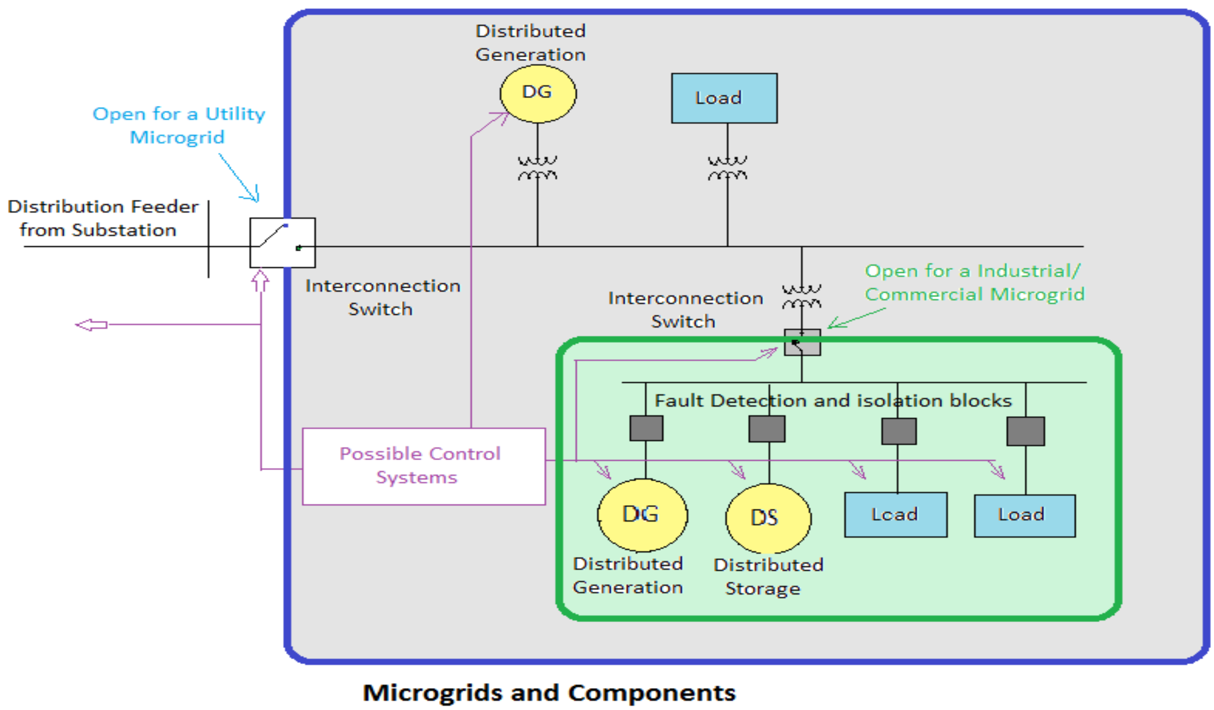


Fig.2.1: Typical microgrid configuration [6]

A microgrid is a network of small-scale power supply which is contrived to provide power to a small residential area or small community. The key concept that discerns this approach from a traditional power service is that microgrids have small power generators and are spread and settled in close proximity to the energy users. This very crucial form of de-centralized electricity supply ensures large environment profits. These profits are the more energy efficiency and alleviating the consolidation of renewable energy sources such as wind turbine, photovoltaic, fuel cell and other clean technologies. A typical microgrid configuration is shown in Fig. 2.1 [6].

2.1.2 Microgrid versus Local Electricity Utility

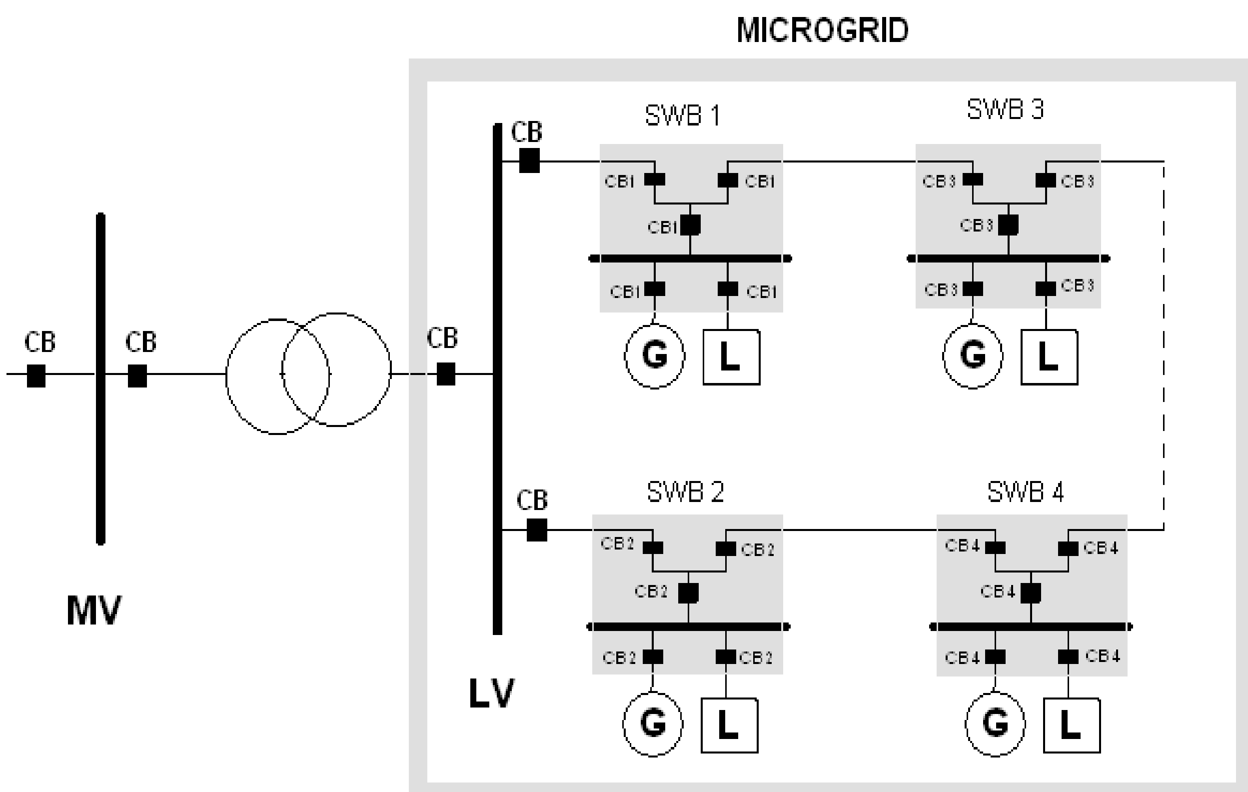
Distributed energy resources (DERs) are the key factors in microgrid system. DERs are small-scale power generators or storage technologies like batteries which are located proximity of loads they serve. The typical range of the Distributed energy resources DERs is between 2kW to 10kW. The small-scale power generation is known as distributed generation (DG). They are used to provide an alternative option to or enhancement of the conventional power systems. DERs usually relate to the devices and engineering including small wind power systems, fuel cells, micro-turbines, photovoltaic systems, etc. These play the significant function in the microgrids which can be “self-sufficient”, but for continuation in supply and flexibility, these DER’s should be connected to the local electrical utility network, or even if possible to adjacent microgrids. The power flow in microgrid is bidirectional, enabling the import or export of electricity although; there might be a unidirectional power flows. From the viewpoint of the microgrid, the utility connection may be viewed as another generator or load. [6]

2.2 Characteristics

A. The Structure of a Micro-Grid

In general, a micro-grid can be defined as a bi-directional power flow network that comprise of loads, distributed generation units (DGUs), storage systems like batteries and power conditioning units. The above definition of a micro-grid states its main features that is the ability to operate as a single controllable power system to generate and distribute electric power to loads within its domain even if it is disconnected form utility grid [4],[7],[8]. Electric power within a micro-grid domain is generated by use of distributed generation units, and is distributed through low voltage distribution networks to loads.

A typical micro grid block diagram is look like:-



Legends:				
	CB	Circuit Breaker	SWB	Switch board
	G	Micro-source/ Energy storage	L	Load
	MV	Medium Voltage	LV	Low Voltage

Fig. 2.2: Block Diagram of Typical single line model of micro-grid system

The bi-directional power flow characteristic of micro-grids states its ability to maintain stable and reliable function of the system, when operated in connection with the host utility grid mode or in stand-alone mode. The utility grid-connected mode of operation is intended for offering advantages to utility grid operators and customers in terms of stability and reliability of the system. These advantages include exchanging power, improving power transmission and distribution, and reducing transmission system overloading [8],[9],[10].

B. Traditional Protection Practices in Micro-Grids

The conventional protection for micro-grids is mostly based on over-current devices that are installed within their domains. Transformers used in micro-grids are usually protected by differential relays to control circuit breakers for tripping and disconnection of defected area. In order to make sure that the smallest number of tripped components installed within the micro-grid domain, back-up fuses are installed at each point-of-branching, as well as at the point-of-connection or disconnection with the host utility grid [9],[10],[11]. In general, micro-grids are subject to variety of current transient disturbances, which can be worsen by power electronic converters used in distributed generation units (DGUs).

2.3 Advantages

The structure of a micro-grid system allows it continue to operate as a single controllable system, which generates and delivers electric power to local loads within its service area in spite of grid connection or disconnection to micro-grid. One of the main advantages of operating micro-grid systems for generating and distributing power is their potential of operating in an islanded mode, and continues to supply its loads when host utility grid is experiencing severe transient disturbances [4]. The bi-directional power flow characteristic of micro-grid systems can be advantageous in furnishing benefits to host utility grid operators and investors, distributed generation units owners and customers.

In many cases distribution energy resources incorporate various kinds of technologies that let generation in small scale (micro-sources) and many of them includes renewable energy resources such as solar, wind or hydro energy. installing distributed generators close to the load have the advantage of minimizing transmission losses as well as keeping network over-crowding. also, the probability of having a power supply disruption for end-users connected to a low voltage distribution grid is minimized since adjacent micro-generators, controllable loads and energy storage like battery systems can operate in the stand-alone mode in case of severe system current transient disturbances on the transmission system level [6]. Micro grids are potentially offering various advantages to end-user, consumers, utilities and society, such as:

1. Improved energy efficiency by exchanging power
2. Improved power transmission and distribution
3. Improved service quality and reliability
4. Reduced transmission system overloading.
5. Reduced greenhouse gases and pollutant emissions
6. Minimized overall energy consumption
7. Cost efficient electricity infrastructure replacement

2.4 Protection issues in Microgrids

Connecting distributred generators to main grid like microgrid, which can work in stand-alone mode also, changed system properties significantly. Voltage and Current profiles and dynamic demeanor of the whole power system are changed. The amount of short-circuit power due to fault is more and current flow becomes more complicated due to bidirectional flows. On the other hand, in case of stand-alone mode of operation, the level of short-circuit power become less dramatically through the disconnection from main grid and but current flows can still flows bidirectional. As a result, the classical protection techniques which are sufficient to detect faults in radial system become inadequate and insufficient. The Problems concerns are as follows[12]:

- loss of selectivity,
- overcurrent protection level and earth-leakage protection,
- disconnection of generators,
- islanding and
- single-phase connections.

The power output of distributed generators in microgrids are frequently irregular. Due of this, the behaviour of the system during faults alters constantly. Also due to interconnection with other adjacent micro grids, existing protection system may not be able to work properly. Because of these issues, fault detection has to count on the state of the local micro-grid (which contains instantaneous production through distributed generators and local consumption) and Protection parameter has to be modified regularly. Protection of microgrid during islanding mode of operation also has to be examined.

A. Selectivity

System protection is more selective when the protective device nearest to the transmission fault is activated as fast as possible to disconnect or isolate the fault from the whole system. If this activity takes more time, then there is a possibility that the protective device which is far away from the faulty place trigger to isolate healthy part of the system. Unlike microgrids, where there is no distributed generator, power flows in one direction from generator to loads in normal operation as well as in faulty operation. This permits for the introduction of a selective system which work on the principle of applying time grading to overcurrent relays. But in case of microgrid, where DG are installed, the above protective system is inadequate. In microgrid we can disconnect healthy feeder by its own by triggering protective relay near to it as it adds to the short-circuit current flowing through a fault in an adjacent feeder. On the other hand, if fault takes place on the connecting transmission line between the main grid and a local microgrid network, disconnection of microgrid should take place. The protective devices which has to trip the flowing current should be located between the peak load current and the minimal fault current. Since the power delivered by distributed generators is not constant and mostly irregular, parameters of protection devices should, be updated constantly.

B. Overcurrent Protection and Earth-Fault Protection

Due to presence of more generators the fault current and overcurrent detection in the system reduces. This can result in prolonged over-currents or earth faults in the system.

C. Protective Disconnection of Generators

Distributed Generators in microgrids has to be saved against all types of short-circuits, over- and under- current and voltages, unnatural frequencies, harmonic distortions, etc. Depending on the position of the fault in a microgrid, the protection system of generators should employ different time delay which assures the selectivity of the system. If there are many protective devices between the generator and faulty place, the devices near to faulty place should be used first to disconnect the line. If the fault occurs proximity to the generator, fast triggering of protective device is needed. If protection system triggers quickly, selectivity can be restored.

D. Islanding mode of Microgrid Operation

In main grid operation, sometimes disconnection of generators is needed to prevent building of unintentional islanding in the system. Microgrid islanding operation through intentional islanding has to be studied as an alternative option which drastically increases the reliability of system because generators in microgrid are capable to supply loads in it even if grid is disconnected. None the less the behaviour of microgrid is completely different when a fault occurs because of the changes in power flows direction than in case of main power system grid which tells us the need of adaptable protective measures.

E. Single-Phase Connection in Microgrid

Some of the distributed generation units outputs single-phase power in microgrid system e.g. batteries, small photovoltaic systems or Stirling engines. This affects the three-phase current, leading more current in the neutral conductor and stray currents in the earth. This single phase current should be confined to forbid overloading.

2.5 Problems

The growing installation and use of micro-grids within utility grids has altered the classical structures of power systems, where micro-grids are often connected or disconnected from distribution network and utility grid. These changes have laid challenges/create problems for conventional protection systems, which are generally established on unidirectional power flow and radial network structures. Challenges for protecting utility grids hosting micro-grids include [8]-[14]:

I. The broad usage of power electronic converters within micro-grid areas has converters which alter, initiate, or worsen current transient disturbances in micro-grids and in utility grids.
II. The substantial changes in magnitudes, frequency contents and decaying rates of transient disturbances occurring in micro-grids are greatly determined by the islanded or grid-connected mode of operation.
III. The frequent bidirectional power flow has made difficulty in selection, calibration, and coordination of protective relays.
IV. The provision of right coordinated and reliable protection system is needed so that it can dependably tripped/disconnect in the event of a fault within micro grid system.

However, there are many technical consequences associated with the installation, integration and operation of micro grids. One of the major challenges, is the protection system for micro grid which must react to the faults occurred in both main grid and micro grid system. The protection system uses fault detection algorithm which should isolate the smallest defected part of the micro grid as quickly as possible to avoid damages to the micro-grid loads during faults [15].

In addition, governable islands of different shape, size and capacity can be formed as a result of faults inside a micro grid. In such instances a loss of relay coordination may exist and generic over-current protection with a single adjusting group will not ensured a selective operation for all possible faults types. Therefore, it is essential to used a new advanced and simple fault detection algorithm to detects faults in a grid connected and/or in islanded topology. In order to deal with bi-directional power flows and low short-circuit current levels in micro grids dominated by micro-generators, a new fault detection method comprising of Cumulative Sum Fault detection and power flow detector is proposed for detecting faults in micro-grid system.

Chapter 3

Cumulative Sum Algorithm

3.1 Introduction

In power systems, the decision made by a relay is straightly concerned with the possible component damage and stability of the system. The basic relays functioning for detecting faults can be classified into two categories:

1) the one using the current / voltage waveforms and
2) the others utilizing the traveling waves as the signal input [16].

In protective relays, a fault detector (FD) separates the normal state of signal from the faulty state and quickly triggers (within a few milliseconds) the main relay algorithm for isolation of defected part to make the system stable. The overall performance of a relay relies very much on the speed and accuracy of this fault detection unit.

3.2 NEED for good algorithm.

The type of relay used initially usually deduces the tripping decision using fundamental components of the system frequency, current and/or voltage waveforms where discrete Fourier transform based and iterative based methods. More complex algorithms are also useable in the literature using Kalman filtering and the phasor estimation approach [17],[18]. In spite of higher computational burden for fault detection, it can be noticed that conventional phasor estimation techniques established on discrete fourier transform method, recursive least square method, or Kalman filtering methods are not viable for detecting faults as the processing time takes more than half a cycle of the fundamental period. Further, above mentioned methods are also sensitive to frequency deviation, harmonics, etc. To overcome these problems/drawbacks a statistical approach for fault detection has been confronted where adaptive sorts of filters are utilized which offers valuable advantages over these fault detectors. Cumulative-Sum method works in time domain and uses sample elements of voltage and current waveform to detect faults. It is very fast, and is resistant to the presences of noise and spike in signal, system frequency deviation and load variations. Furthermore, its implementation is also simple as no special hardware is required due to presence of only additions and comparators. A cumulative-sum (CUSUM)-based fault detector is being employed widely as a means for noticing abrupt changes in various fields [19]. As power signals (sinusoidal) alternate, the two-sided CUSUM algorithm is appropriately designed for the purpose of fault detection in power system. A comparative performance of the above method with traditional methods has been studied to find out the better algorithm for fault detection.

3.3 Traditional algorithms and CUSUM

With the origin of a fault in the power system, the voltage and current waveforms changes from the normal sinusoid and make system unstable. A fault detection algorithm in a digital relay utilizes either of these signals to separate out the faulty situation from the normal steady state condition. For the prevention of faults occurred to loads, these alters/changes/transients in the current signals are to be identified on-line as quick as possible with the lowest degree of false detection to protect the other equipment in the system. Numerous techniques are available for this purpose as mentioned above but mainly two simple approaches are utilized in digital relaying for fault detection and are as follows:

- Sample to Sample Comparison Algorithm
- Cycle to Cycle Comparison Algorithm

I. **Sample-to-Sample Comparison Method**

In this method, a module computes the difference between the present sample and previous sample and continuously checked whether the difference value is greater than a defined threshold value to register a fault. During normal steady state of the power system, the sample difference is expected to be fixed and at the faulty condition, it will be very high. Mathematically the algorithm can be defined as [19]

$$d_k = |s_k - s_{k-1}| \tag{3.1}$$

Wheres_k represents the sample value of the signal at the kth instant.

A fault is recorded if

$$d_k > h \tag{3.2}$$

Where h is a threshold parameter for fault determination. In steady state this h value is low compared to amplitude of given sine wave.

II. Cycle-to-Cycle Comparison Method

This method computes the difference between sample values which are one cycle apart. This difference value should to be zero normally whereas after the occurrence of a fault, it would be very high for the algorithm to differentiate it as fault. Mathematically it is represented as

$$c_k = |s_k - s_{k-N+1}| \tag{3.3}$$

where N is the number of samples per cycle.

A fault is recorded if

$$c_k > h \tag{3.4}$$

Where h is the threshold parameter for fault detection.

III. Cumulative-Sum based Fault detection method (Cusum).

The traditional fault detection algorithms mainly use the differential principle for detecting faults and because of this they are sensitive to noises or spikes in the signal. In this algorithm unlike the moving sum technique, an integral approach is applied [19]. The CUSUM method for fault detection uses the current samples (s_k) of any phase and prepares two complementary signals such as

$$s_k(1) = s_k \tag{3.5}$$

$$s_k(2) = -s_{k.} \tag{3.6}$$

Using the above mentioned two signals, the two-sided CUSUM test is expressed as [18]

$$g_k(1) = \max(g_{k-1}(1) + s_k(1) - v, \ 0) \tag{3.7}$$

$$g_k(2) = \max(g_{k-1}(2) + s_k(2) - v, \ 0) \tag{3.8}$$

Where $g_k(\,)$ represents the test statistics and v is the drift parameter in it.

A fault is registered if

$$g_k(1) > h \text{ or } g_k(2) > h \tag{3.9}$$

Where h is an arbitrary constant and which should be ideally zero during normal state of operation.

The max-operation in above mentioned relations provides a positive or zero value for the $g_k(\,)$. In the above relation, v provides the low-pass filtering effect and determines the performance of the fault detection algorithm. In general, the value of v is little more than amplitude of current signals. With an increased level in the current signal due to transient disturbances, if any $s_k > v$, the corresponding g_k starts growing. As observed from (3.7) and (3.8), the g_k value increases by a factor of the difference between s_k and v. With more current samples available, the cumulative sum process of the above relations provides an easy and simple way to detect the fault situation using (3.9). The two-sided approach fits here as a power system signal (sinusoidal) alternates and is advantageous from the detection-speed point of view.

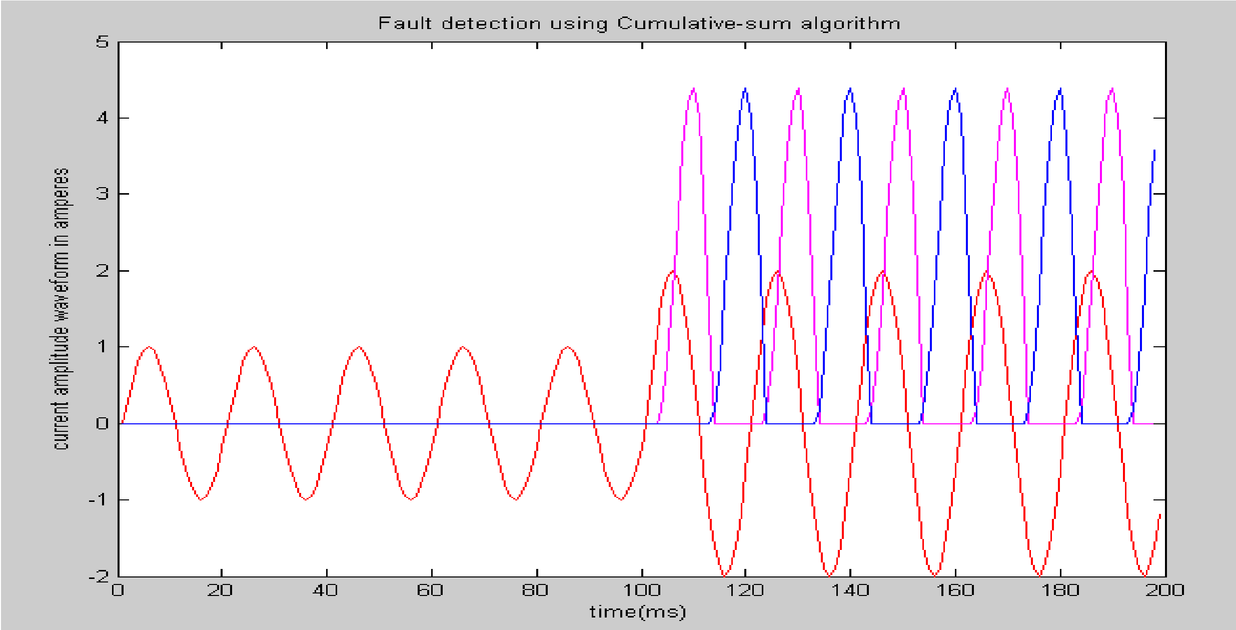


Fig. 3.1: Signal and indices of cumulative sum approach for Fault Detection
(Red => current signal, Pink & Blue => indices g_k of cumulative sum algo.)

Fig. 3.1 shows the signal and indices of cumulative sum approach here the value of v is 1.5 Amps so if the current amplitudes increase beyond 1.5 amps, g_k starts growing which can be seen from Fig 3.1. The Cumulative sum algorithm has been widely used to detect abnormal changes of state variables in processes in relatively less time. At the reaching of each samples, the algorithm will carry out some steps of additions and comparative-logical operations. The power system sinusoidal current signals are considered to be fast-changing variables with a typical sample interval being 1ms. With the present processing power, aforementioned operations can be easily done with any standard hardware platform within the stipulated time.

3.4 Comparative study between CUSUM and traditional algorithms

In this study, only current signal is employed as current amplitude becomes significantly high after the onset of a fault. The following is the comparison between two traditional fault detection methods and cumulative sum based fault detection method.

A sampling rate of 1 kHz and a full-cycle window of N=20 samples (50-Hz nominal frequency) are maintained for all 4 simulations. As mentioned earlier, for fault detection applications, the value of v is to be set little more than the peak of the relay setting current. For example, for 1 A (peak) of set current, v should be one or little more than 1 depending on our allowance for fault detection in a system. Accuracy and speed are two important aspects while measuring the performance of a relay. The comparative results for fault detection are provided in five subsections cases as follows:

A. Effect on normal sinusoidal wave
B. Effect of amplitude variation,
C. Effect of frequency,
D. Effect of noise and
E. Effect of load change in a power system.

A. Normal sinusoidal wave

In this case we applied all three algorithm viz- Sample-to-Sample, Cycle-to-cycle and cumulative Sum algorithms to a sine wave to check the behavior and output of these algorithms.

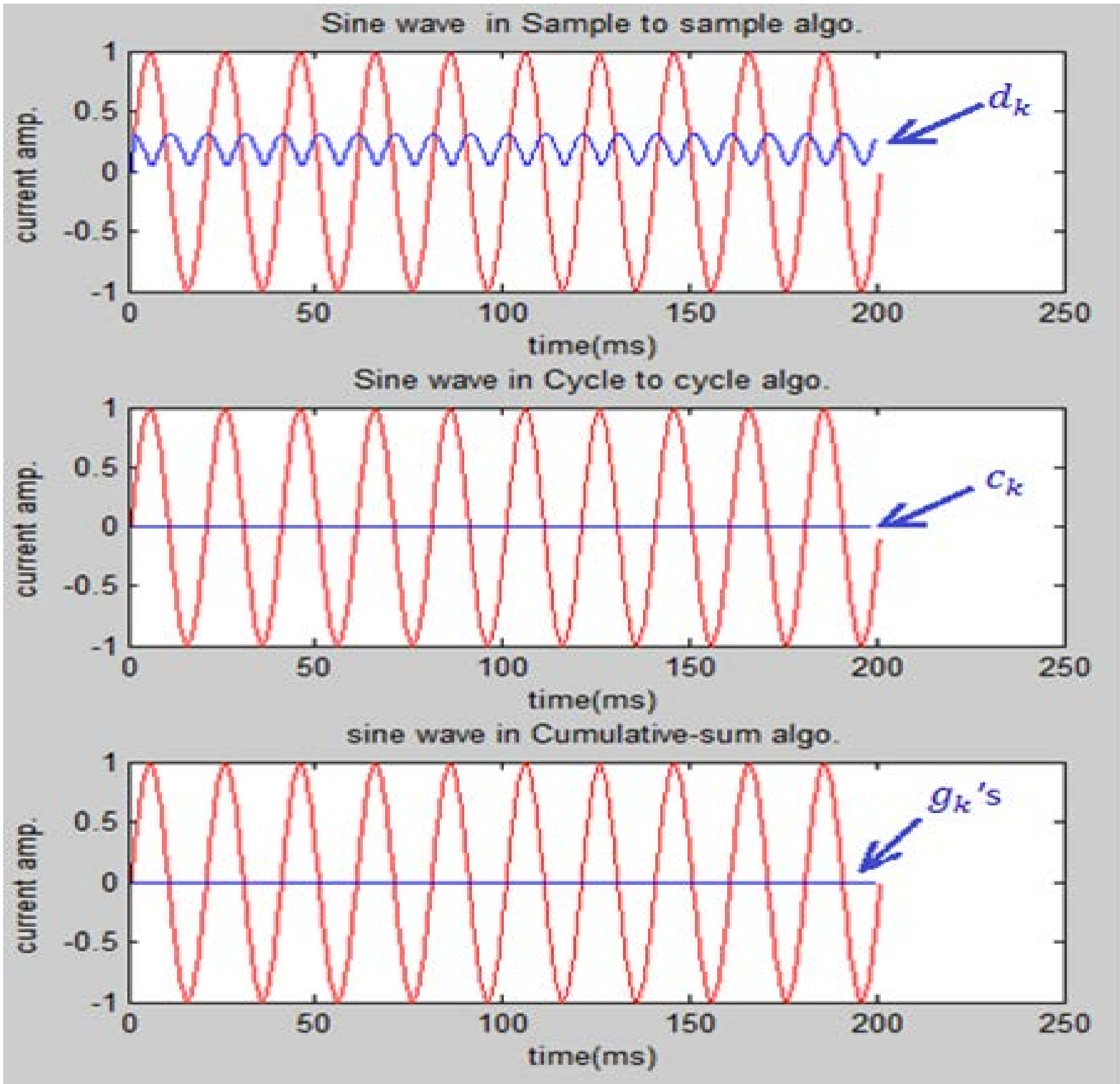


Fig 3.2: Sine wave in all three Algorithms

From Fig 3.2, it is clear that Cumulative sum and cycle to cycle output is zero in normal sine wave whereas the output of sample-to-sample algorithm shows some variation which is low compared to amplitude of sine wave. Cycle to cycle gives zero output for normal sine wave and in Cumulative Sum case, the g_k's indices of the approach are of zero value in normal sine wave.

B. Amplitude Variation

In this case the algorithms are tested for the variation in amplitudes of sine wave which is changed to 2 amp. at 0.1 s without changing the other signal parameters. Here the indices of all the methods are computed and shown in Fig. 3.3.

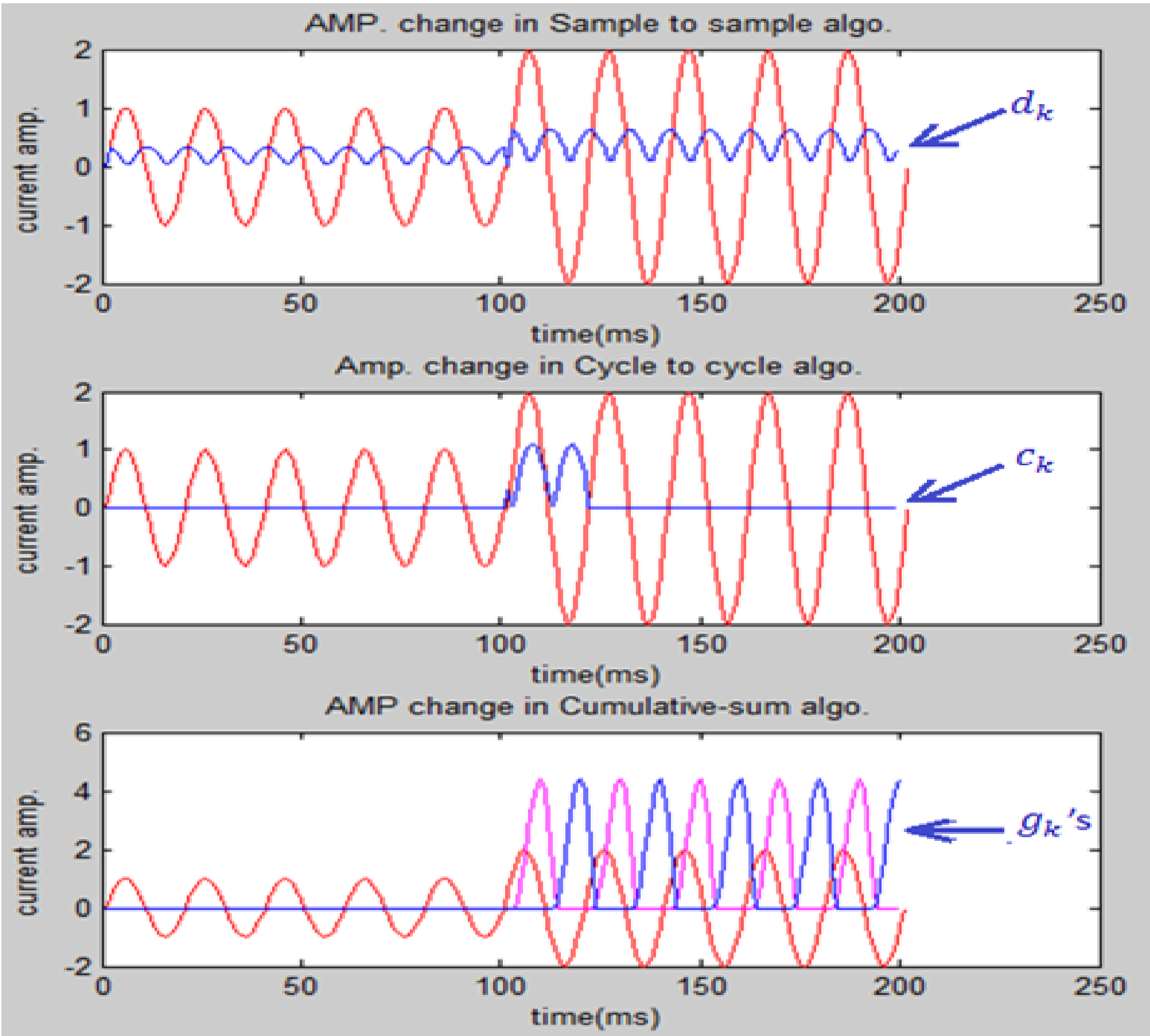


Fig. 3.3: Signal Amplitude changed from 1 amp to 2 amps at 0.1s in all 3 cases

The Sample-to-Sample method needs a higher threshold value for amplitude variation from the nominal as is observed from the values of the index before and after 0.1 s. The cycle-to-cycle approach is also affected significantly for the amplitude change. Also we can see that the $g_k(1)$ and $g_k(2)$ indices of the Cusum approach are influenced by the amplitude variation which is clearly noticed from the Fig. 3.3. This is because the approach uses the peak of the set signal in its processing and as the amplitude exceeds this value fault is detected.

C. Frequency Variation

The algorithms are tested for the deviation in system frequency which is changed to 52 Hz instead of 50 Hz at 0.1s with the other signal parameters remaining the same. Similar to previous simulation results, the indices of all the methods are computed and shown in Fig. 3.4.

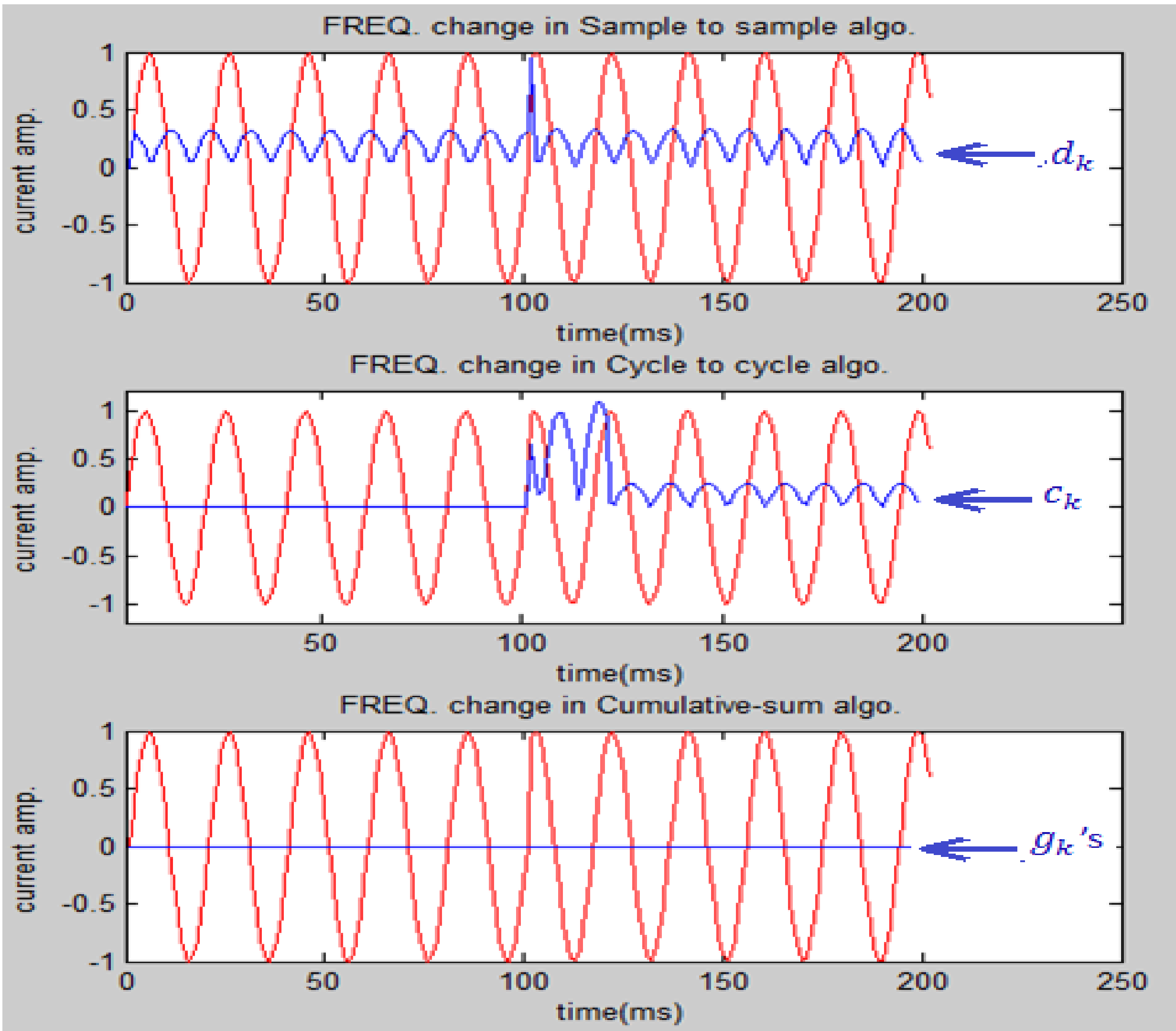


Fig. 3.4: Signal frequency changed from 50 Hz to 52 Hz at 0.1s in all 3 cases

The Sample-to-Sample method needs a higher threshold value for frequency drifting away from the nominal as is observed from the values of the index before and after 0.1 s. The cycle-to-cycle approach is also affected significantly for the frequency change. Both approaches are also similarly affected for the system frequency below the nominal. However, the $g_k(1)$ and $g_k(2)$ indices of the Cusum approach are not influenced by the system frequency drift which is clearly noticed. This is because the approach uses the peak of the set signal in its processing.

D. Noise

A synthesized signal of 50 Hz is considered where from 0.0 to 0.2 s, the signal is purely sinusoidal till 0.1s beyond that it is contaminated by noise (as shown in Fig. 3.5).The parameter v is set to 1.5 for the proposed algorithm.

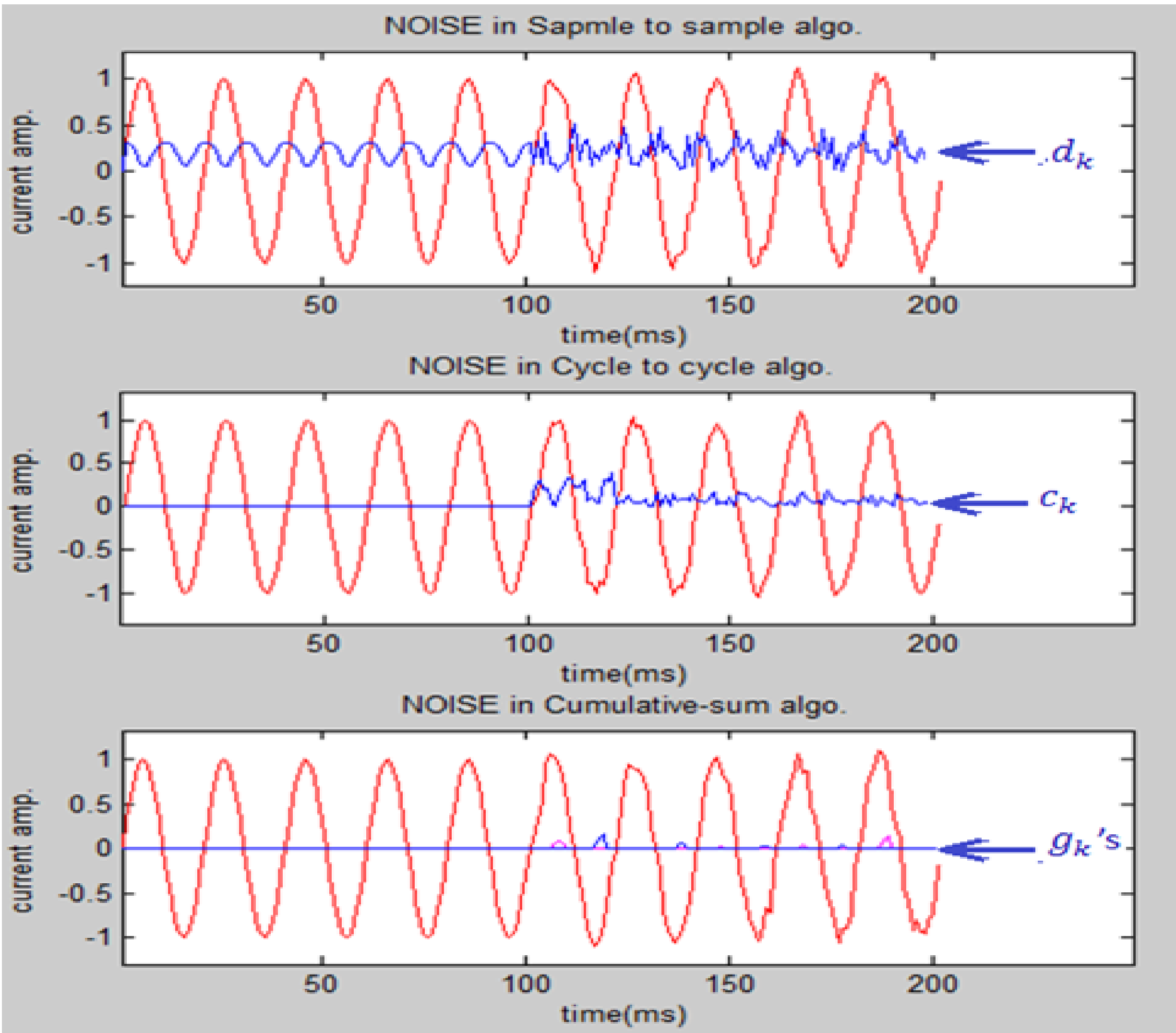


Fig. 3.5: Detection indices for noisy signal after 0.1s in all 3 cases

In a sample-to-sample comparison, the difference [d_k in (2)] for a pure 50-Hz signal is less than that for a noisy signal portion as observed from the Fig. 3.5. The cycle-to-cycle comparison [c_k in (4)] for a 50-Hz pure signal of the difference value is zero whereas it is around 25% of the peak value of the signal for the noisy portion. In both of the aforementioned approaches, the selection of threshold will depend on the noise component. Further, for a higher value of the threshold, an algorithm may miss many faults which is not allowed in critical installations. In

CUSUM case, the $g_k(1)$ and $g_k(2)$ indices are computed for the signal and are shown in the last plot of the figure. It is found that the two indices provide values that are greater than zero intermittently and of lesser strength comparatively. By selecting higher threshold value we can neglect the presence of noise.

Table:-Relative performance of fault detection method viz, cumulative sum, sample-to-sample and Cycle-to-cycle are shown in the following table.

Table. 3.1: Relative performance of fault detection methods

Method	Amp. change	Freq. change	Noise	Load change	Consistency
Sample-to-Sample	Affected	Affected	Affected	Affected	oscillating
Cycle- to-Cycle	Affected	Affected	Affected	Affected	Good
Cumulative Sum	No - effect	No- effect	Least- effect	No - effect	Good

E. Working of cumulative sum algorithm in a single phase system during load change

A 1V, 50-Hz supply system operating at a loading condition and another load was switched on to the system at 0.05s. In this case, the Cumulative sum method is used to detect the faults in system if any. As the load switching cause the current level to increase beyond the threshold value fault is detected as shown in Fig 3.8 at 0.05 second. This is due to the fact that the set peak value of current for relaying is lower than the current peak due to loading in the system. Fig. 3.7 shows the Simulation model of 1V, 50 HZ system. The single line diagram of a single phase 1V, 50 Hz system is shown in Fig. 3.6.

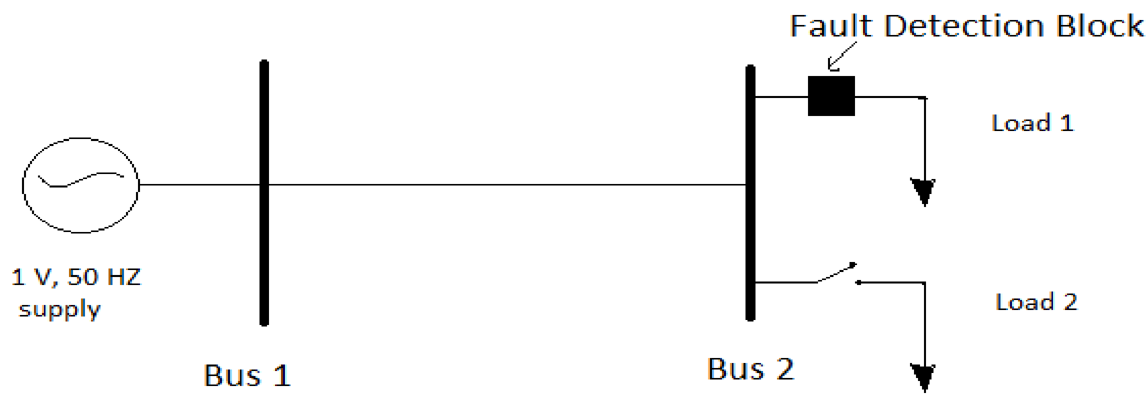


Fig. 3.6: Single line diagram of a single phase system

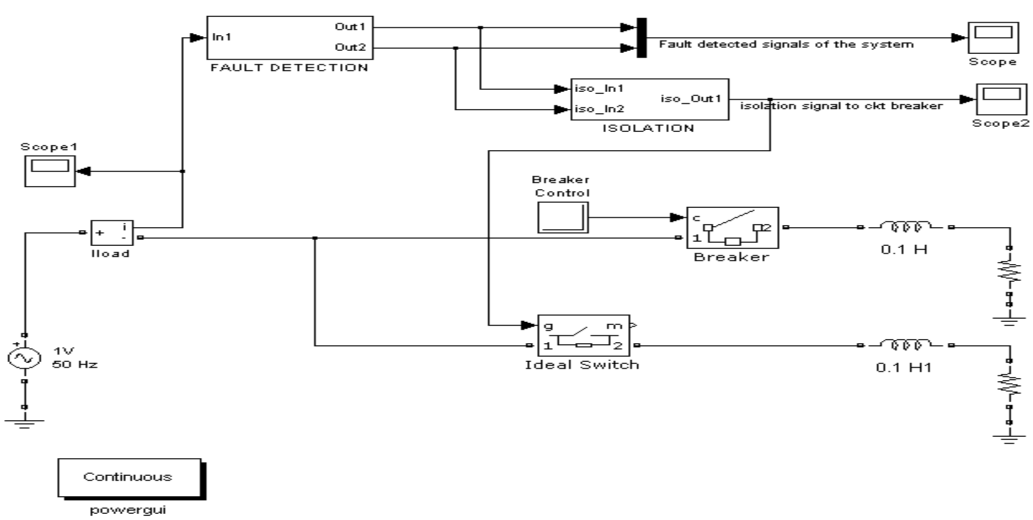
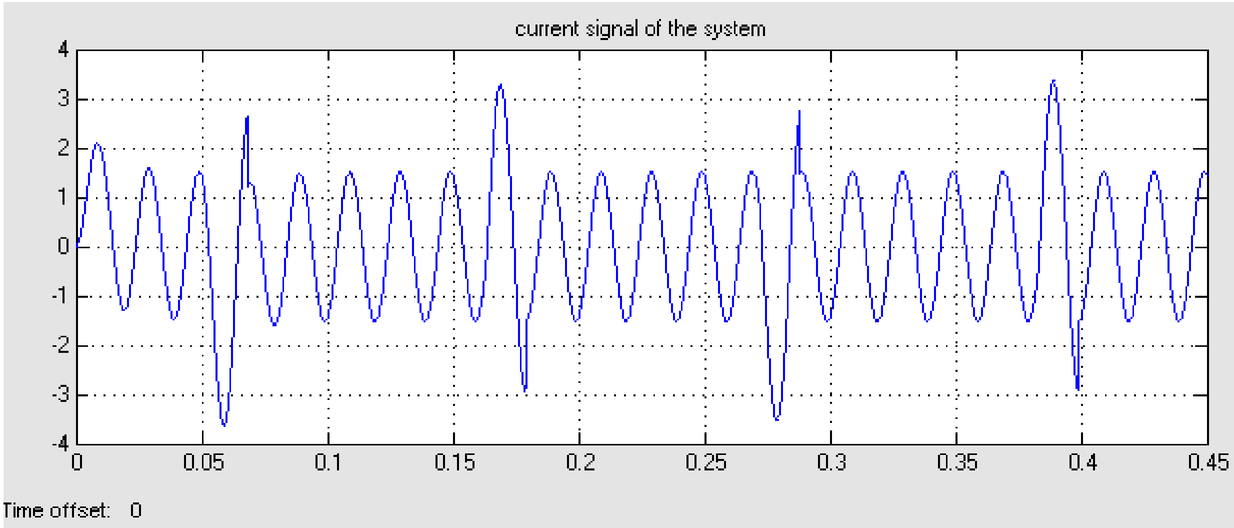
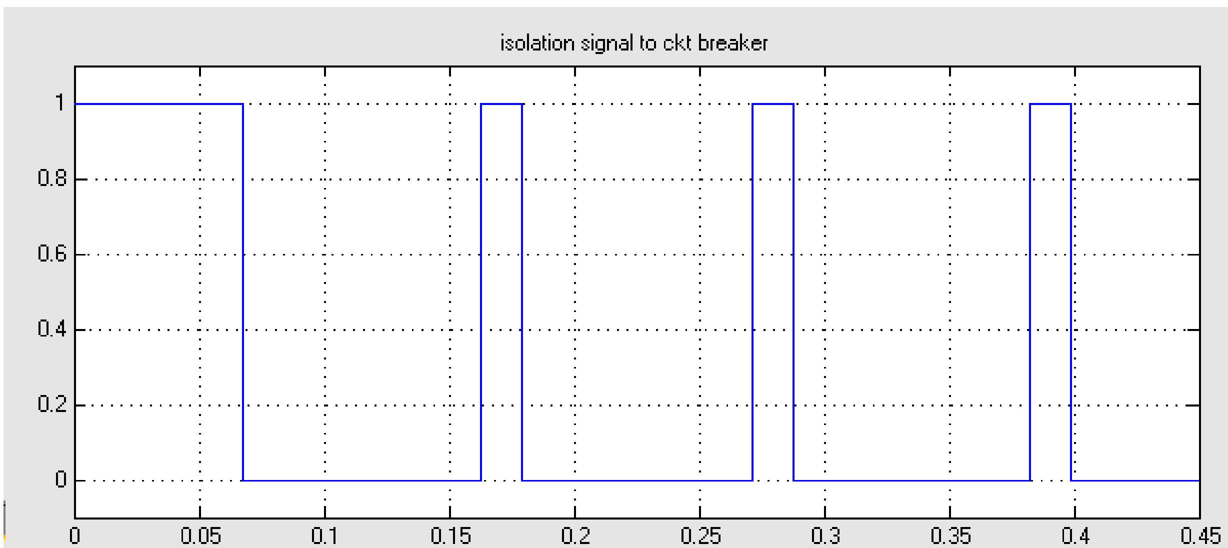


Fig. 3.7: Simulation model for load change



TIME in seconds

a) Current signal flowing through the system.



TIME in seconds

b) Fault detected signal given to the circuit breaker whenever current amplitude exceed above certain value.

Fig. 3.8: Fault detected signals by cumulative sum algorithm for load change

Here load is added to existing circuit which causes current to increase at 0.06 second which is detected by the fault detector subsystem as the current amplitudes exceeds the threshold value and to make system stable some part of the circuit is isolated to bring back the current level to the normal value.

3.5 Summary

The selection of the additional parameter in the Cumulative sum approach ν is simple and important. As mentioned before, it should be same as the peak value or some specified value of relay-setting current. The cumulative summation process and dependency on amplitude of the setting current provide advantages of this method particularly for power system applications where fault current is expected to be much higher than normal current. The response time of the three methods is almost the same as all three works on the consecutive samples of current signal. By adjusting the threshold value h and ν the number of false detections can be reduced.

Chapter 4

Simulation of Cumulative Sum and Power flows

4.1 Introduction

In this project, we use cumulative sum fault detection algorithm and power flows method for detecting faults in a micro grid system. In order to verify the performance of the Cumulative Sum algorithm along with power flow study for digital Fault Detection algorithm, simulation tests of it is performed using Simulink. The first simulation test is done on a three phase 3-bus system to check the working of cumulative sum algorithm for simple radial system. Then Simulation tests for the proposed digital fault detection algorithm comprising of Cumulative sum and Power Flows in micro-grid system is carried out to check the performance of the proposed algorithm.

A detailed simulation studies is done for the following cases:-

1. A three phase 3-bus (radial) system.
2. A 4-bus micro-grid (looped) system.
3. A 4-bus load connected micro-grid (looped) system and
4. A 5-bus micro-grid (looped) system is given in this chapter.

4.2 CASE STUDY 1: 3-Bus Power System

Part A: Implementation of cumulative sum algorithm for Fault Detection in a 3φ power system using Simulink

The experimental performances for the Cumulative-Sum based Fault Detection were conducted on a 3 phase model which composed of a 600 MVA, 13.8 KV synchronous generator supplying power to 100 MW load through transmission line of 50 km in which a load of 100MW is added to the circuit at 0.3 second which makes the Fault Detector block to detect the increase in current level above threshold value and give signal to isolate the circuit to prevent the load to get damaged. In this experiment we can check the performance of Cumulative sum based fault detection to detect fault in the system. The circuit model with implementation of cumulative sum fault detection algorithm in a three phase system is shown in Fig 4.1.

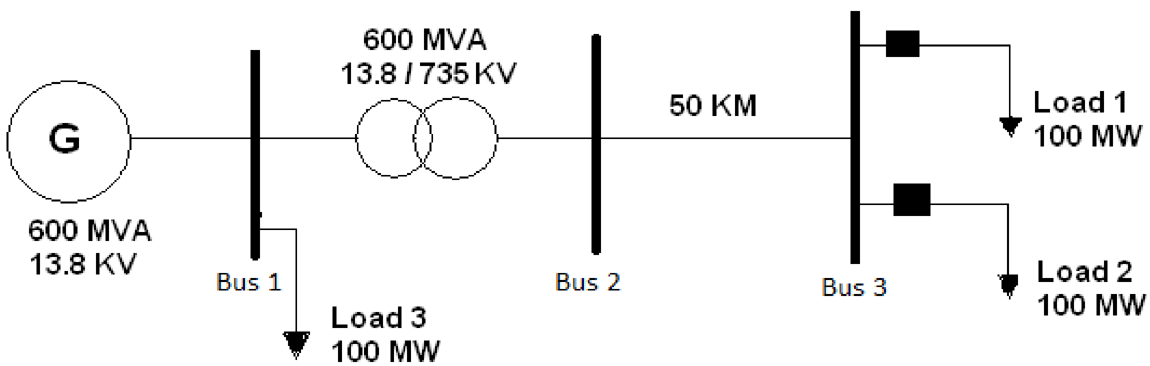


Fig 4.1 Single line diagram of a 3 phase system for fault detection

In above simulation model the black colour block has fault detection block which monitors the current amplitude and if any disturbance or increase in amplitude occurs, Cumulative sum based fault detector will detect the fault and a signal is send to circuit breaker to isolate the load from generator to avoid damage to the other loads. The isolated part (load) after some specified time is then connected to the generator as in normal case and fault is checked again. And if it persists again we will isolate the load from generator to avoid damage. The above process continues for three times and if fault still persist the circuit is tripped permanently (for long time) to prevent further damage to it.

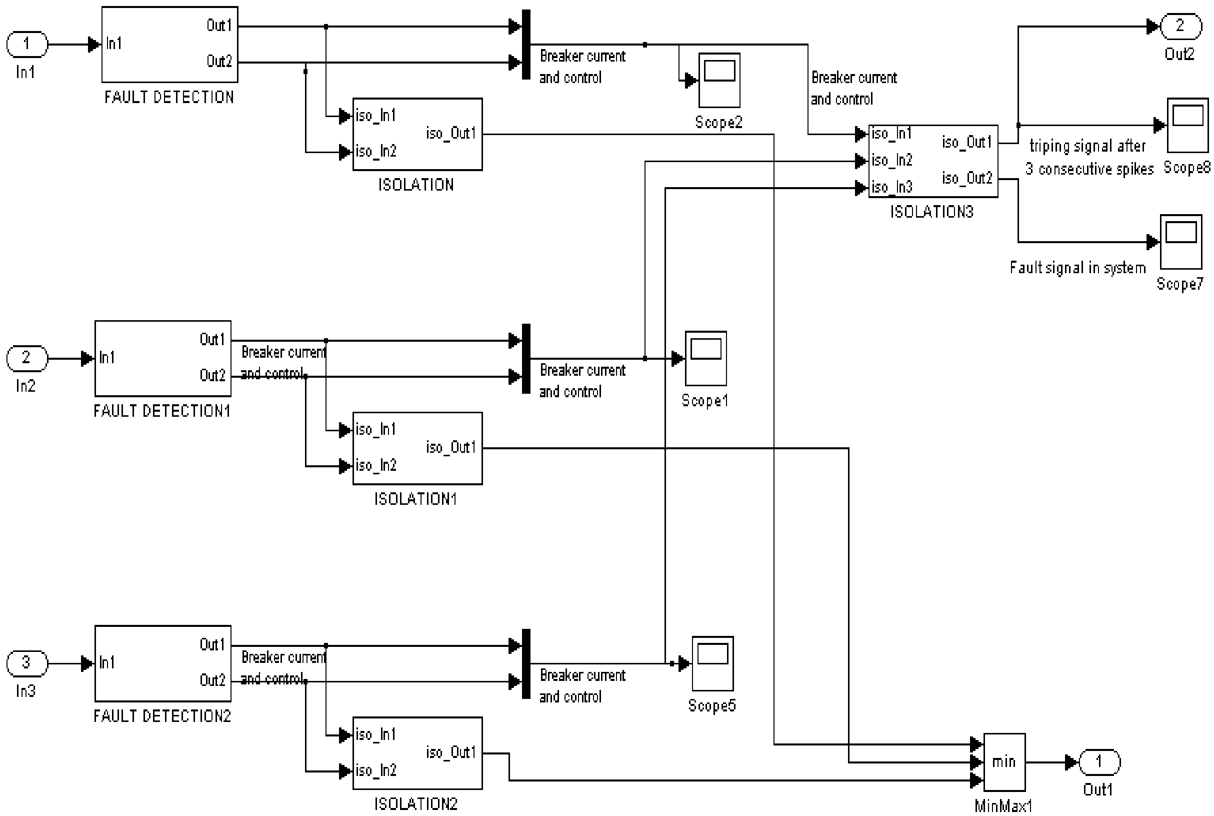


Fig 4.2 Simulink subsystem having Fault Detector and Isolation block

The implementation of the equation of Cumulative sum based fault detector in simulink model is shown in Fig 4.3. In this subsystem model the constant 230 block is representation of threshold value constant. If the input (current amplitude) exceeds beyond 230 level, fault is detected and signal is feed to isolation block to disconnect some part of the system to make system stable.

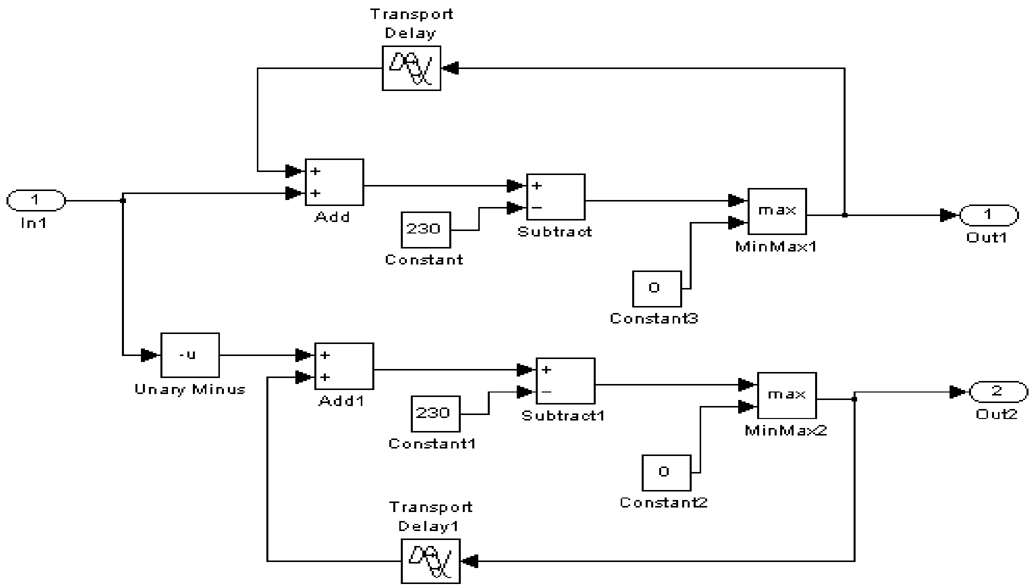


Fig 4.3 Implementation of Cumulative sum fault detection algorithm using simulink blocks

As the Fault is detected then isolation subsystem block is used to isolate some part of the circuit through circuit breaker. Here in this case isolation pertains for 0.04 seconds. The simulink model of isolation subsystem is shown in Fig 4.4.

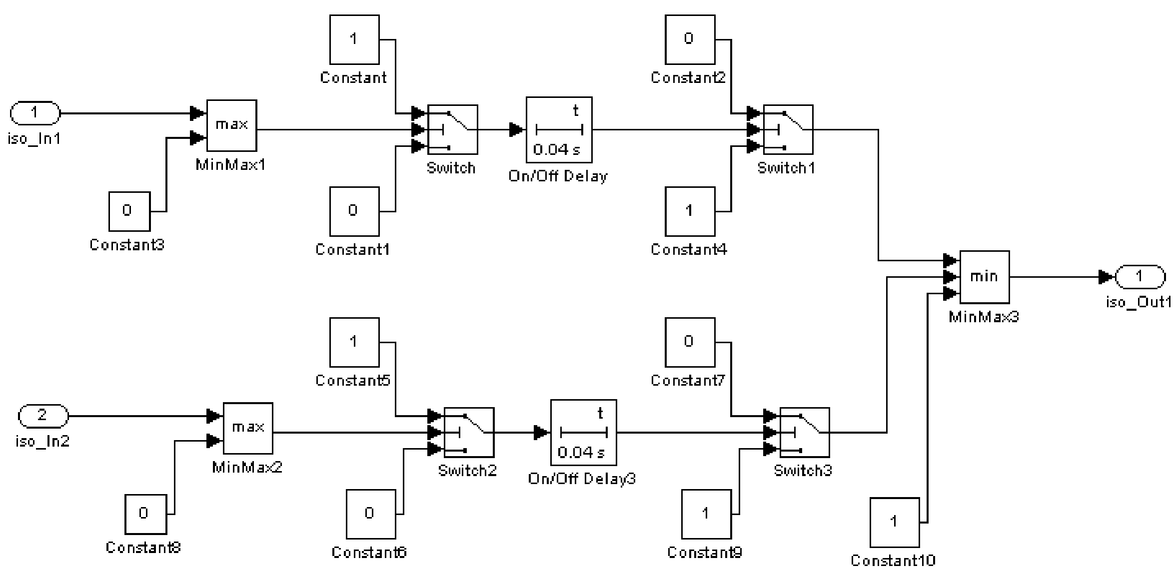


Fig 4.4 Simulink model of an Isolation block

If 3 consecutive faults are detected the system has to be tripped permanently to avoid further damage to the load this is carried out by isolation_3 simulink block model as shown in Fig 4.5.

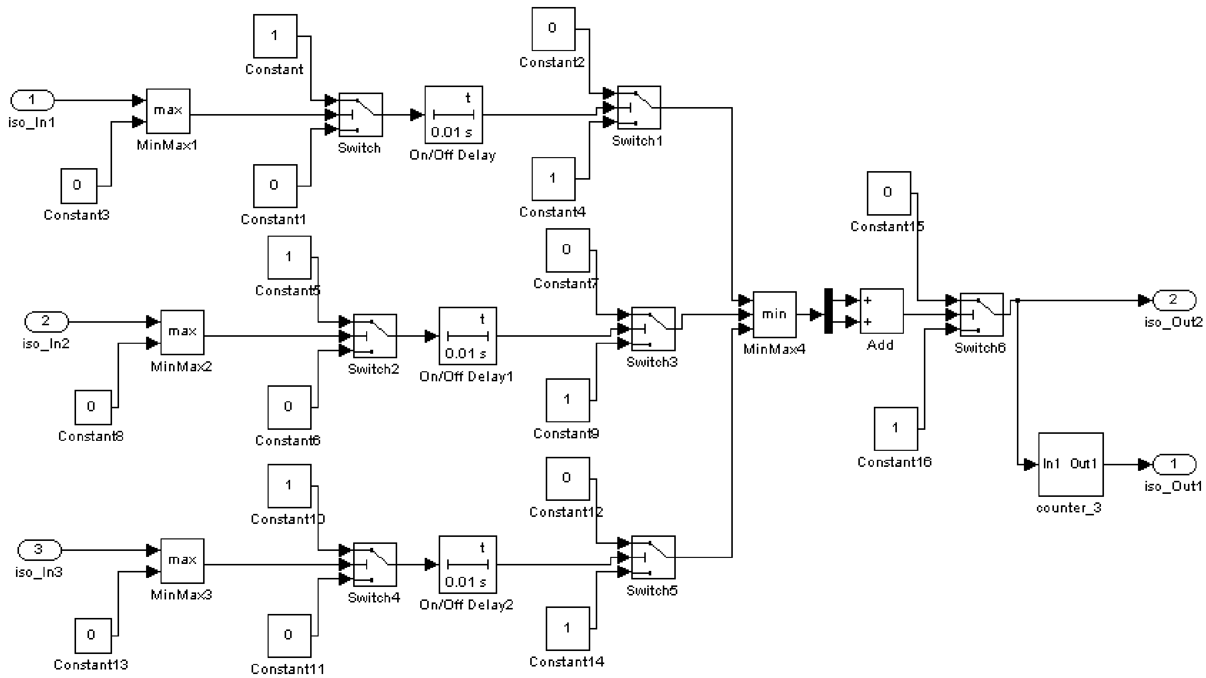
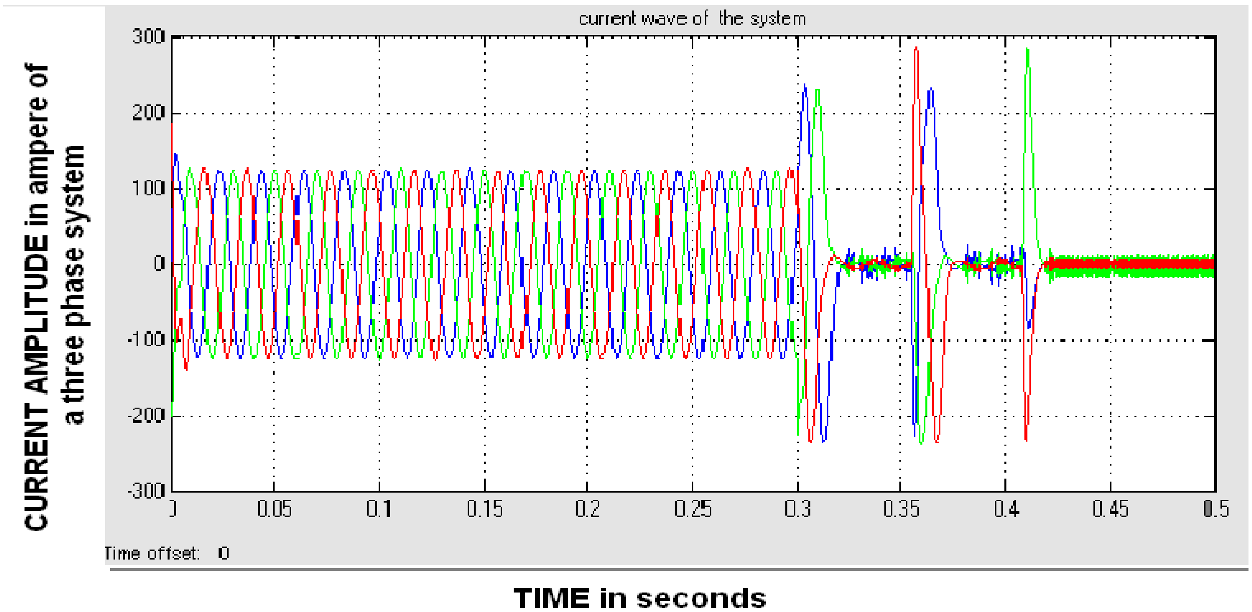


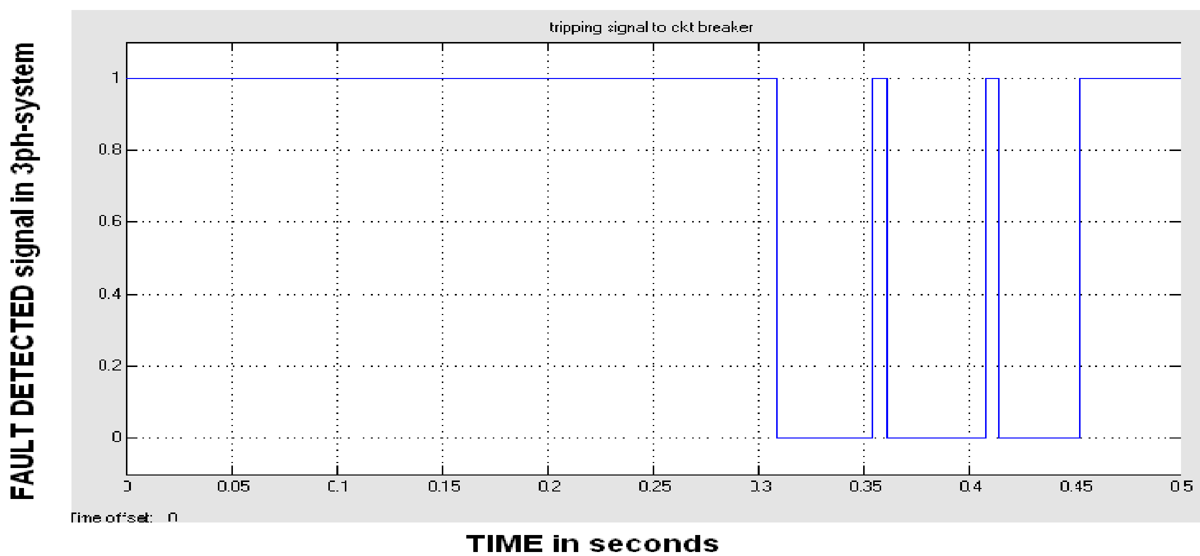
Fig 4.5 Simulation model of Isolation_3 subsystem

Part B : Simulation

The simulation is carried out for 0.5 seconds on a 3 phase model which composed of a 600 MVA, 13.8 KV synchronous generator is supplying power to 100 MW load through transmission line of 50 km in which a load of 100MW is added to the circuit at 0.3 second which makes the Fault Detector block to detect the increase in current level above set-point value and give tripping signal to isolate the load to prevent it. The current amplitude signal and a Fault Detected signal of above system is shown in Fig 4.6.



a) Current waveform of the 3φ, 3-bus power system

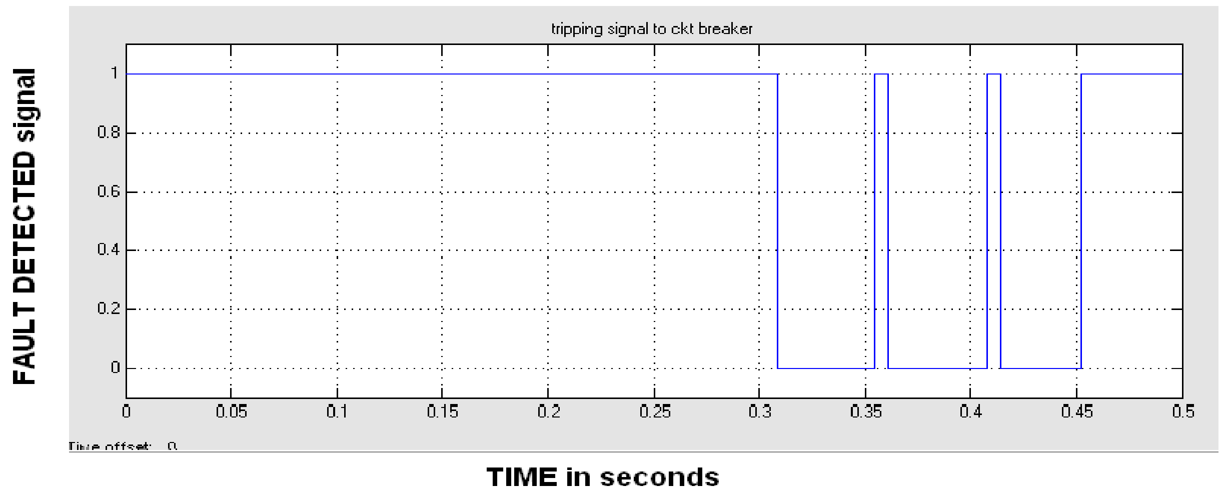


b) Fault detected signal given to circuit breaker to trip the load to maintain stability of the system

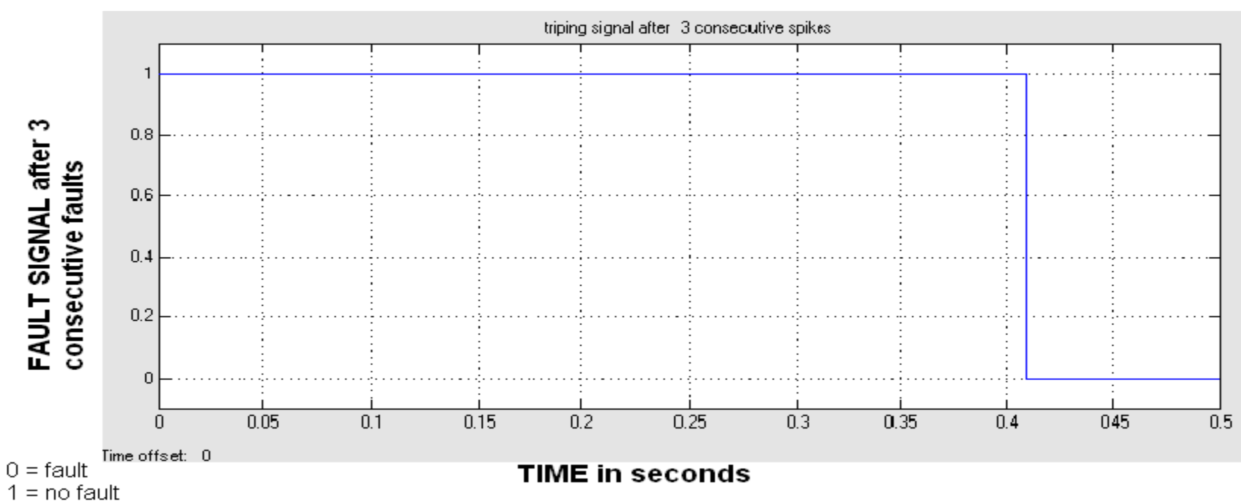
Fig 4.6: Current signal and Fault detected signal of a three phase system

From Fig. 4.6, we can see that fault detection by using cumulative sum based algorithm is much faster and gives tripping signal as fast as possible to circuit breaker to avoid further damage to the system.

Here we can see that a fault is detected at 0.3 seconds when a load is increased causing current level to increase. The load is isolated for 0.04 second after that a load is connected again to circuit to check if the fault persists or not. If fault exist, circuit is tripped again to avoid damage to load. This happen for three times and if the fault pertains we will tripped the circuit permanently (for long duration). In Fig 4.7, fault detected signal and Faulted signal after 3-consecutive fault detected is shown.



a) Fault detected signal given to circuit breaker to trip the load to maintain stability.



b) Fault detection signal after three consecutive faults are detected in the system.

Fig 4.7: Fault detected signal and Faulted signal after 3-consecutive fault detected is shown.

4.3 CASE STUDY 2 : 4-Bus Microgrid System

Part A : Implementation of 4-bus microgrid system.

The experimental performances for the Cumulative-Sum based algorithm and power flow for Fault Detection were conducted on a laboratory micro-grid model which composed of the following components [20]

1) A 208 V, 60 Hz supply (the utility grid);

2) A 2.5 kVA, 4-pole, 208 V synchronous generator (HU);

3) A 1.8 kVA, 4-pole, 208 V synchronous generator (HU);

4) Two 1.8 kW Y-connected resistive loads;

The operating voltage of the laboratory micro-grid was set for one level, which is 208, in order to match the grid voltage. The single line diagram of above 4-bus micro-grid system is shown in Fig 4.8.

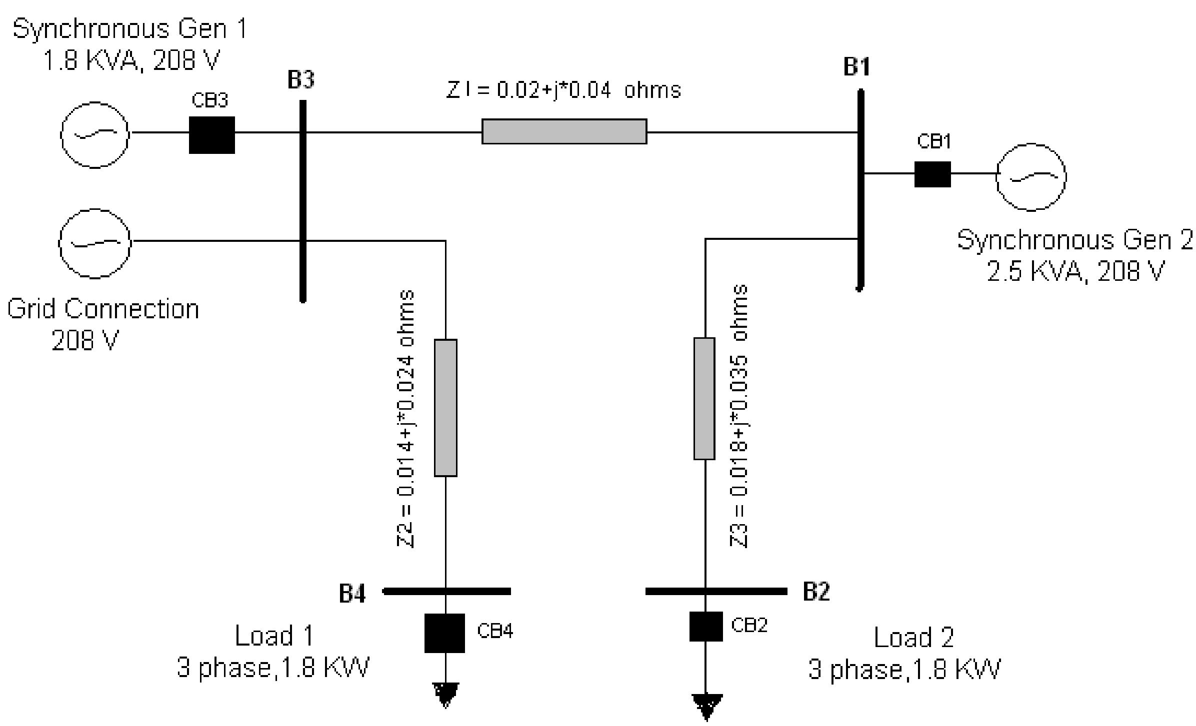


Fig 4.8 : Single line diagram of a 4-bus micro grid system

In above 4-bus micro-grid system voltage will be same in all 4 buses therefore, we will monitored current signal amplitudes waveforms as during fault current will change drastically. The threshold value (provide low pass filtering effect) is chosen to be 28 amperes so whenever the current amplitude exceeds beyond 28 amperes a fault is detected by Fault Detection subsystem Block as shown in Fig 4.9.

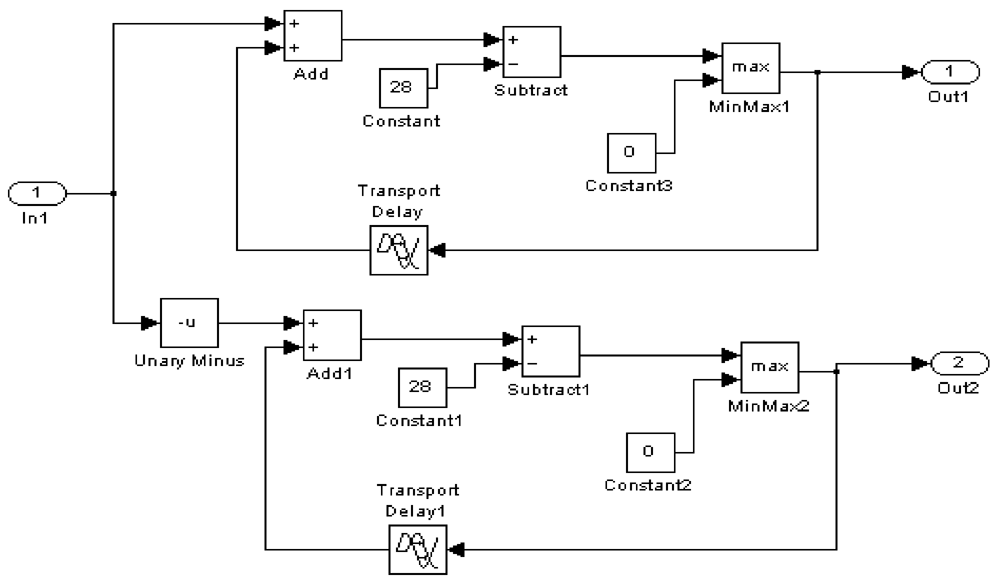


Fig 4.9 : Simulink subsystem for Fault Detection

Now in micro-grid system, if the Fault occurs near load bus the fault detection block near faulted load bus and all generator buses will detect the similar current transient waveform i.e. increase in current amplitudes. As only one load bus is showing the disturbed current waveform the area near to that bus is tripped immediately to avoid damage in other areas. But if a fault occurs near one of the generator bus then the fault detection block near all generator bus will shows same transient effect (Due to micro-grid structure). So to figure out where exactly the fault occurs among the generator buses we need little more than the Cumulative sum Fault detection algorithm, we will use idea of Power Flow study to find out the exact location of fault in a micro-grid system. By monitoring the power flows between generator buses we can figure out the actual location of fault as faulted generator bus will take in high amount of current from other generator buses. The Flow Chart of the proposed fault detection algorithm is shown in Fig.4.10.

During faults the theta θ value (voltage angle) of each generator bus will change which we are using to find out the direction and the amount of Power Flows in them. If this theta (θ) difference i.e. power flow values are beyond the specified range and direction we can figure out the exact location of the fault in a micro-grid system.

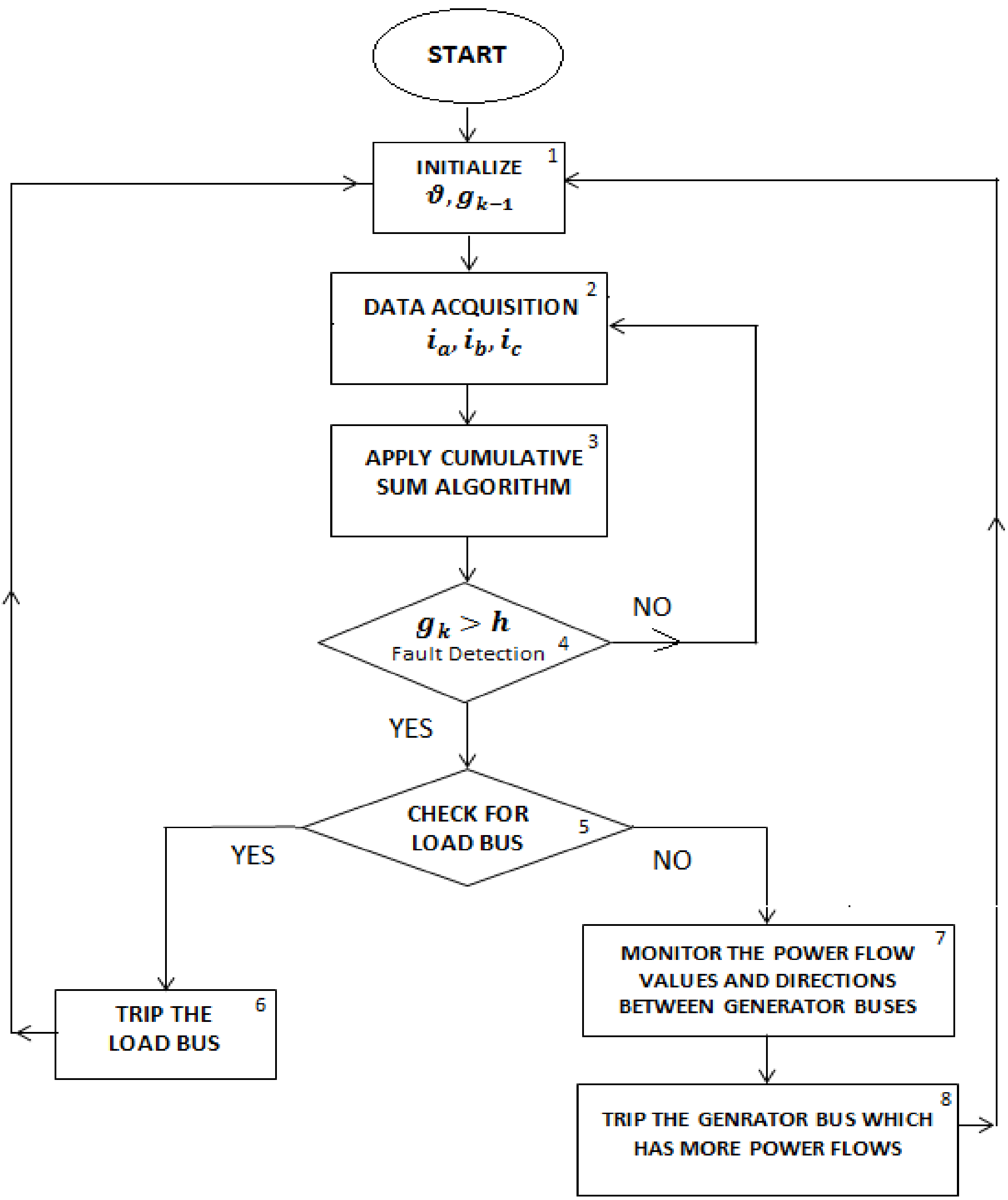


Fig. 4.10 : Flow chart of the proposed algorithm for fault detection in Microgrid

1. : Initialization of ϑ, g_{k-1} for Cumulative sum Fault detection algorithm
2. : Data Acquisition of every connecting line of a Micro grid system
3. : Applying Cumulative sum Fault Detection algorithm for detecting faults in the system in all 3 phases.
4. : Monitor the Fault Detection condition $\mathrm{g_k} > \mathrm{h}$, if it is satisfied then check whether it is a load bus else continue the process of data acquisition.
5. : Check whether the faulted bus is load bus or not. If it is load bus then tripped else trip generator bus
6. : Tripped that specific load bus which has fault detection signal near it.
7. : Monitor the power flows and direction between generator buses
8. : Tripped the generator bus which has more power flows in to it.

Part B : Simulation test of 4-bus micro-grid system.

In this case the θ_{13} (theta difference) between buses 1 and 3 is 0.021 in grid connection mode and also in islanded mode in normal state (without faults). The threshold values for detecting fault location in case of generator faults in this case are '0.055' and '-0.08' for generator bus 1 and 3 respectively. Fig. 4.8 shows the single line diagram of a 4-bus micro-grid system. The waveforms (current) for various fault condition are shown in Fig. 4.11 to Fig 4.16.

1. Grid connection and disconnection

The grid is connected to micro-grid system through bus 3 at 0.1 second (initially in islanded mode). The 3φ current waveform of all 4-buses for grid connection mode is shown in Fig 4.11.

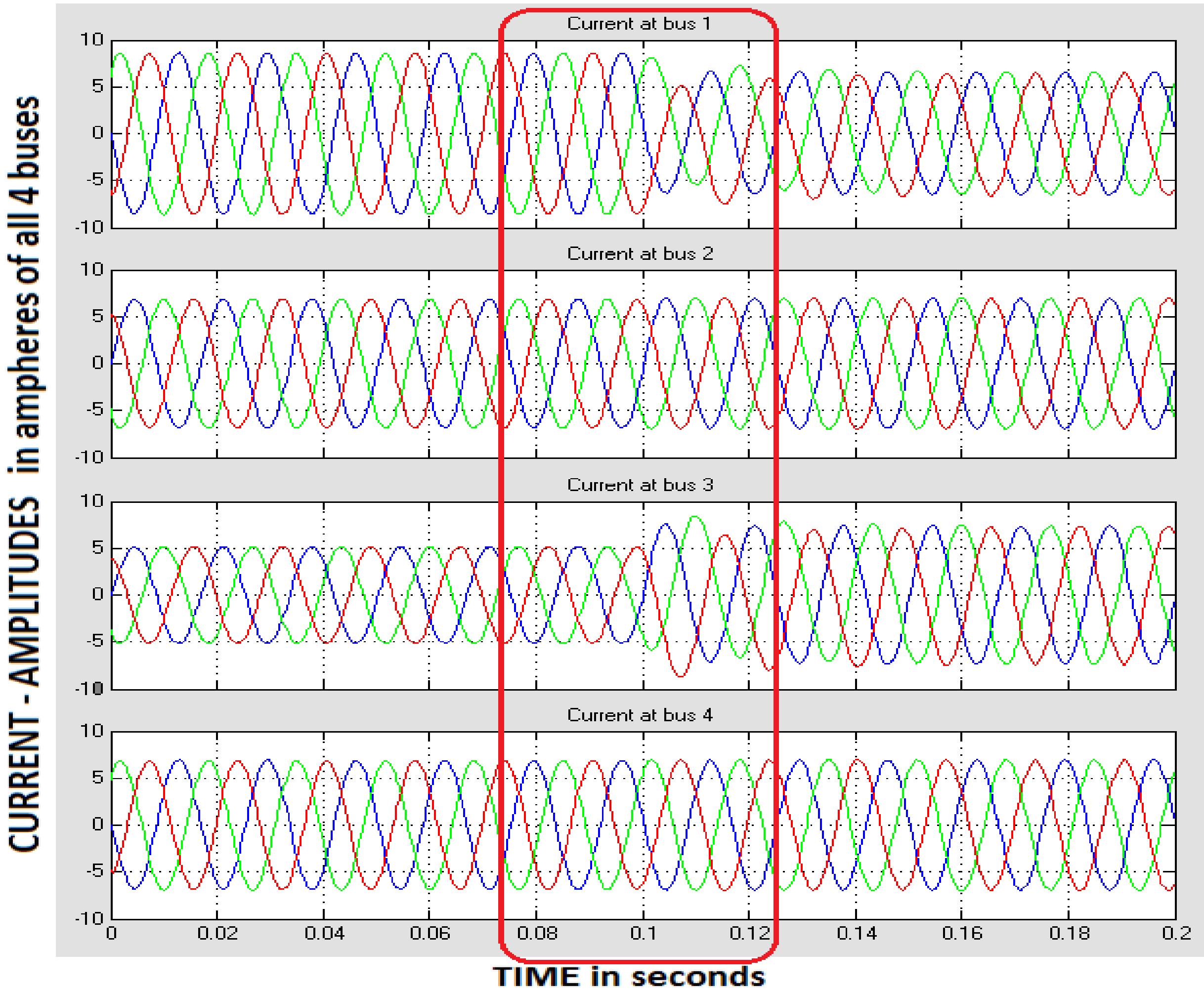


Fig 4.11: Grid connection to micro-grid at 0.1 second

After grid connection we can see some transient disturbance at all buses and current level at bus 1 decreases and that of bus 3 increases to maintain same voltage in system.

2. 3 phase-to-ground fault at bus 1 with grid connection.

Fig.4.12 shows the current waveform of all 4-buses when a 3-phase-to-ground Fault is created at bus 1 in present of grid connection to micro-grid.

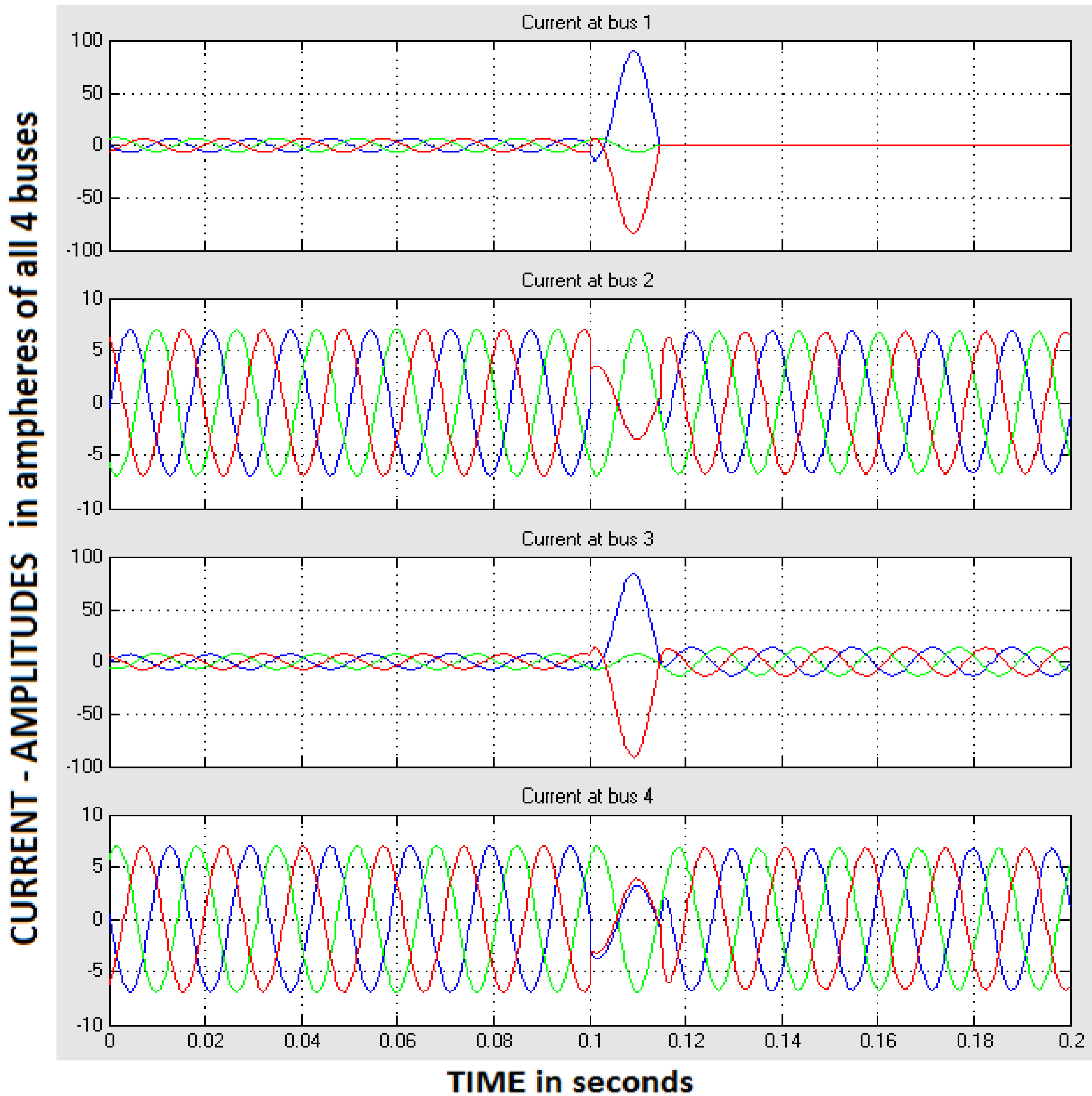


Fig 4.12: Current waveform during 3phase-to-ground Fault at bus 1

Due to the fault at gen. bus, the current wave-form at both the generator bus increases and has same transient effects (due to micro-grid structure). By monitoring the θ_{13}, between bus 1 and 3 we can figure out the change in magnitude and direction of power flows in it. In this case the θ_{13} is greater than 0.06 degrees so we can say that a fault is occurred at bus 1 as more amount of current flows from bus 3 to bus 1.

3. 3 phase fault at bus 2 with grid connection

A 3 phase-to-ground fault is occurred at bus 2 in present of grid connection at 0.1 sec. Fig 4.13 shows the current waveform signal which detects the fault at bus 2 (load bus).

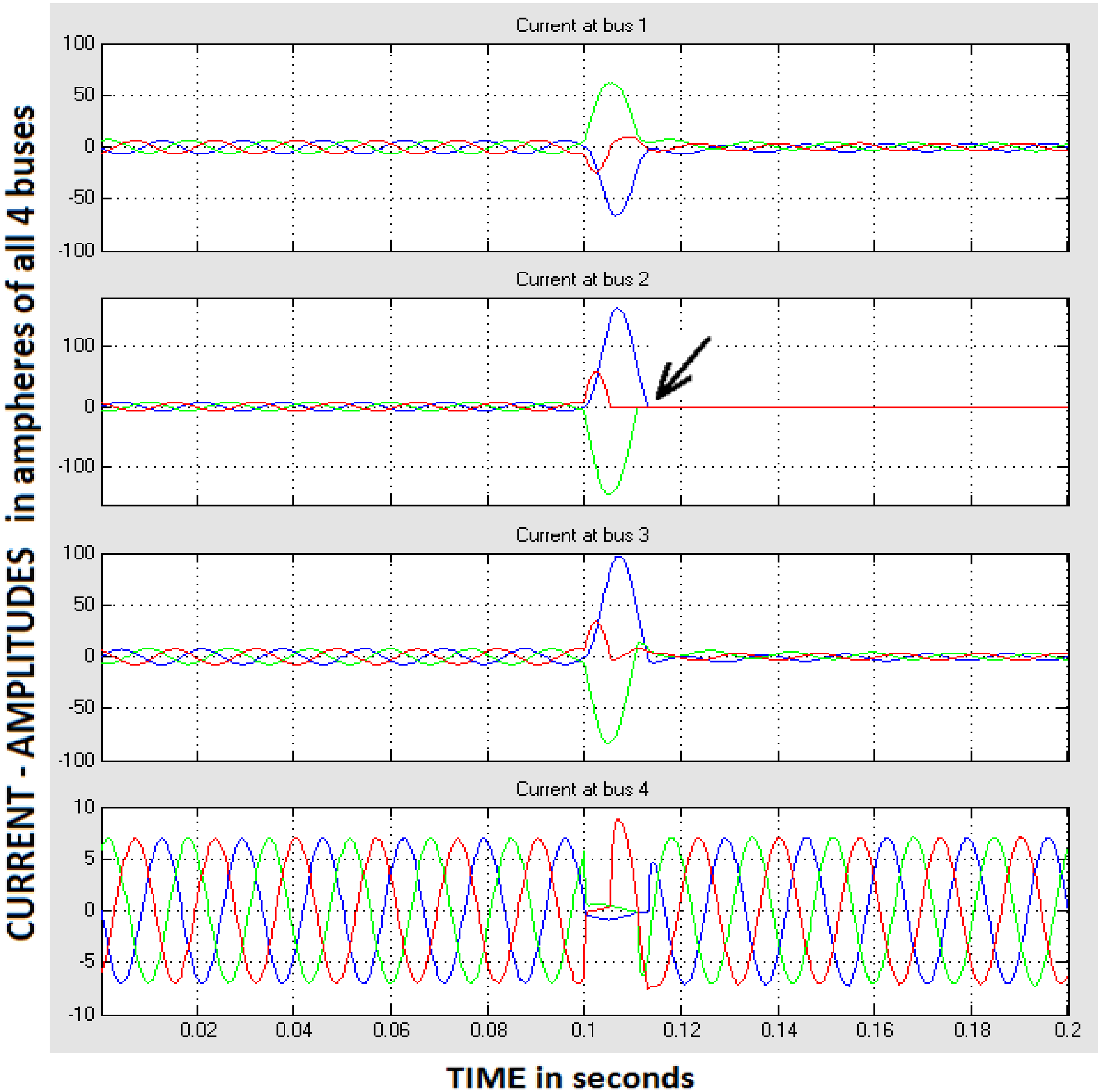


Fig 4.13: Current waveform during 3phase-to-ground Fault at bus 2

We can note from the plot that whenever there is a fault near load bus, current transients waveform can be detect at all generator bus and faulted load bus alone. Therefore by introducing some delay in generator bus fault detection algorithm, fault signal detected near load bus can be distinguished from generator bus fault signal. And the load at bus 2 is tripped immediately to avoid further damage to the system.

4. 2 phase fault at bus 4 in autonomous mode of operation

Phase A -to- Phase B (line-line) fault is created near bus 4 in islanded mode of micro-grid. From Fig 4.14 it is clear that fault is occurred and is detected at bus 4 which is a load bus.

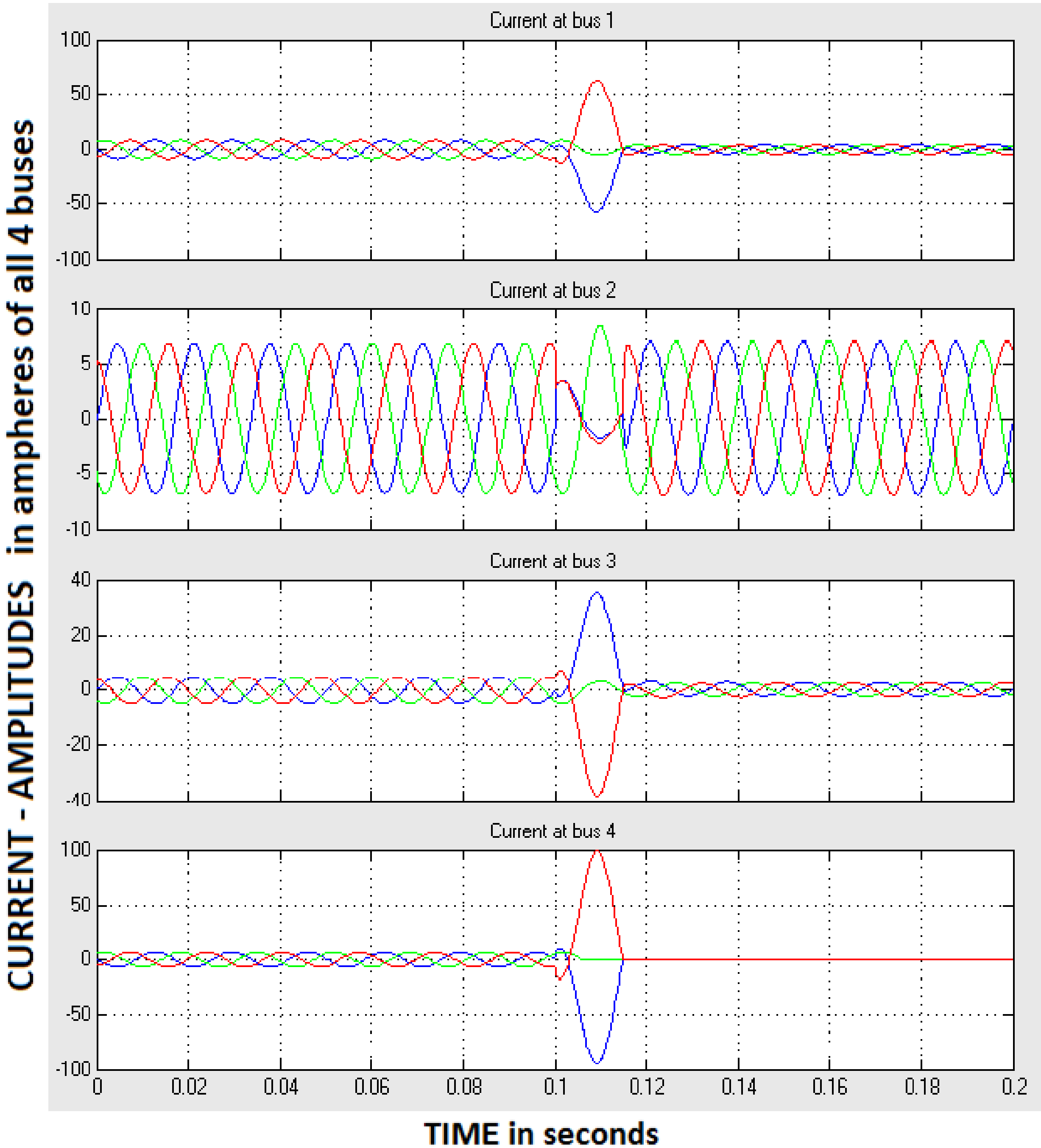


Fig 4.14: Current waveform during 2 phase Fault at bus 4

Here in 2 phase fault we can see that phase A and phase B current waveform become abruptly high from the normal current levels.

The Fault detected signal during 2 phase fault at bus 4 is shown in Fig. 4.15. From the fig. 4.15 we can see that as the threshold value is taken as 28 amperes, as soon as the current amplitude is greater than 28 ampere, fault is detected and signal is given to circuit breaker to isolated the defected region at bus 4.

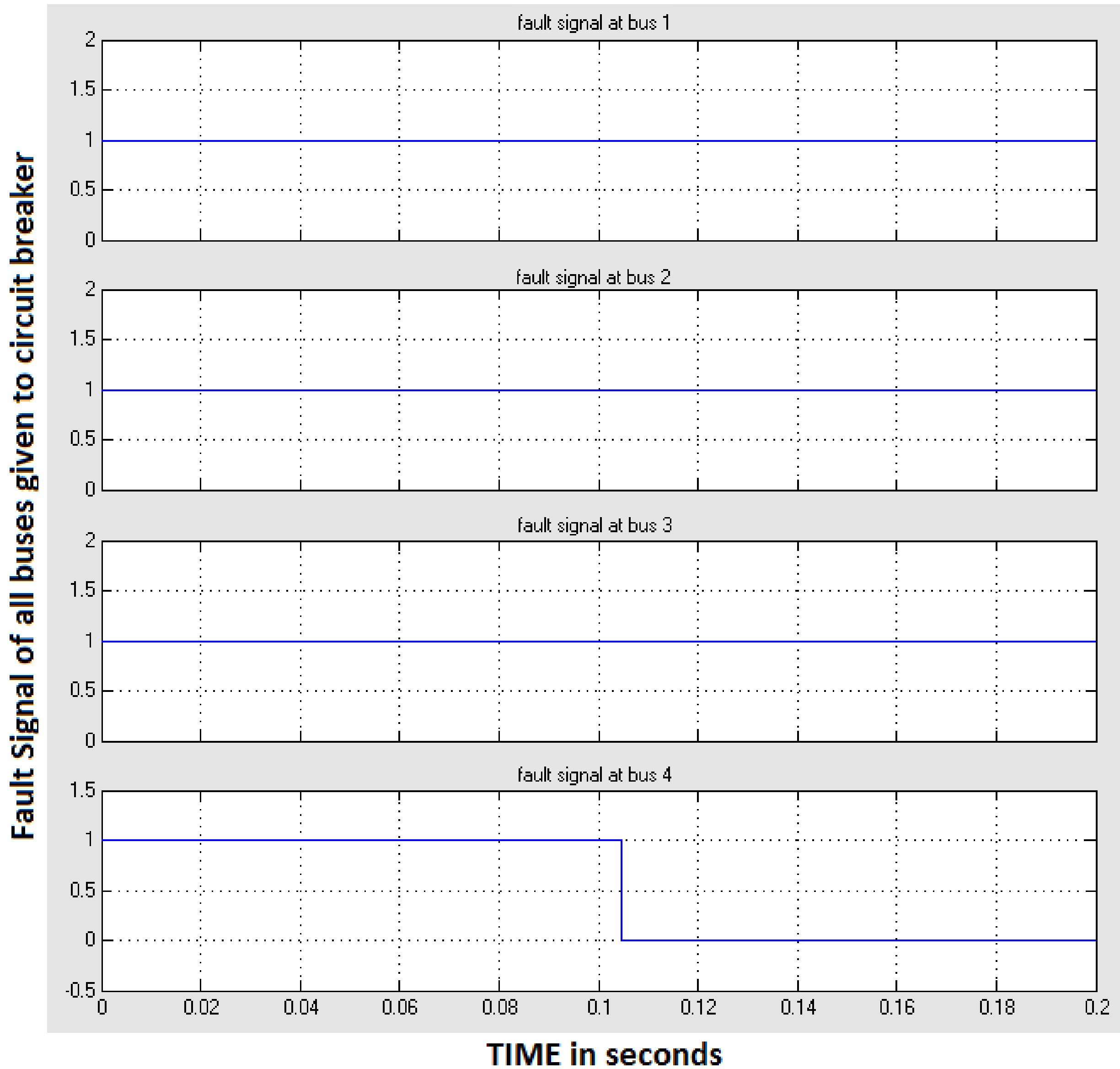


Fig 4.15: Fault detected signal during 2 phase Fault at bus 4

5. 1 phase to ground fault at bus 3 with grid connection

Fig 4.15 shows the current waveform when a single phase A-to-ground fault is occurred near bus 3 (generator bus) in present of grid connection at 0.1 second.

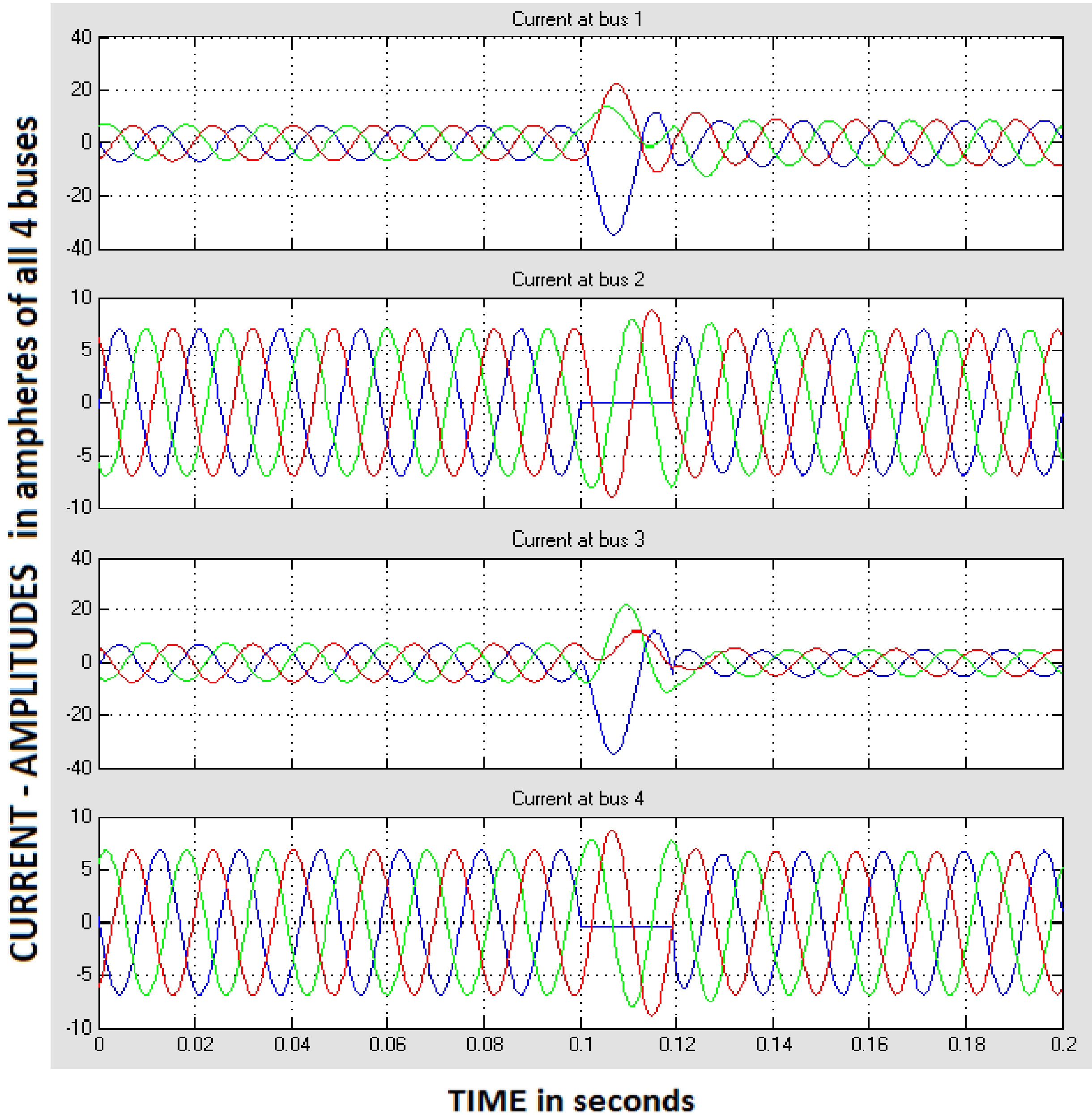


Fig 4.16: Current waveform during 1phase-to-ground Fault at bus 3

From Fig 4.16 we can see that after fault is detected near bus 3, current supply from bus 1 increase to meet the requirement of loads. Also current signal from bus 3 will not be zero as grid is still connected to micro-grid from bus-3 only the generator which is connected through bus 3 to micro-grid is isolated due to fault in it.

6. Voltage plots when a 2 phase fault occurred at bus 1

Fig 4.17 shows the voltage waveform when a fault between phase A-to- phase B is created near bus 1. We can see that even after fault is detected and defected area is isolated, the voltage remains same due to micro-grid characteristics.

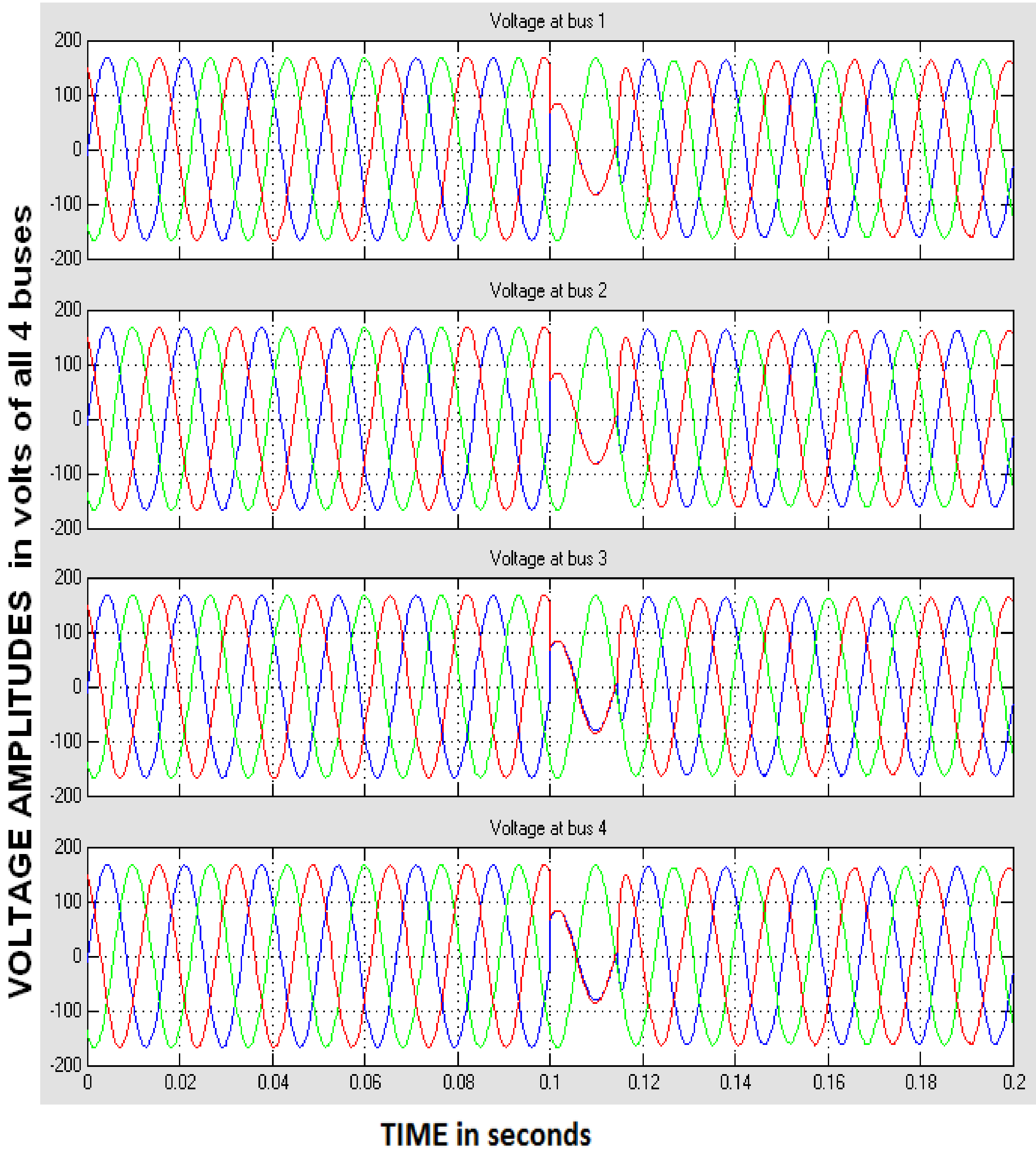


Fig 4.17: Voltage waveform during 2phase Fault at bus 1

4.4 CASE STUDY 3 : 4-bus Load Connected Micro-grid System

Part A : Implementation of 4-bus load connected microgrid system

The experimental performances for the Cumulative-Sum based algorithm and power flows for Fault Detection were conducted on a laboratory micro-grid model which composed of the following components (same as before but configuration is changed)

1) A 208 V, 60 Hz supply (the utility grid);

2) A 2.5 kW, 4-pole, 208 V synchronous generator (HU);

3) A 1.5 kW, 4-pole, 208 V synchronous generator (HU);

4) Two 1.8 kW Y-connected resistive loads;

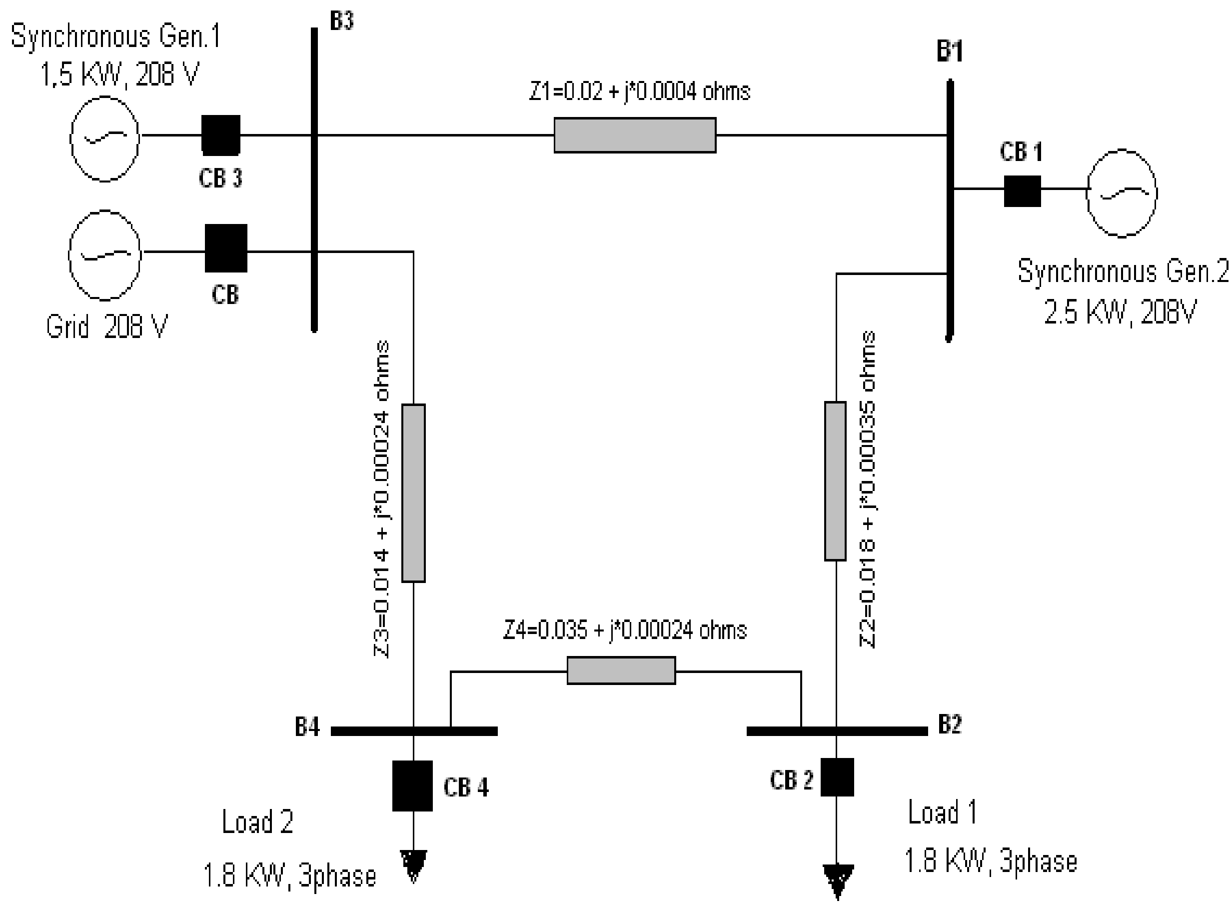


Fig 4.18 : Single line diagram of a 4-bus load connected micro grid system

The operating voltage of the laboratory micro-grid was set for one level that is 208, in order to match the grid voltage. The single line diagram of above 4-bus load connected micro-grid system is shown in Fig 4.18.

In this case, as the configuration of the system changes its theta value i.e. power flow between generators buses will also changes. This causes the threshold value (theta θ_{13} range) for fault detection to change to new value. Rest of the fault detection and isolation model is same for this configuration.

Part B : Simulation test of 4-bus load connected micro-grid system.

In this case the theta (θ) values of all buses will change as configuration changes. Due to connecting load bus 2 and 4, theta (1-3) θ_{13}changes to 0.002 in normal state (without fault). So the new threshold value for detecting fault location in case of generator faults are '0.06' and '-0.06' for generator bus 1 and 3 respectively in both grid connected and islanded mode. Fig. 4.18 shows the single line diagram of a load connected 4-bus micro-grid system.

1. 1 phase to ground fault at bus 3 in grid connected mode.

Fig 4.19 shows the current waveform when a single phase A-to-ground fault is occurred near bus 3 (gen. bus) in present of grid connection at 0.1 second.

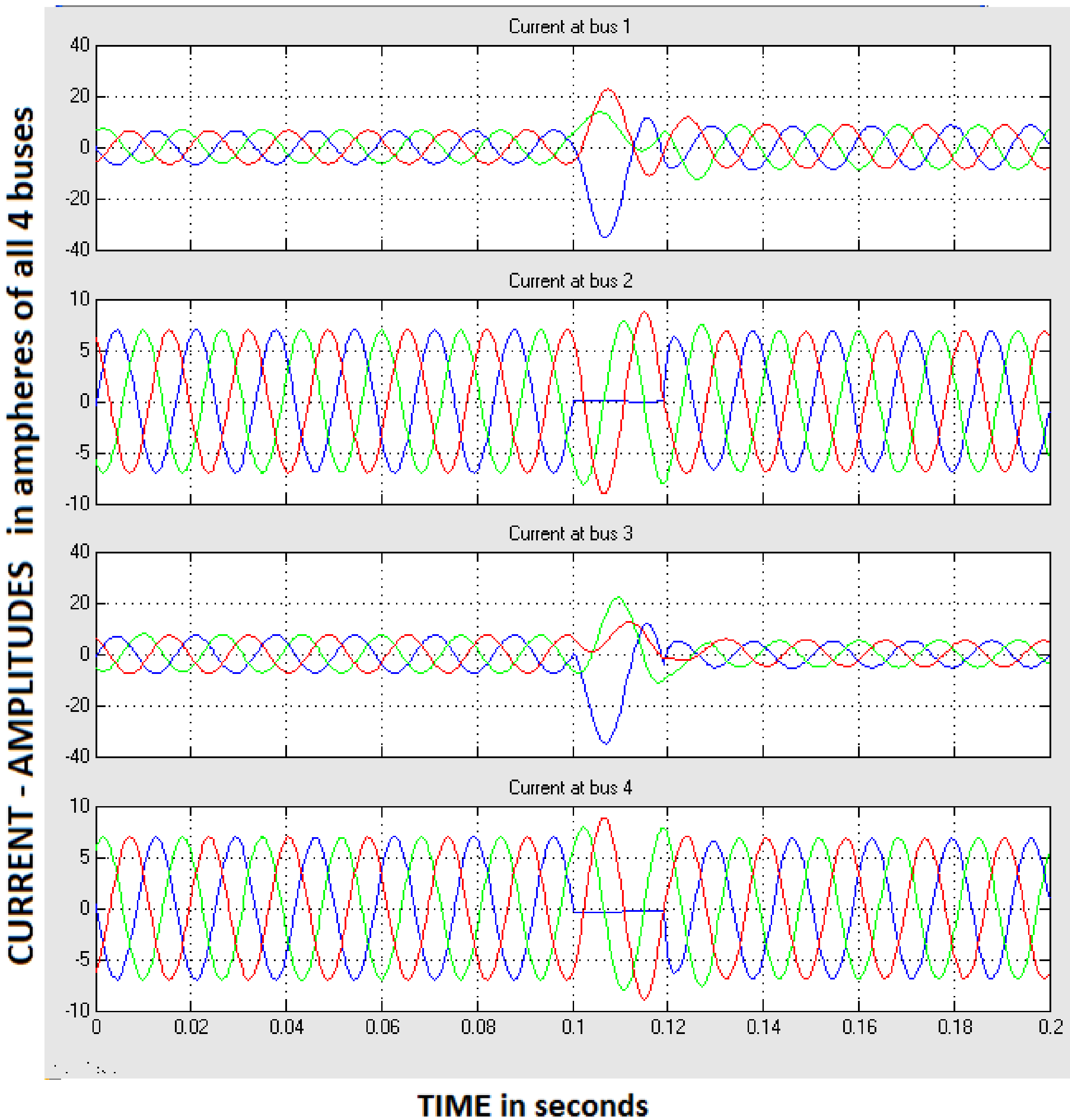


Fig 4.19: Current waveform of SPG fault at bus 3 in grid connection mode.

From Fig 4.19 we can see that after fault is detected near bus 3, current supply from bus 1 increase to meet the requirement of loads. Also current signal from bus 3 will not be zero as grid is still connected to micro-grid from bus-3 only the generator which is connected through bus 3 to micro-grid is isolated due to fault in it.

2. 2 phase fault at bus 1 in islanded mode

Phase A-to-Phase B fault is created near generator at bus 1 in islanded mode of the micro-grid at bus 3.

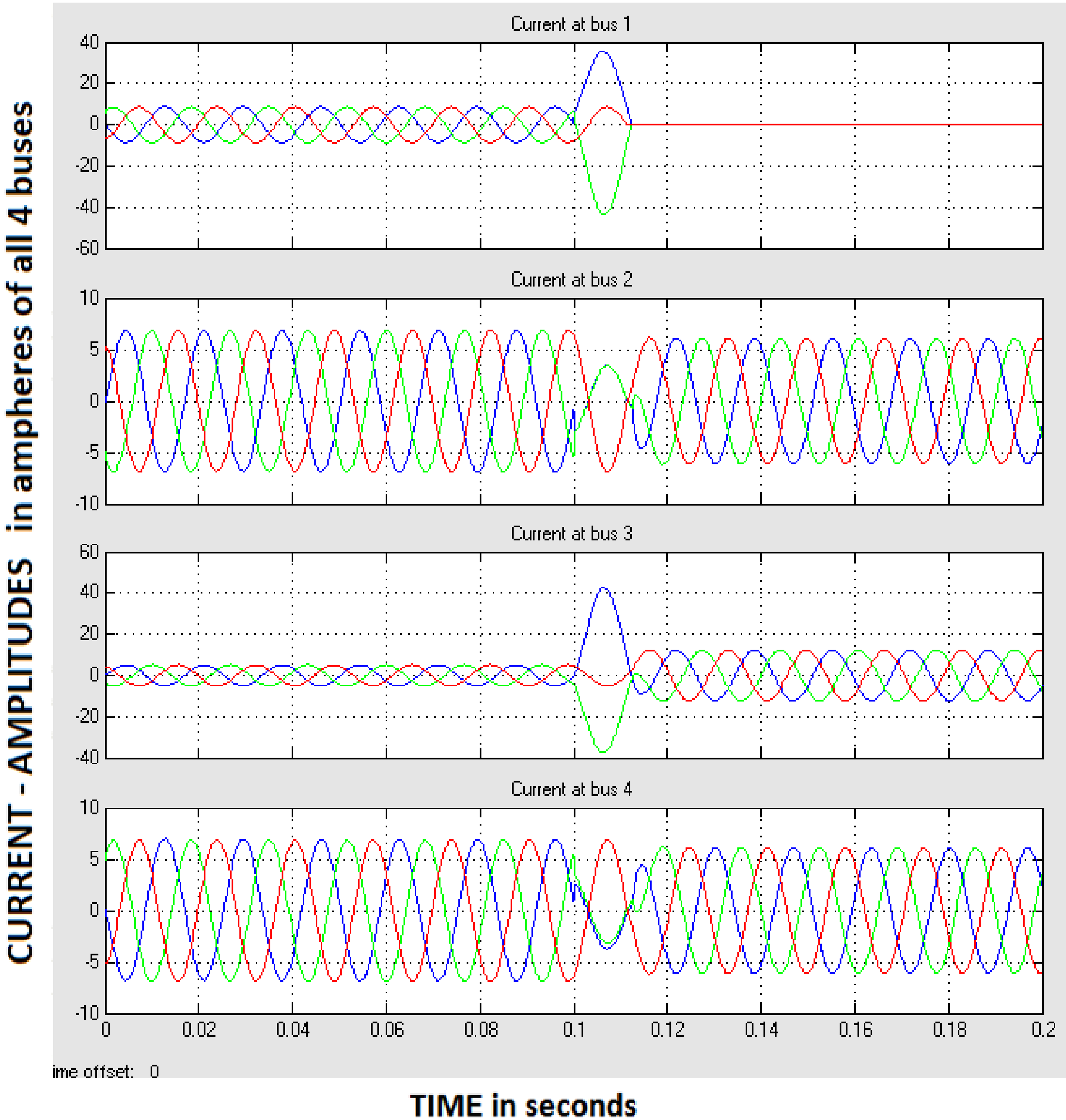


Fig 4.20: Current waveform of 2phase fault at bus 1 in islanded mode

From Fig 4.20 it is clear that fault is detected at bus 1 which is a generator bus. Here in 2 phase fault we can see that phase A and phase B current become abruptly high from the normal current levels. By monitoring the θ_{13}, we can figure out exact location of fault, in this case the value of θ_{13} is greater than +0.06 which tells that fault is near bus 1.

The fault detected signal during 2 phase fault at bus 1 is shown in fig 4.21, where we can see that as soon as the current signal goes higher than 28 amperes a fault is detected and tripping signal is given to circuit breaker.

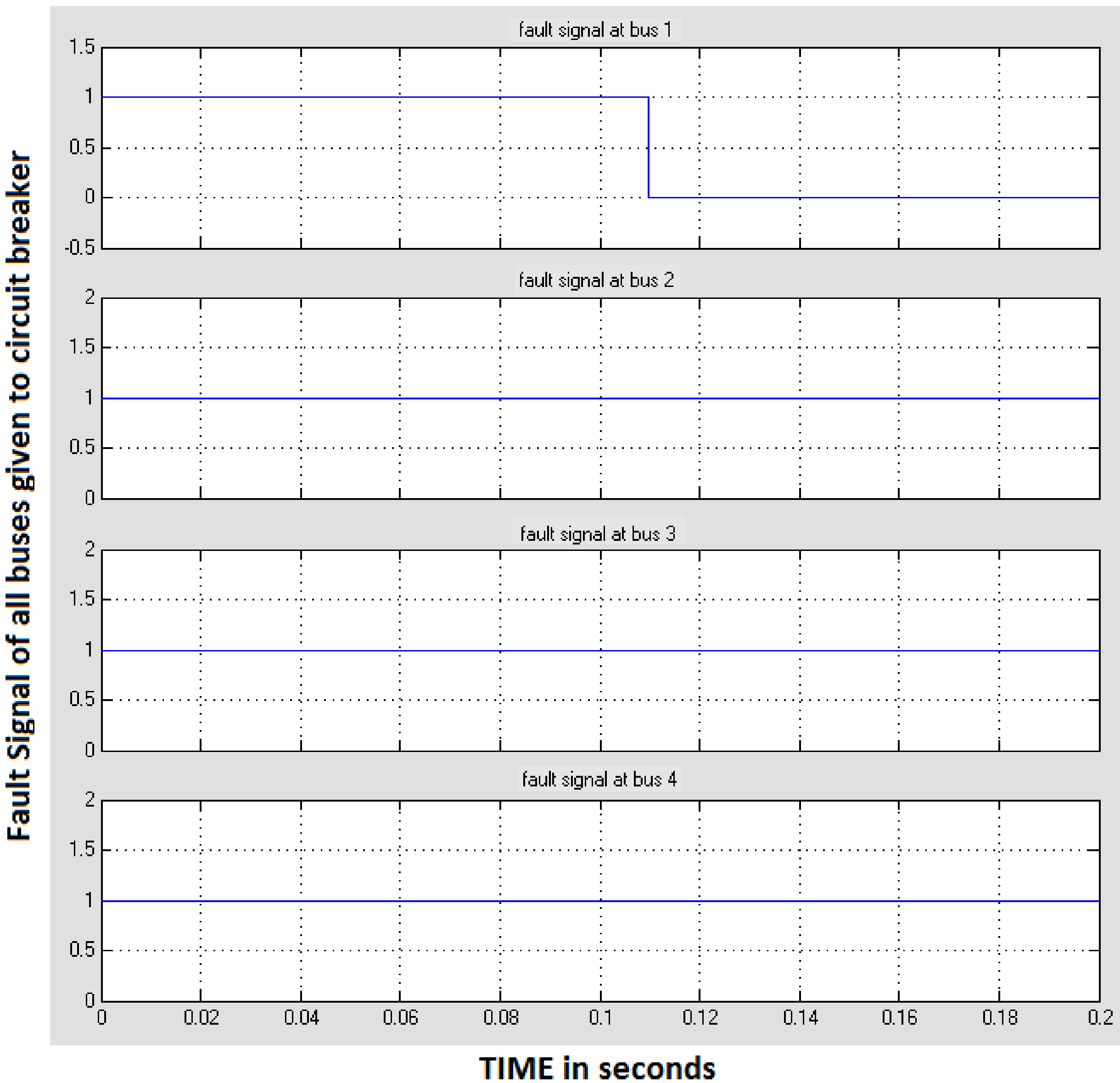


Fig 4.21: Fault detected signal during 2phase fault at bus 1 in islanded mode

3. 2 phase fault at bus 4 with grid connection

Phase A -to- Phase B fault is created near load bus 4 in grid presence to the micro-grid.

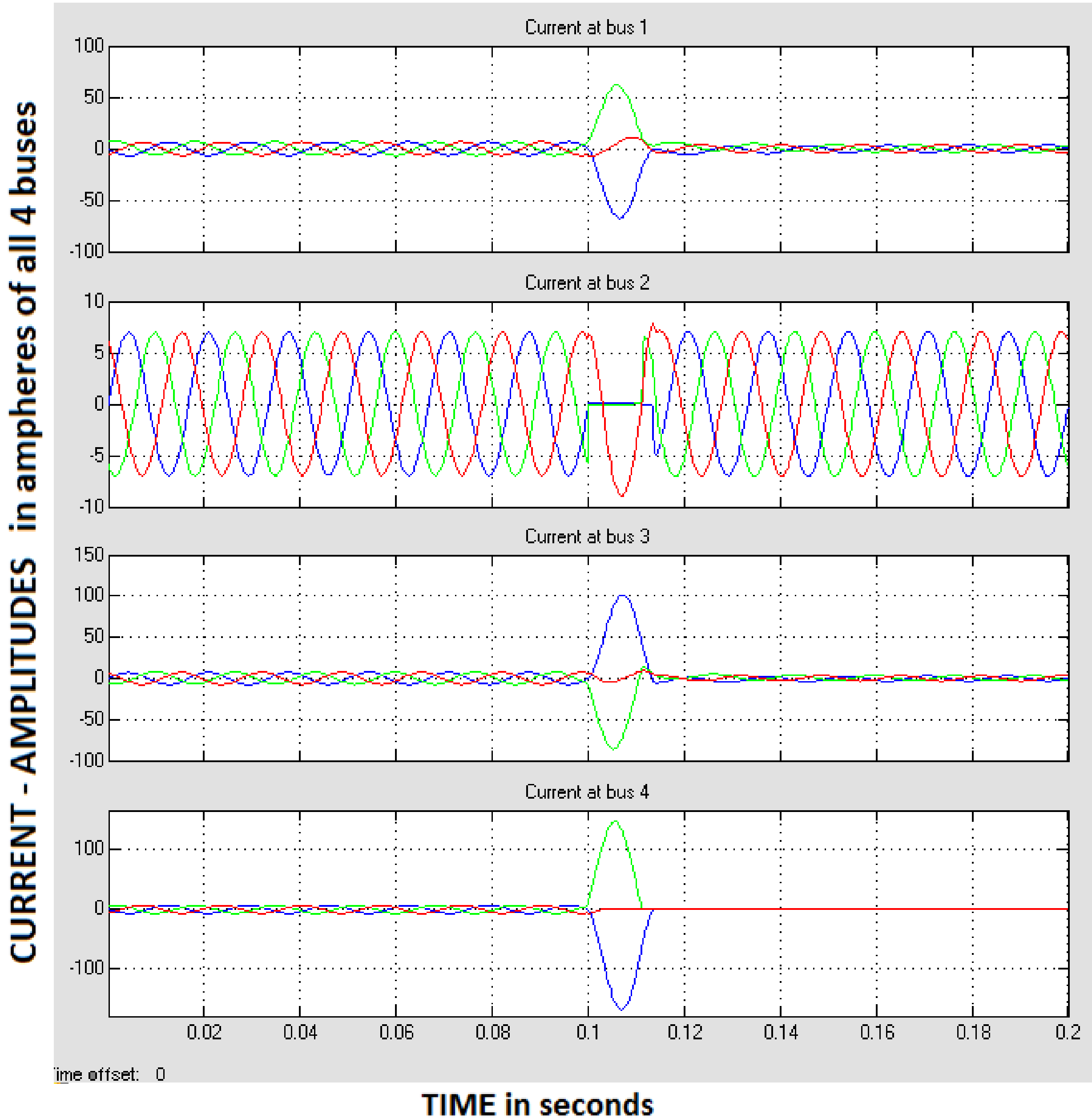


Fig 4.22: Current waveform of 2-Phase fault at bus 4 in grid connection mode

From Fig 4.22 it is clear that fault is detected at bus 4. As the fault occurs we can see that phase A and phase B current become abruptly high from the normal current level which is detected by the CUSUM algorithm in all generator bus and in faulted bus. By introducing delay in gen. fault detection algorithm, faults near load bus can be detected first and is distinguished from gen. bus.

4. 3 phase fault at bus 2 with grid connection

A 3 phase-to-ground fault is created near bus 2 in present of grid connection at 0.1 sec. Fig 4.23 shows the current waveform signal which detects the fault at bus 2 (load bus).

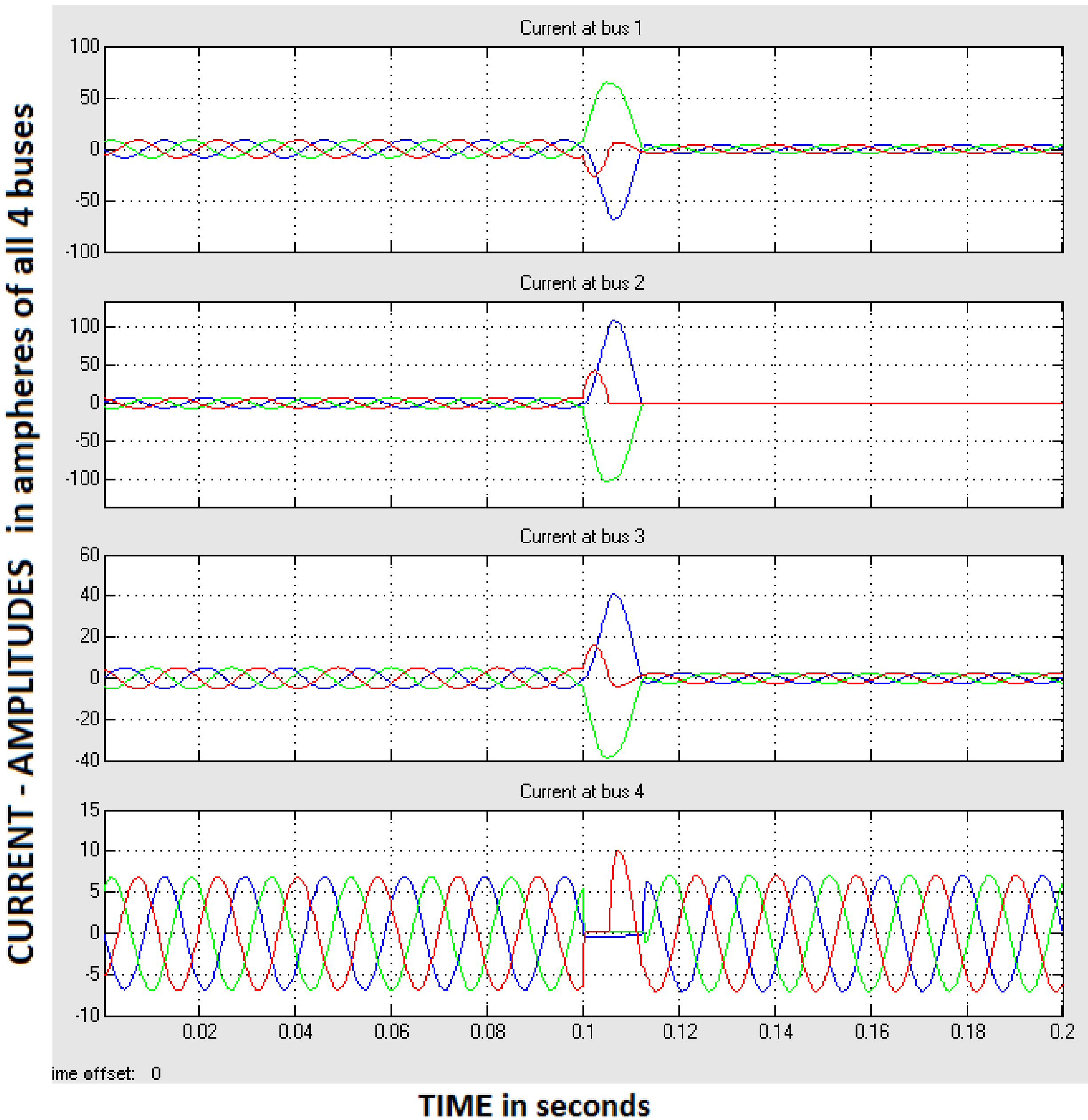


Fig 4.23: Current waveform of 3phase-to-ground fault at bus 2 in grid connection mode

We can note from the plot that whenever there is a fault near load bus, current transients can be detected at all generator bus and faulted load bus alone. The detection of faults near load bus is faster than in case of generator bus due to delayed generator fault detection algorithm.

4.5 CASE STUDY 4 : 5-Bus Micro-grid System

Part A : Implementation of 5-bus Microgrid system

The experimental performances for the Cumulative-Sum based algorithm and power flows for Fault Detection were conducted on a 5-bus micro-grid model which composed of components shown below. The operating voltage of the laboratory micro-grid was set for one level, which is 208, in order to match the grid voltage. The single line diagram of above 5-bus micro-grid system is shown in Fig 4.24.

1) A 208 V, 60 Hz supply (the utility grid);

2) A 2.5 kVA, 4-pole, 208 V synchronous generator (HU);

3) A 1.8 kVA, 4-pole, 208 V synchronous generator (HU);

4) Three Y-connected resistive loads of 1.8 kW, 3 KW and 2 KW respectively;

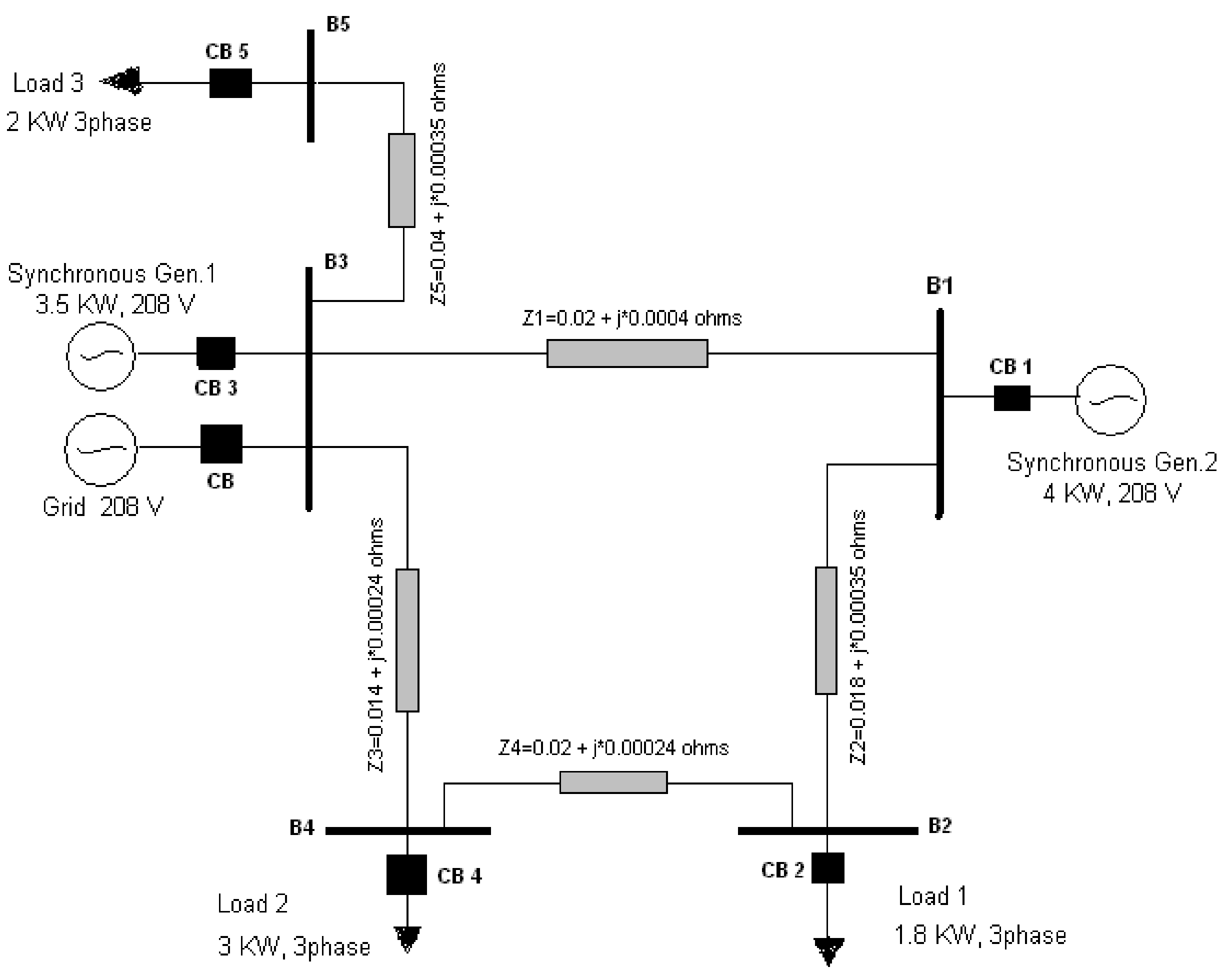


Fig 4.24 : Single line diagram of 5-bus micro-grid system

In above 5-bus micro-grid system we are using the same type of Fault Detection algorithm- Cumulative Sum to detect faults in it. The Simulink subsystem block diagram of the fault detection module is similar to that used in earlier cases. Here the value of the threshold used is 28 amperes. So if the current amplitude goes above 28 amperes then Fault is detected.

Part B : Simulation test of 5-bus Micro-grid System.

The waveforms (current) for various fault condition are shown in Fig.4.23 to Fig 4.29. The fault is occurred at 0.1 second in all cases. In this case the theta θ values of all buses will change as configuration changed to 5-bus micro-grid system. Theta (1-3) θ_{13}in this case changes to 0.036 in grid connection mode and 0.056 in islanded mode (2 different values) during normal state(without fault). The threshold value for detecting fault location in case of generator faults are '> 0.062' and '< -0.01' for generator bus 1 in grid connection and islanded mode respectively and '< -0.01' and '> 0.09' for generator bus 3 in grid connection and islanded mode respectively. The single line diagram of a 5-bus micro-grid system is shown above in Fig 4.24.

1. Grid connection/disconnection mode.

The grid is connected to micro-grid system through bus 3 at 0.1 second. The three phase current waveform of all 5-buses for grid connection mode is shown in Fig 4.25.

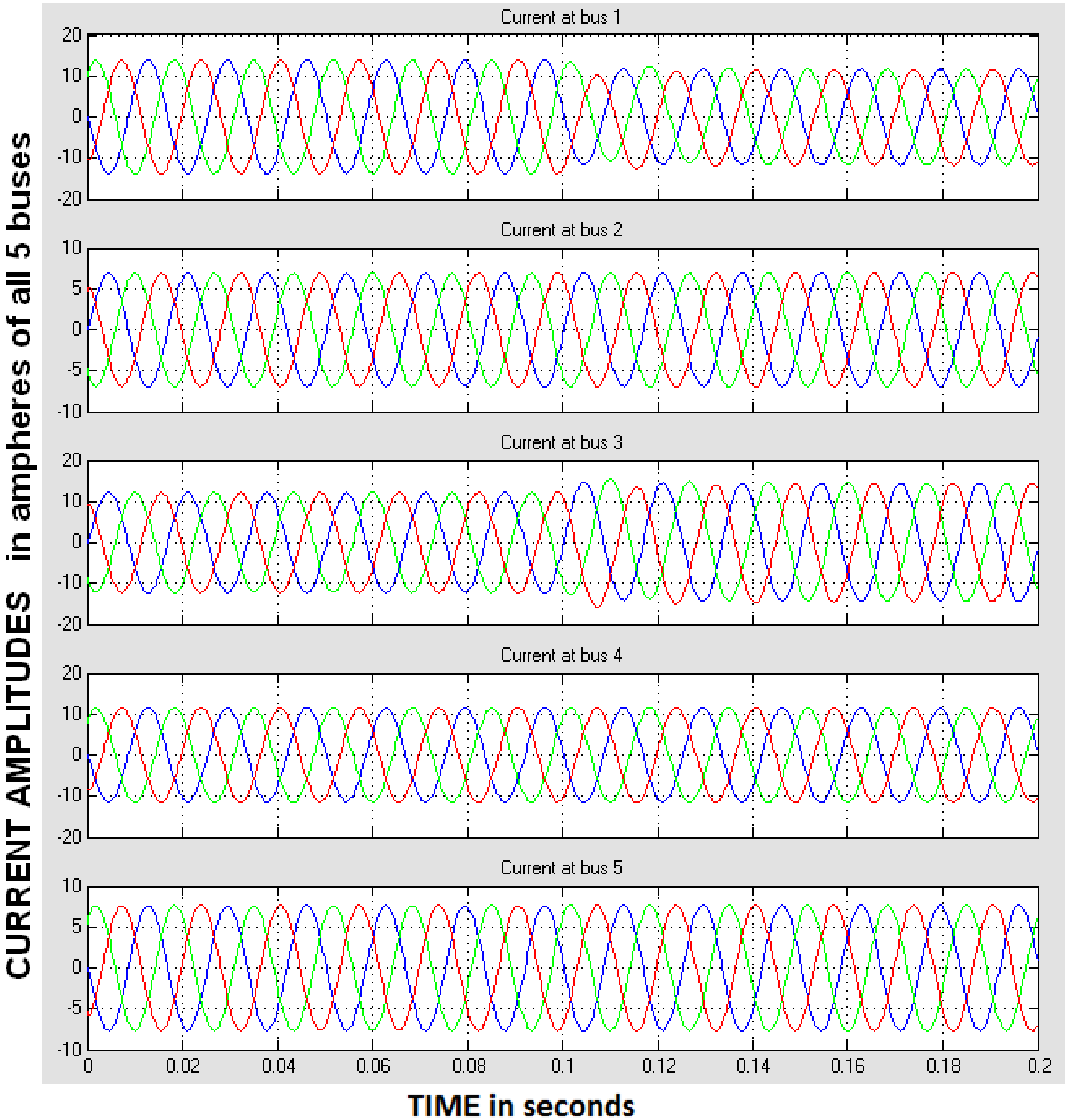


Fig 4.25: Current waveform of Grid disconnection/connection Mode of micro-grid

After grid connection we can see some transient disturbance at all buses and current level at bus 1 decreases and that of bus 3 increases to maintain same voltage in system. As more current is supplied through bus 3, current waveform level is increased in that bus.

2. 3 phase-to-ground fault at bus 2 in grid connection

A 3 phase-to-ground fault is created at bus 2 in presence of grid connection. Fig 4.26 shows the current waveform signal which detects the fault at bus 2 (load bus).

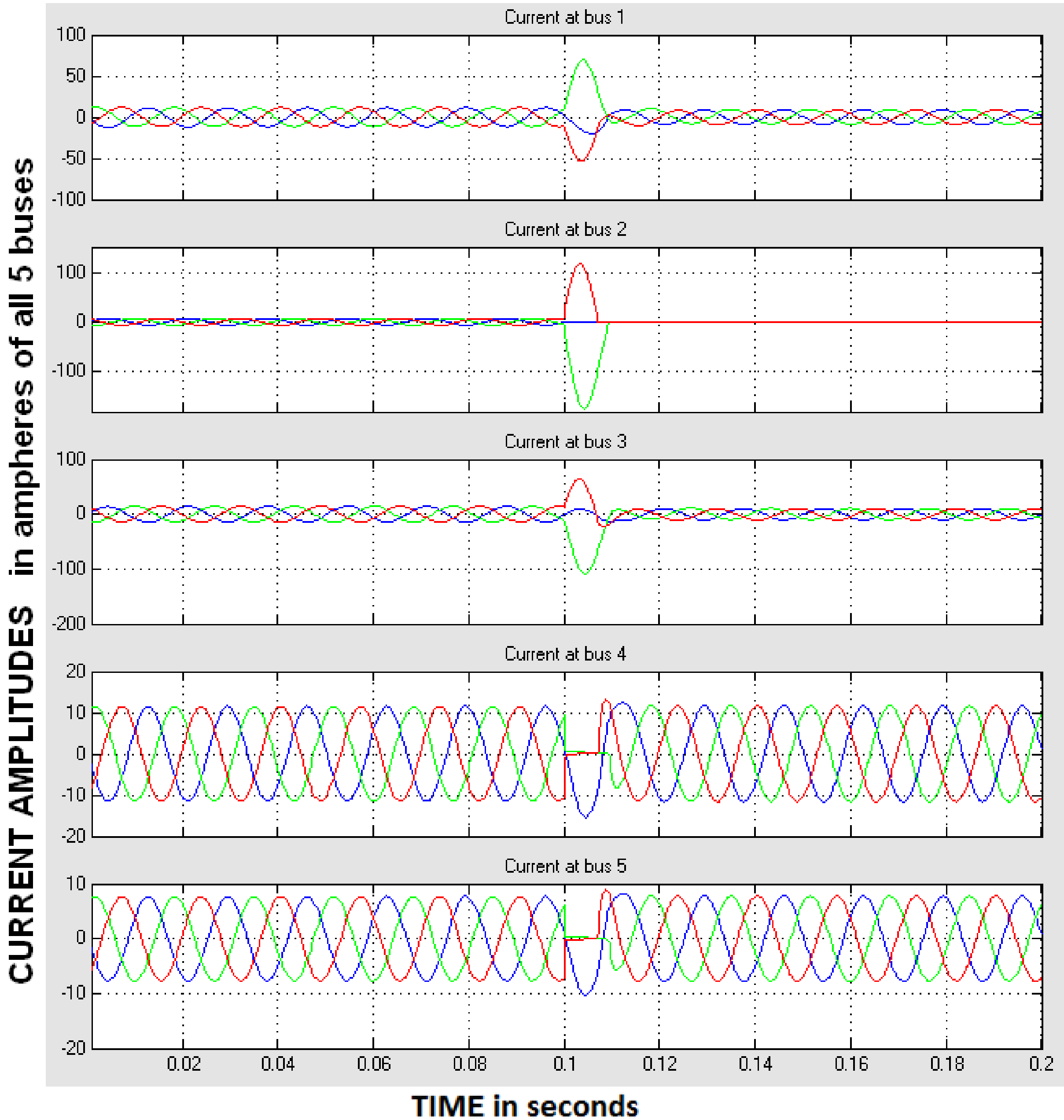


Fig 4.26: Current waveform when 3phase-to-ground fault at bus 2

We can note from the plot that whenever there is a fault near load bus, current transients can be detected in all generator bus and faulted load bus alone, other load bus current signal won't affect. Due to introducing delayed fault detection algorithms in generator buses, the detection of faults near load bus can be done faster.

3. 2 phase fault at bus 4 without grid connection

Phase A–to-Phase B fault is occurred near bus 4 in islanded mode of operation of micro-grid. Here in 2 phase fault we can see that phase A and phase B current become abruptly high from the normal current levels in bus 1, bus 3 and bus4. Therefore from Fig 4.27 it is clear that fault is occurred at bus 4 which is a load bus by using proposed algorithm for fault detection.

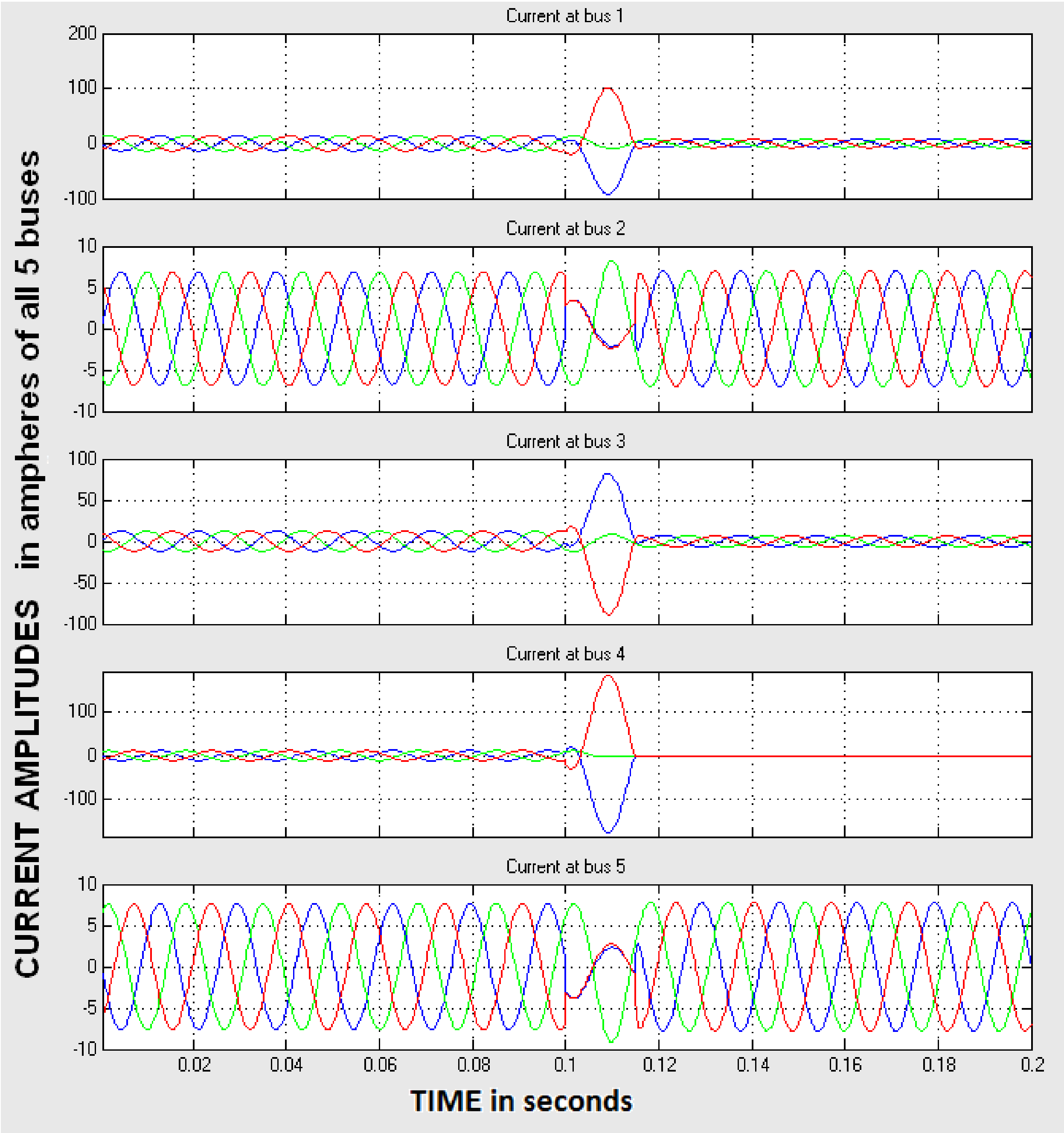


Fig 4.27: Current waveform when 2phase fault at bus 4 without grid connection.

4. 2 phase fault at bus 1 with grid connection.

Phase A-to-Phase B fault is created near bus 1 in grid connected mode.

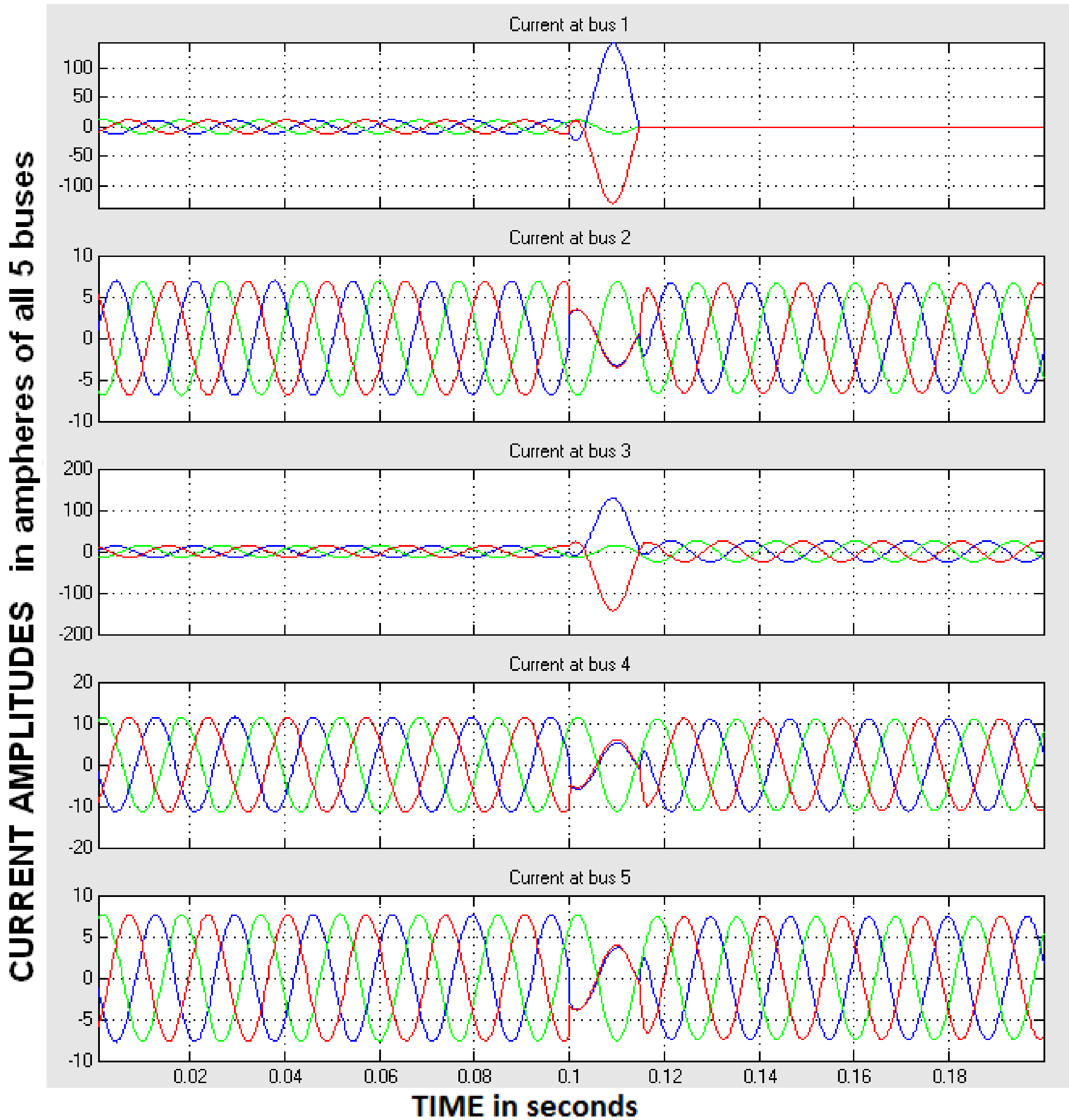


Fig 4.28: Current waveform of 2phase fault at bus 1

From Fig 4.28 it is clear that fault is occurred at bus 1 which is a generator bus. In 2 phase fault we can see that phase A and phase B current become abruptly high from the normal current levels in both generator buses. By monitoring theta difference between buses 1 and 3 i.e. θ_{13} which is greater than 0.062 in this case, we come to conclude that fault is occurred near bus 1. So by isolating bus 1 region from micro-grid we are making the system stable.

5. 1 phase to ground fault at bus 3 without grid connection

Fig 4.29 shows the current waveform when a single phase A-to-ground fault is created near bus 3 (generator bus) without grid connection.

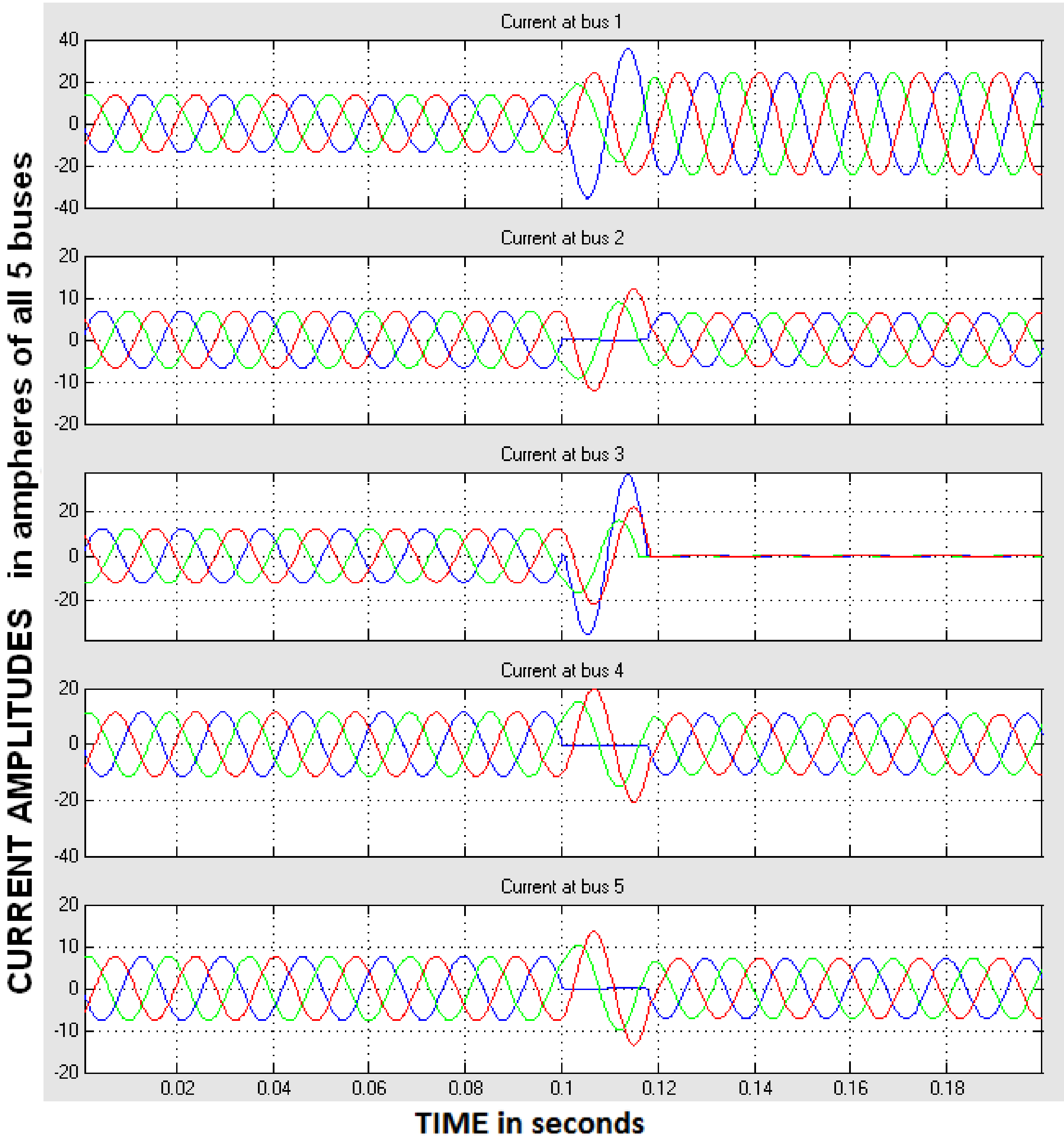


Fig 4.29: Current waveform of 1phase-to-ground fault at bus 3

From Fig 4.29 we can see that after fault is detected near bus 3 by using proposed algorithm, current supply from bus 1 increase to meet the load requirement. And as grid is not connected and generator at bus 3 is isolated current signal at bus 3 is zero.

6. 2 phase fault at bus 3 with grid connection

Fig 4.30 shows the current waveform when a 2phase fault is made near bus 3 (generator bus) in grid connection mode.

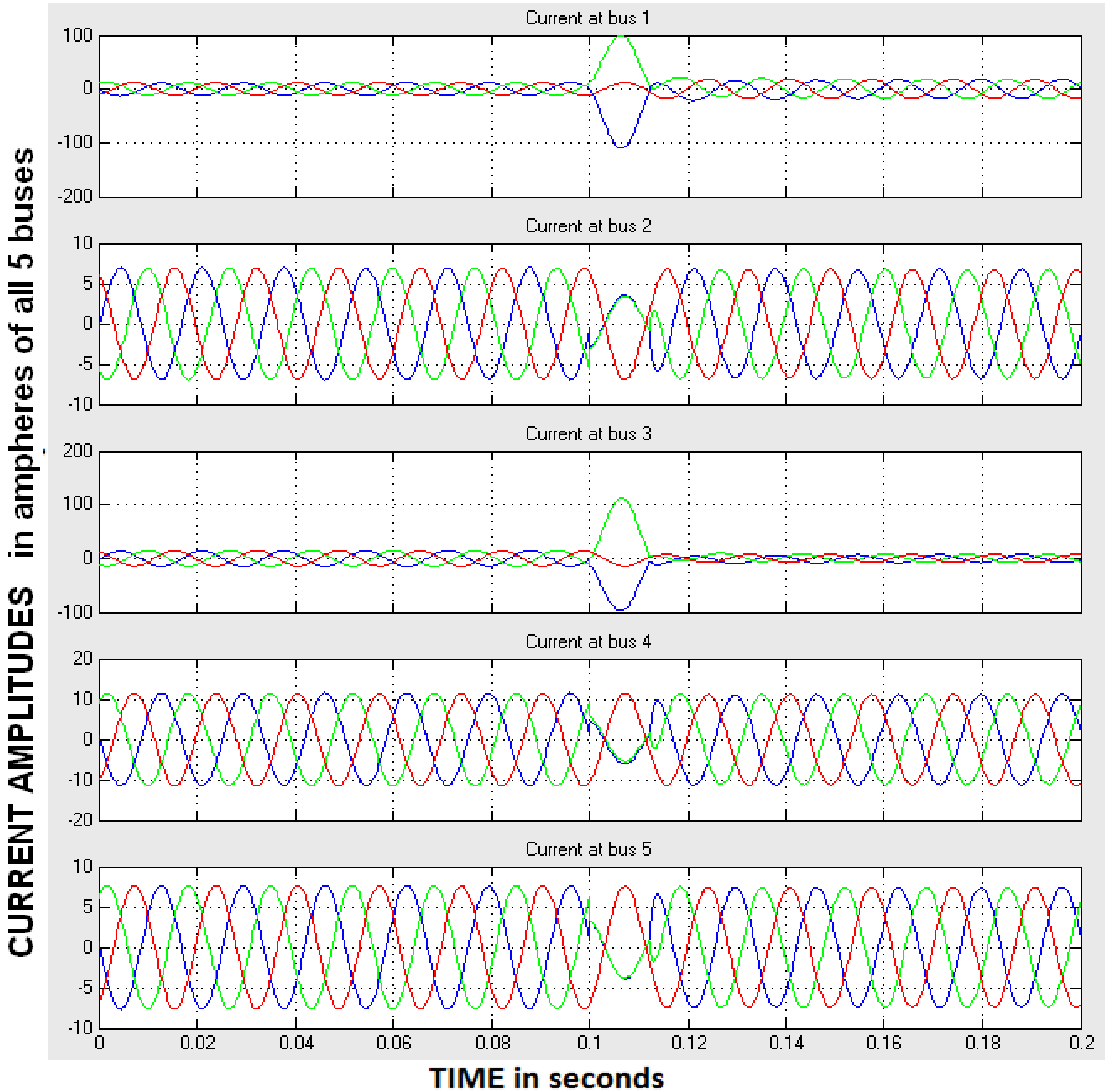


Fig 4.30: Current waveform of 2phase fault at bus 3

From Fig 4.30 we can see that after fault is detected near bus 3 by using cumulative sum method and monitoring power flow (proposed algorithm), current supply from bus 1 increase to meet the requirement of loads. Also current signal from bus 3 will not be zero as grid is still connected to micro-grid from bus-3 only the generator which is connected through bus 3 is isolated due to fault in it.

Fig.4.31 gives us the fault detected signal when a 2 phase fault is detected at bus 3, as we are using some delay to increase the selectivity of the whole system, we can see that the fault detected signal give output signal with a delay of 6 ms, after the current signal amplitude cross threshold value of 28 amperes.

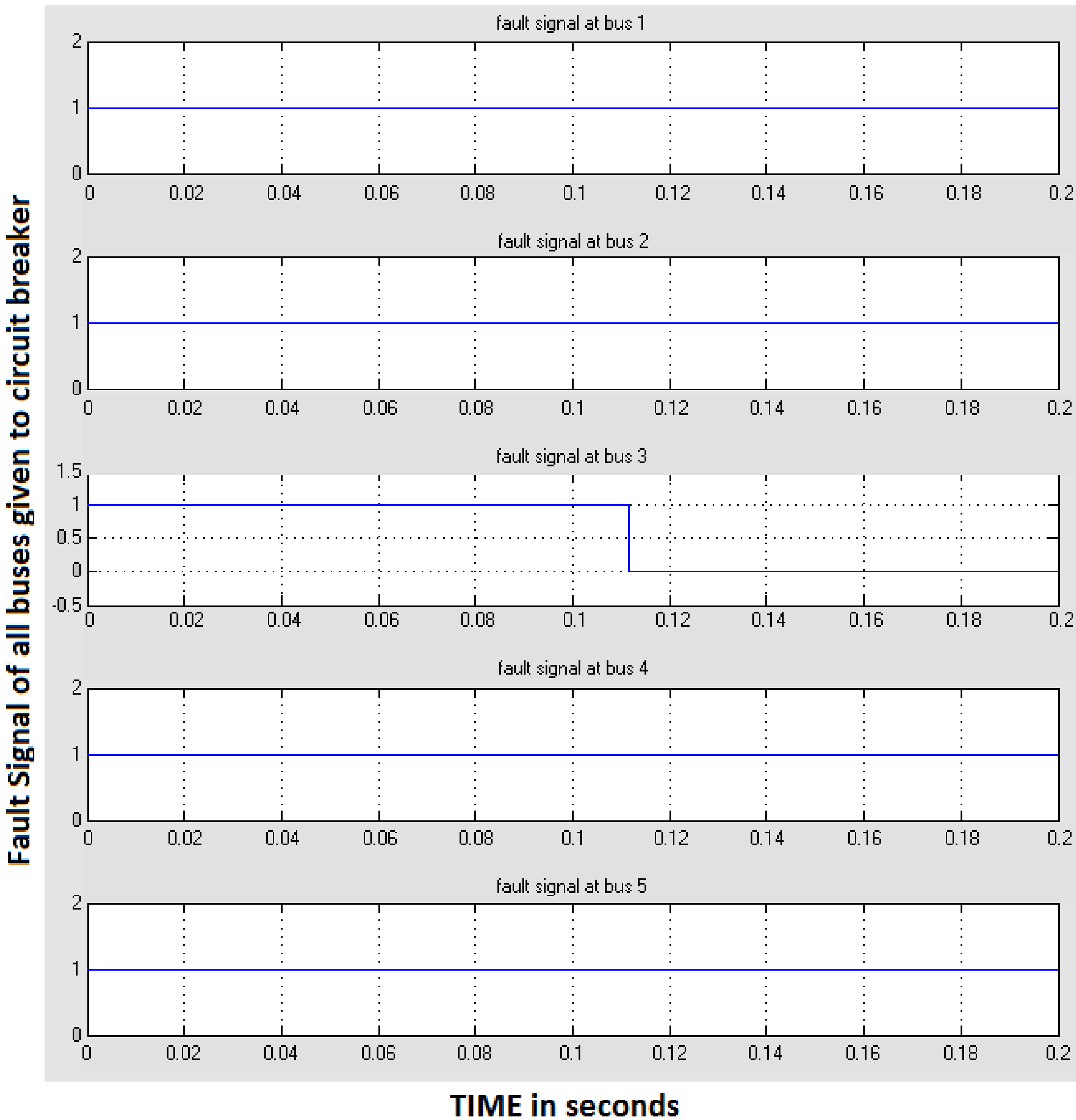


Fig 4.31: Fault detected signal when a 2phase fault is present at bus 3

7. 1 phase-to-ground fault at bus 5 with grid connection

A single phase A-to-ground fault is created near bus 5 (load bus) in grid connection mode. Fig 4.32 shows the current waveform of all 5 buses.

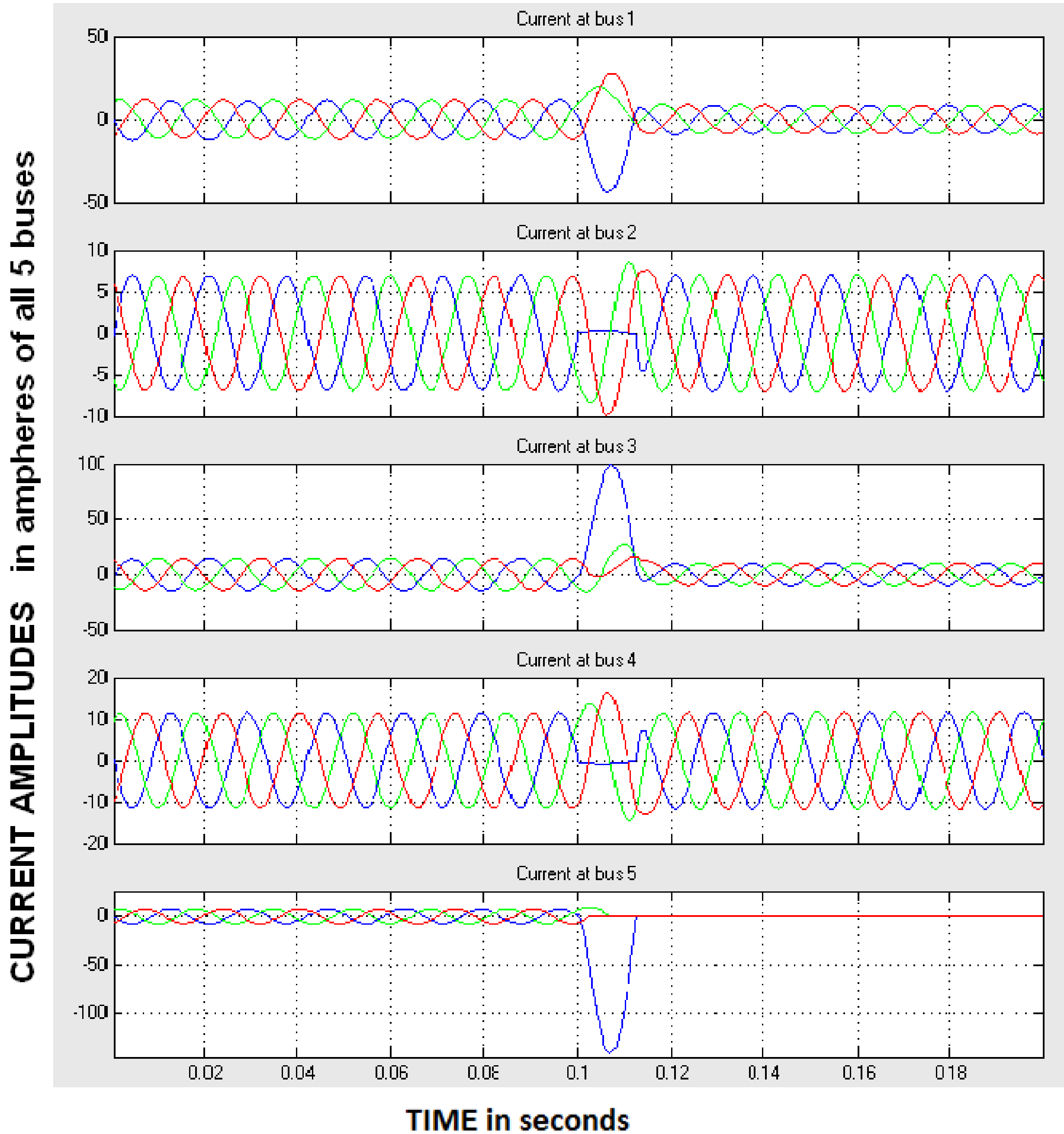


Fig 4.32: Current waveform of 1phase-to-ground fault at bus 5

From following Fig 4.32 we can note that fault is occurred near bus 5, as current transient is detected at all generator buses and fault load bus i.e. bus 5.

From Fig. 4.32 and Fig.4.33 we can see that as soon as the current amplitude increase higher than 28 amperes the fault is detected and tripping signal is given to circuit breaker to make the system stable.

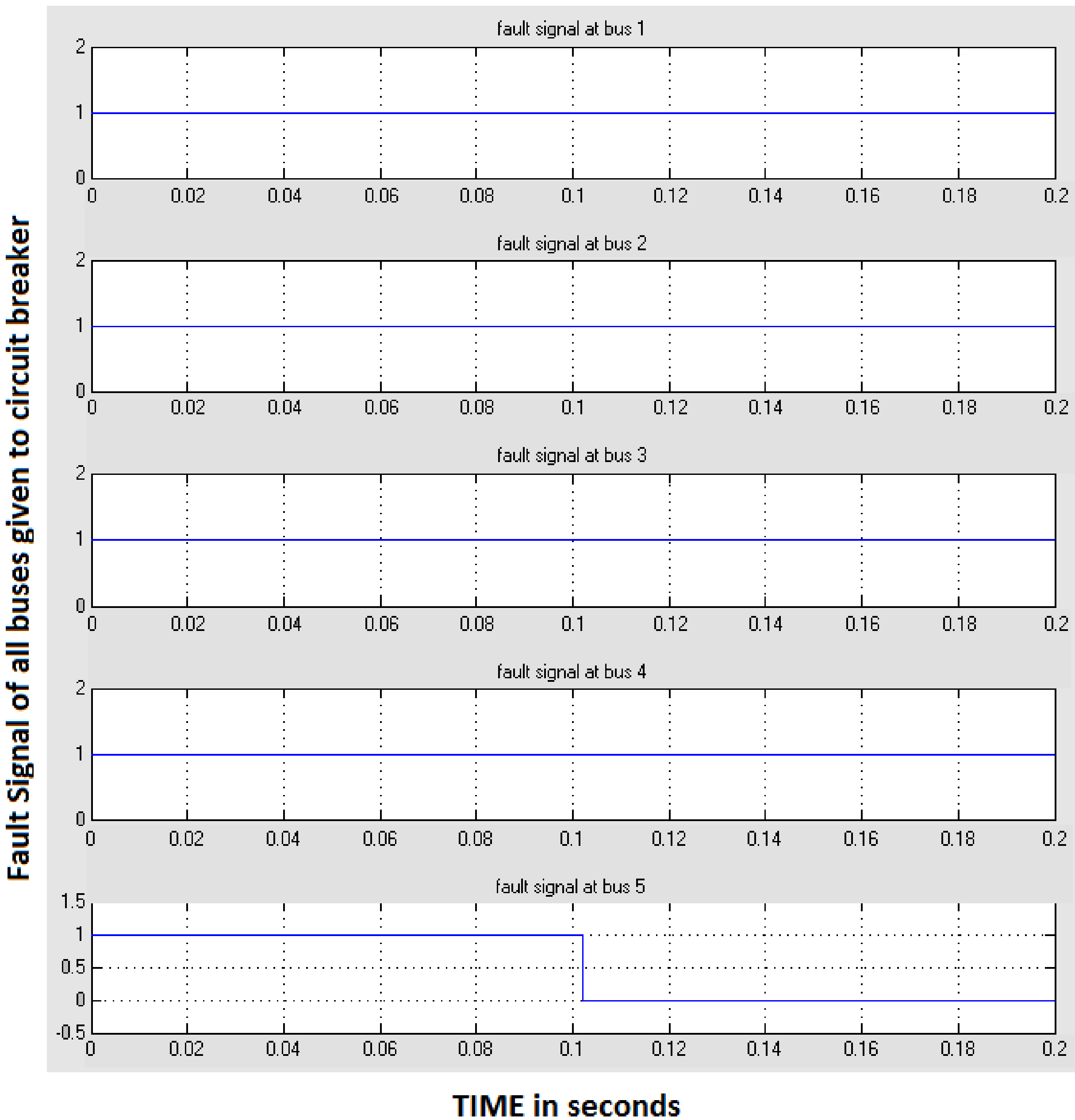


Fig 4.33: Fault detected signal during 1phase-to-ground fault at bus 5

8. Voltage plots of all 5 buses when a single line to ground fault occurs at bus 1 with grid connection.

Fig 4.34 shows the voltage waveform when a fault between phase A-to-ground is occurred near bus 1. We can see that even after fault is detected and defected area is isolated, the voltage remains same due to micro-grid characteristics.

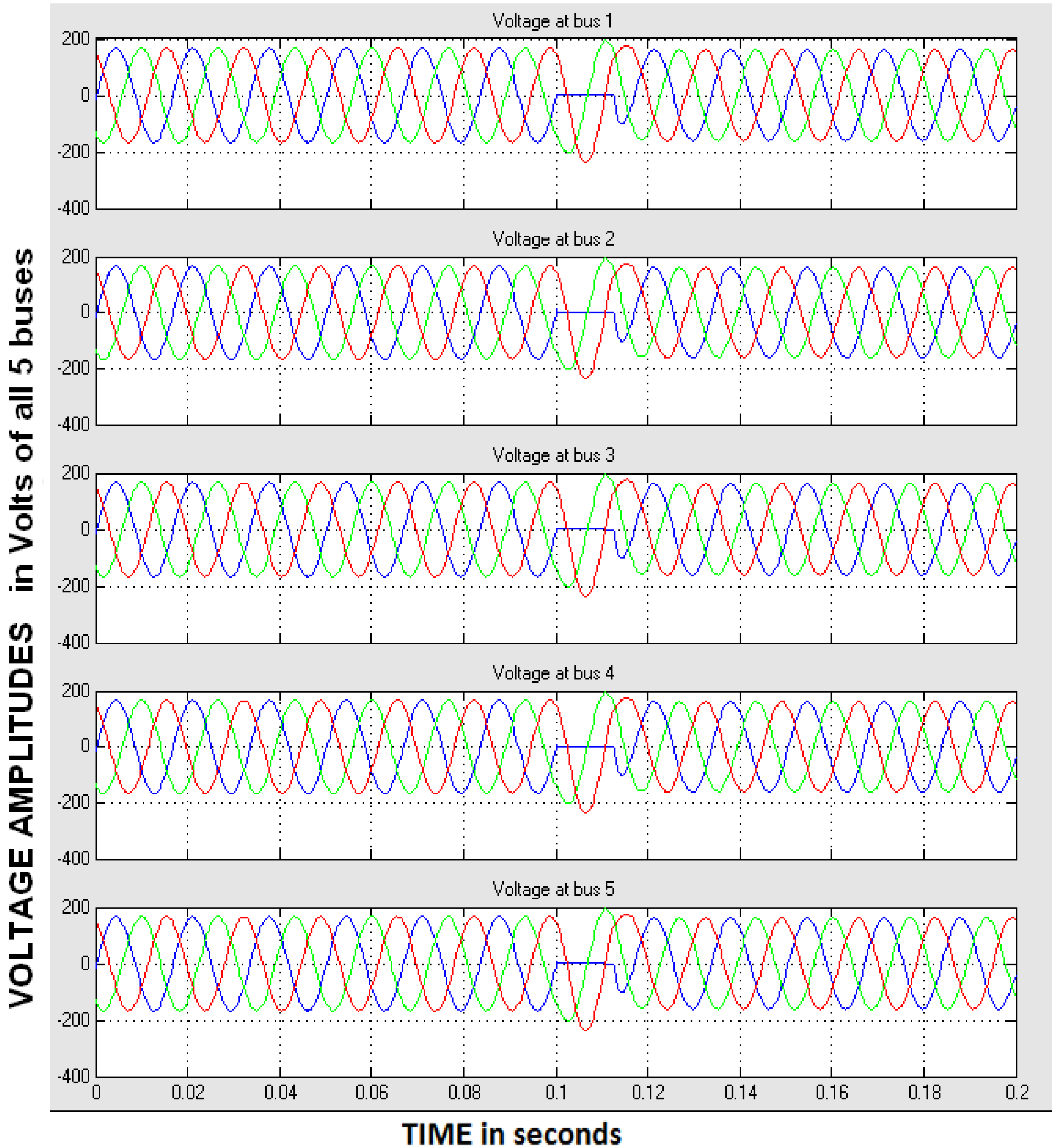


Fig 4.34: Voltage waveform of single phase-to-ground fault at bus 1

Chapter 5

Conclusion and Future work

5.1 Conclusion:

With the development and wide diligence of distributed generation technologies, enhancing a higher quest for the distribution network protection and new protection strategy requires great attention. In this thesis, a simple and fast way of fault detection algorithm is proposed for micro-grid systems. Cumulative sum based fault detection method alone is not sufficient for detecting faults in a looped system like microgrid, power flows concept is used along with it for exactly detecting fault location in micro-grid systems.

From simulation results we can conclude that faults at load bus can be easily detected by using cumulative-sum fault detection algorithm but for generator bus fault detection we need to use the conception of Power Flows. By monitoring theta (θ) value i.e. power flows through all generator buses we can detect the actual location of faults in micro-grid (looped) system. Also we can conclude that threshold values for cumulative sum algorithm and θ's of all buses are different for different micro-grid structures. Furthermore, the theta θ value gets affected if we change the values of generators and/or loads in micro-grid system causing threshold values to get affected every time the system configuration changed.

Simulation results demonstrate that the proposed method gives a simple and fast way to detect faults in a looped system such as micro-grid system. The results confirm the potential of the proposed approach and show its effectuality and superiority over classical conventional techniques like differential energy based, for detecting faults in micro-grid system in terms of speed and complexity.

5.2 Future Work:

Further work needs to be carried out for implementing and validating, through comprehensive dynamic testing with a hardware platform using the proposed Fault Detection algorithm for micro grid protection. Future research can be carried out in this direction to come up with robust generic, hardware efficient technique for fault detection in micro grid system.

Chapter 6

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APPENDIX A

Phase system for fault detection using cumulative sum:-

The simulation block diagram of a 3phase 600MVA, 13.8KV (radial) power system is shown in Fig. A.1. Here green coloured block is fault detection block which detects faults using cumulative sum algorithm.

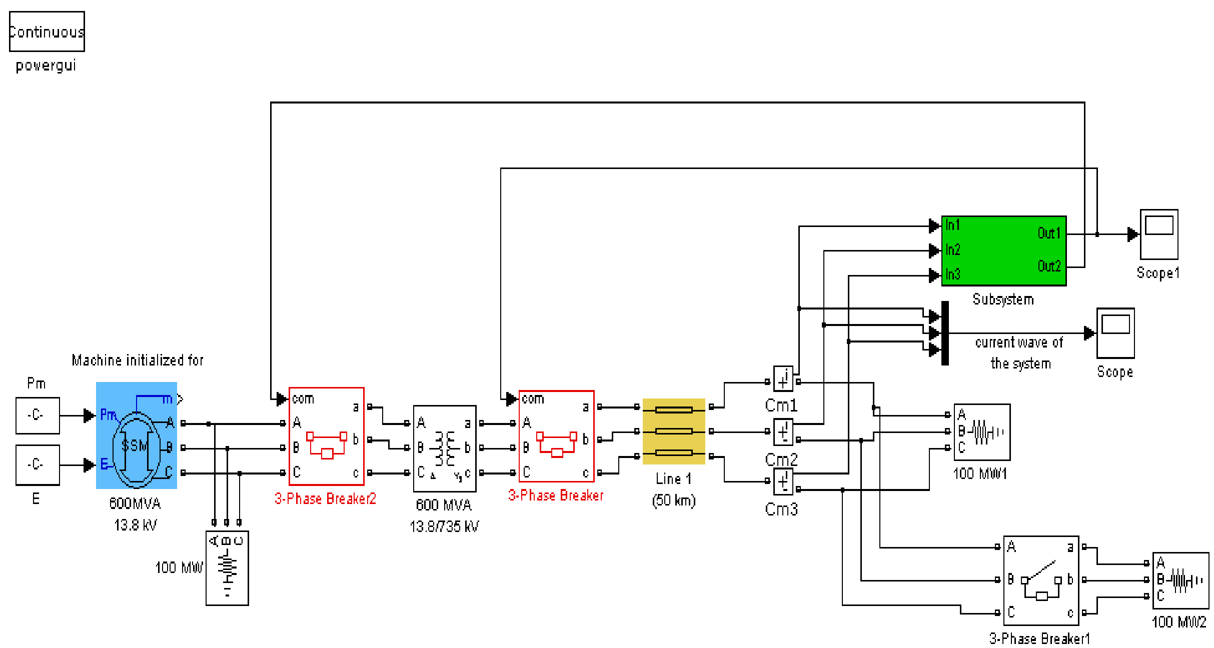

Fig. A.1: Simulation model of 3phase system

In above simulation model the green coloured block has fault detection block which monitors the current amplitude and if any disturbance occurs, Cumulative sum based fault detector will detect the fault and a signal is send to circuit breaker to isolate the load from generator to avoid further damage to the other loads. Fig. A.2 shows the Simulation block model of fault detection and isolation blocks for a 3phase radial system.

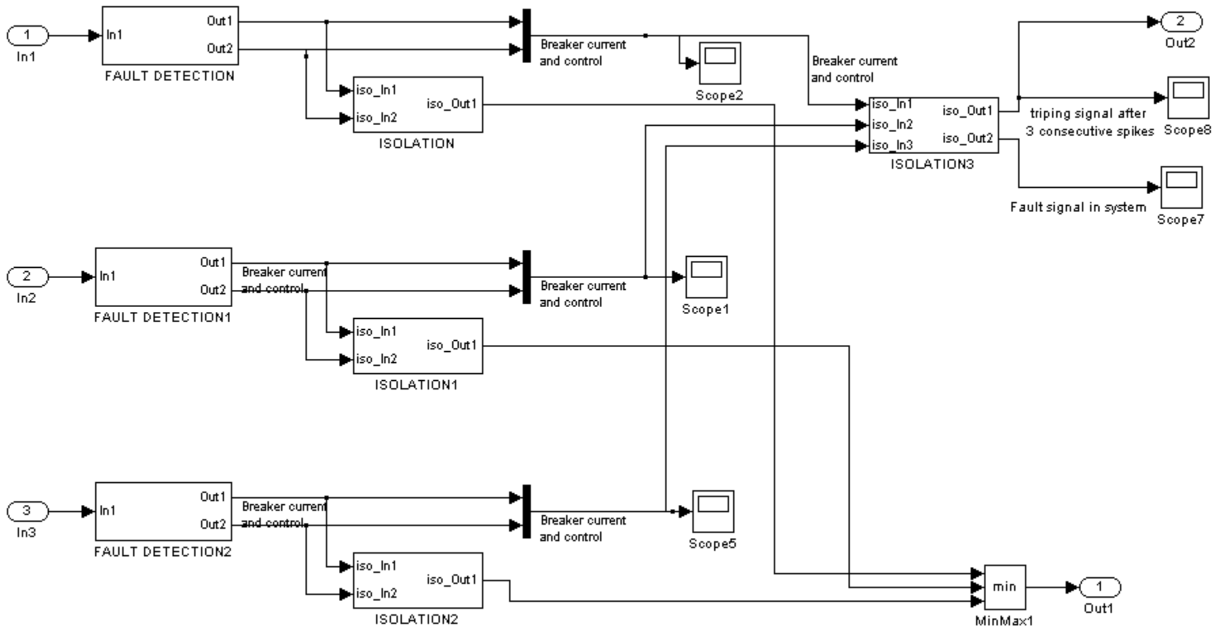

Fig. A.2 Simulation block model of fault detection and isolation blocks in simulink

Fig. A.3 shows the simulation block model of fault detection in simulink. The value of the threshold ν used here is 230, so if the current amplitudes exceeds beyond 230 amperes fault is detected using cumulative sum algorithm.

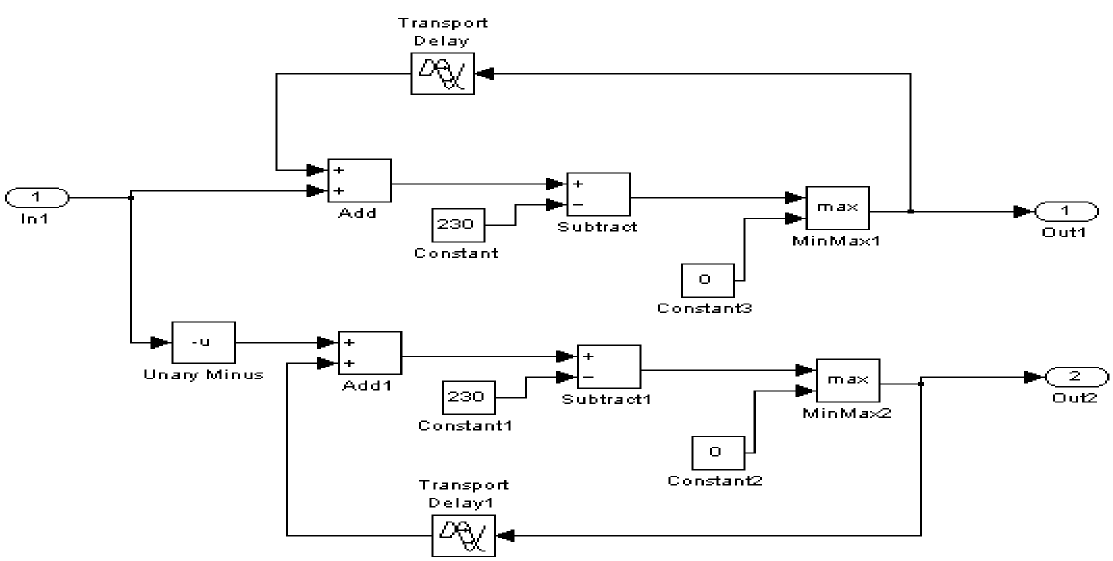

Fig. A.3 Simulation block model of fault detection using simulink

Fig. A.4 shows the simulation model of isolation in simulink for isolation of the part of the system after fault is detected to avoid further damage to the system. Here after fault is detected isolate is used to disconnect defected part for 0.04 seconds.

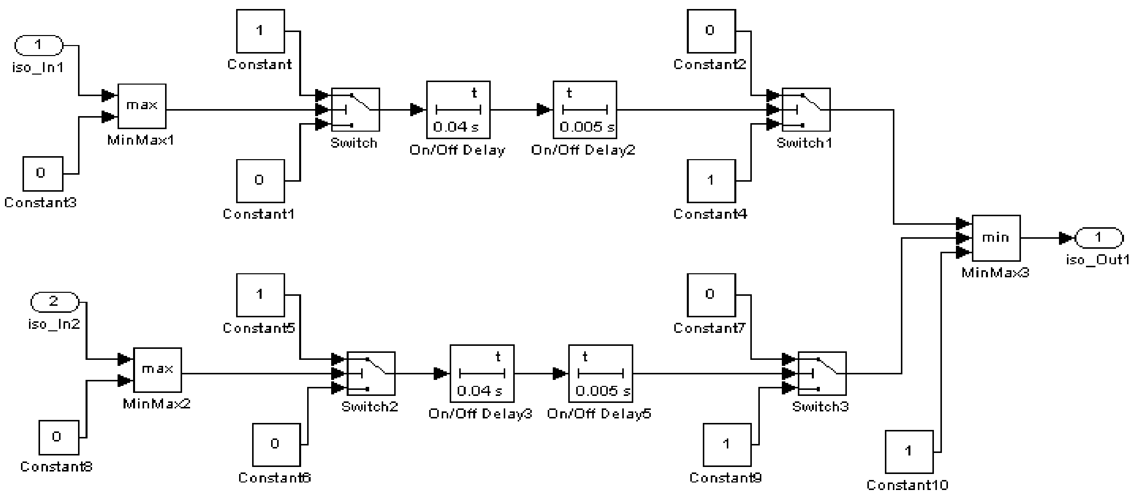

Fig. A.4 Simulation model of isolation using simulink

After the fault is detected and defected part is isolated and reconnection of defected part is carried out to check fault still exist or not, if the fault pertains defected part is isolated again. This process continues for three consecutive times and even after that fault persists then default part is isolated permanently to protect the system. Fig.A.5 shows the simulation model of isolation_3.

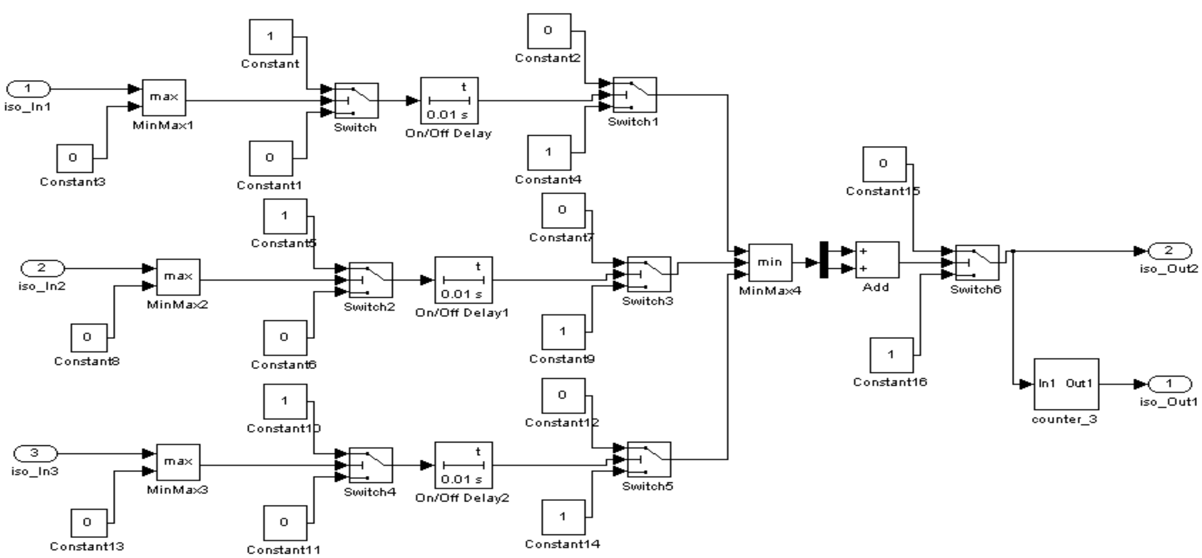

Fig.A.5 Simulation model of isolation_3 using simulink.

APPENDIX B

3phase 4-bus test Micro-grid system

Fig. B.1 shows the simulation model of a 4-bus micro-grid system. Here green coloured block are fault detection and isolation blocks. Light blue coloured blocks are synchronous generators, dark blue is a grid connection and orange coloured block are y-connected loads. Vpq measurment block at bottom left is used to measure the theta (θ) angle of all generator buses to monitor the power flows between them.

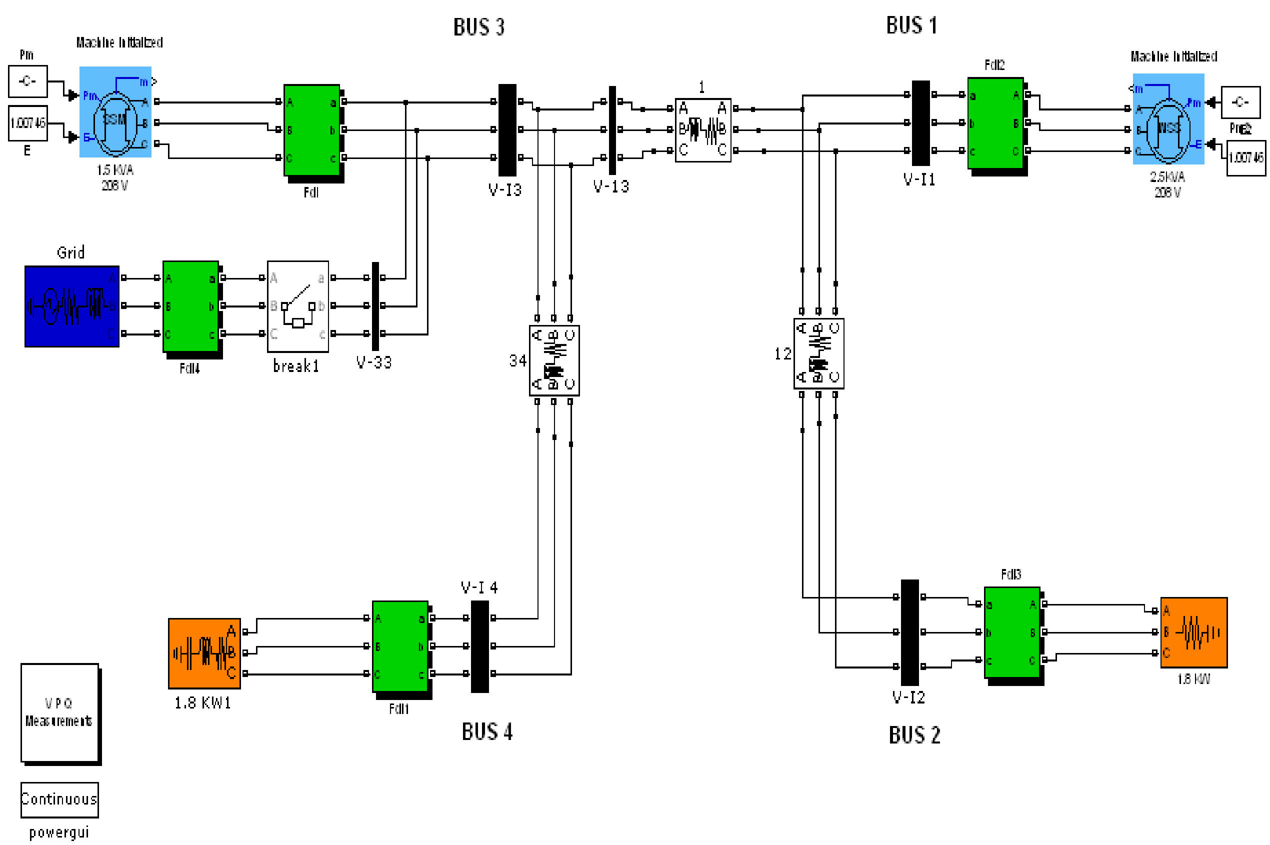

Fig. B.1 Simulation model of a 4-bus micro-grid system using Simulink

Green coloured block in above Fig. B.1 contains a circuit breaker, current measurements and fault detection and isolation subsystem. Simulated block model of above green coloured block is shown in Fig. B.2. Here cm1, cm2,cm3 are current measurement block used to measure 3 phase current flowing through the line. Circuit breaker block model is used to break the circuit whenever the signal input to it B31 becomes low. Subsystem_3 block is used to detect the faults and give isolated signal to ckt.breaker.

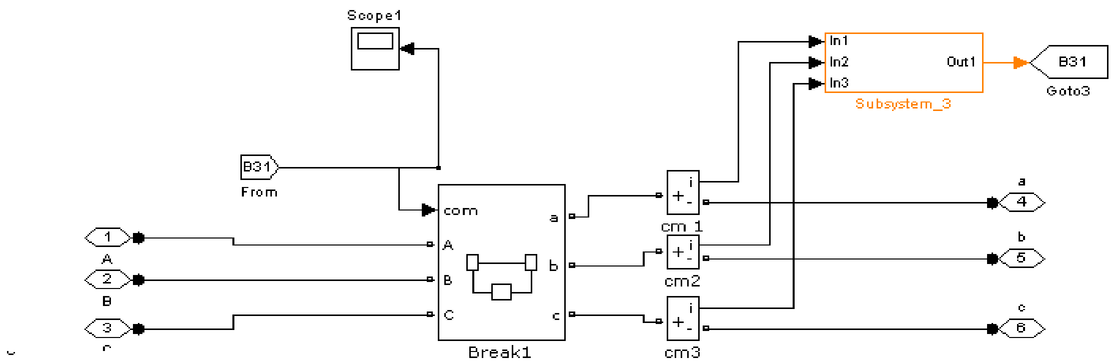

Fig. B.2: Simulation model for current measurements and circuit breaker

Fig. B.3 shows the simulation model of fault detection using simulink. This model is developed using equation of cumulative sum fault detection method. The value of the threshold ν used here is 28, so ifthe current amplitudes exceeds beyond 28 amperes fault is detected using cumulative sum algorithm.

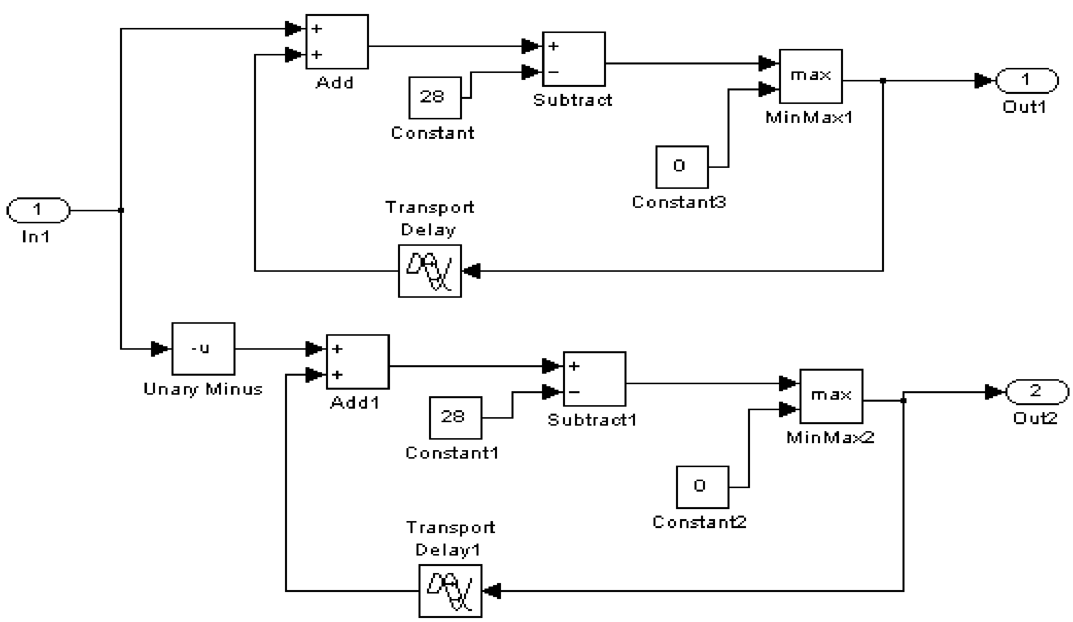

Fig. B.3: Fault detection block using simulink

Fig. B.4 shows the simulink model of Power Flow study which monitors the difference between thetas of bus 1 and 3, if the difference is above or below some specified range then we can figure out the exact location of fault in a micro-grid system. This block will come in to picture whenever there is a generator bus fault. After figuring out that fault occurred near generator bus which requires some delay, we used this model to measure change in power flows between the line connecting generator buses. Depending on the micro-grid structure, the thetas value in grid connected and in islanded mode is different. So for exact location of the fault, we need to use different threshold values of thetas.

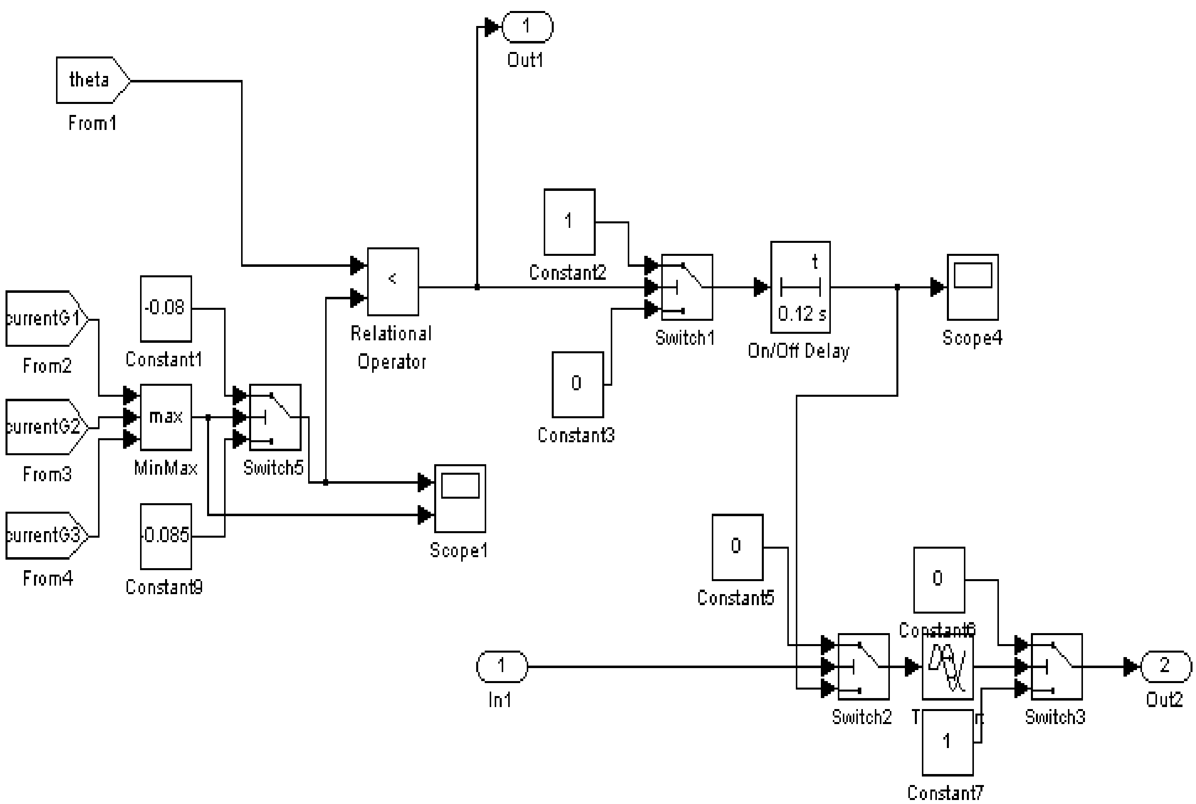

Fig. B.4: power flow detection block using simulink

To monitor the power flows between generator buses we use 3-phase sequence analyzer model block present in simulink. Using Simpower system toolbox, we can find out the angle of the generator bus voltages i.e. thetas and used it to monitor the power flows between them. Fig. C.5 shows the simulation model for theta measurements. During faults the theta (θ) value of each generator bus will change which we are using to find out the direction and the amount of Power Flows. If this θ difference value is beyond the specified range we can figure out the location of the fault in a micro-grid system.

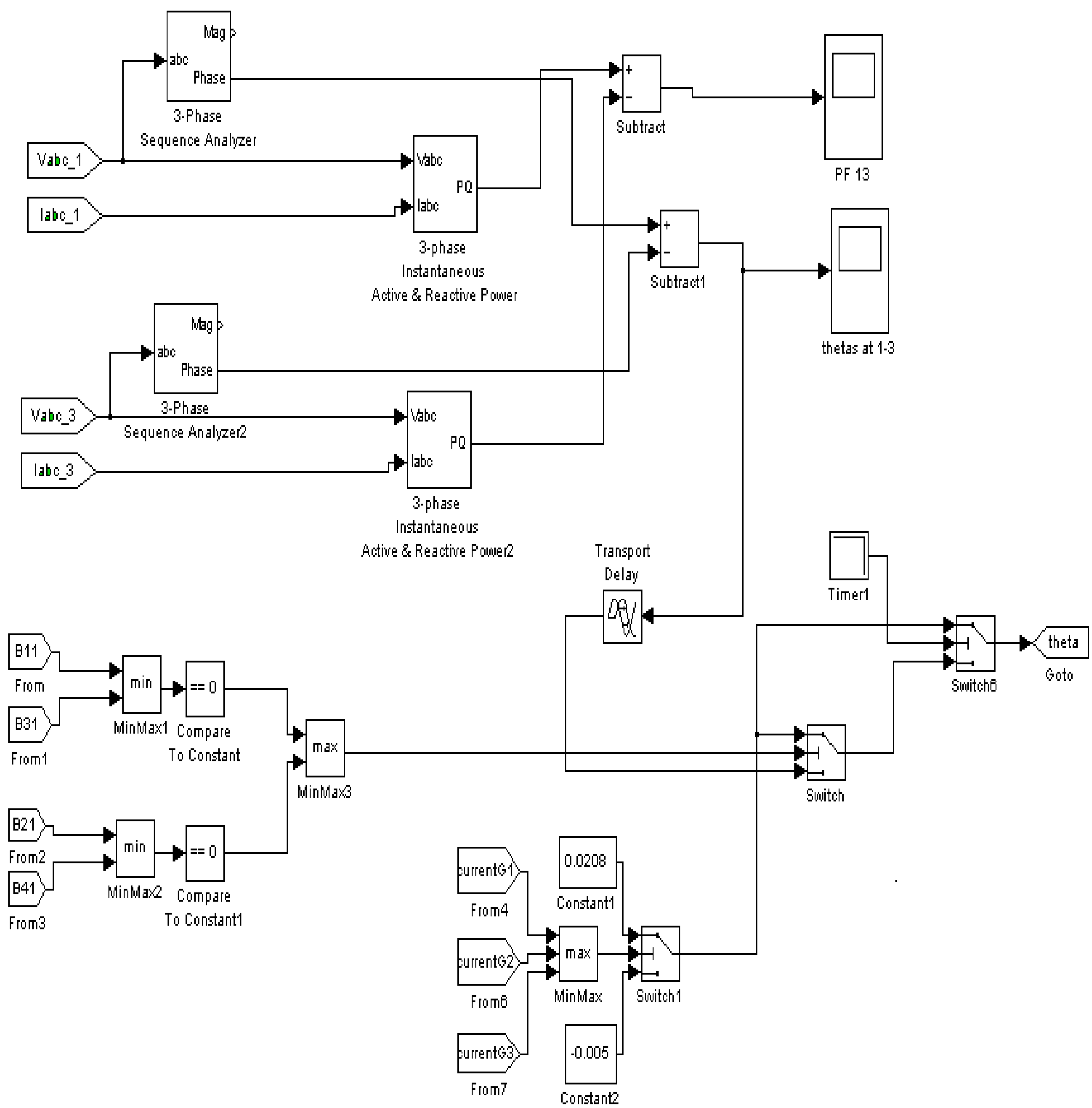

Fig. B.5: Theta measurement model block using Simulink

Table B.1 : Data of the Equipment used in Simulation of 4-bus microgrid system

Equipment	Data
1st synchronous machine (Blue colour)	Nominal power- 1.5 KW line to line voltage- 208V Frequency – 60 Hz Mechanical input- Pm, mechanical power
2nd synchronous machine (Blue colour)	Nominal power- 2.5 KW line to line voltage- 208V Frequency – 60 Hz Mechanical input- Pm, mechanical power
Grid (violet colour)	voltage- 208 V Frequency- 60 Hz Internal connection- Yg 3φ short circuit level at base voltage- 10e3V
Load 1 (orange colour)	Nominal phase to phase voltage- 208 V Nominal frequency- 60 Hz Active power- 1.8e3 W Configuration- Y grounded
Load 2 (orange colour)	Nominal phase to phase voltage- 208 V Nominal frequency- 60 Hz Active power- 1.8e3 W Configuration- Y grounded
Connecting wires	RL type

APPENDIX C

3phase 4-bus load connected micro-grid system

The simulation model of 4-bus load connected micro-grid system is shown in Fig. C.1. In this case data used is same as in above case 4-bus microgrid system.

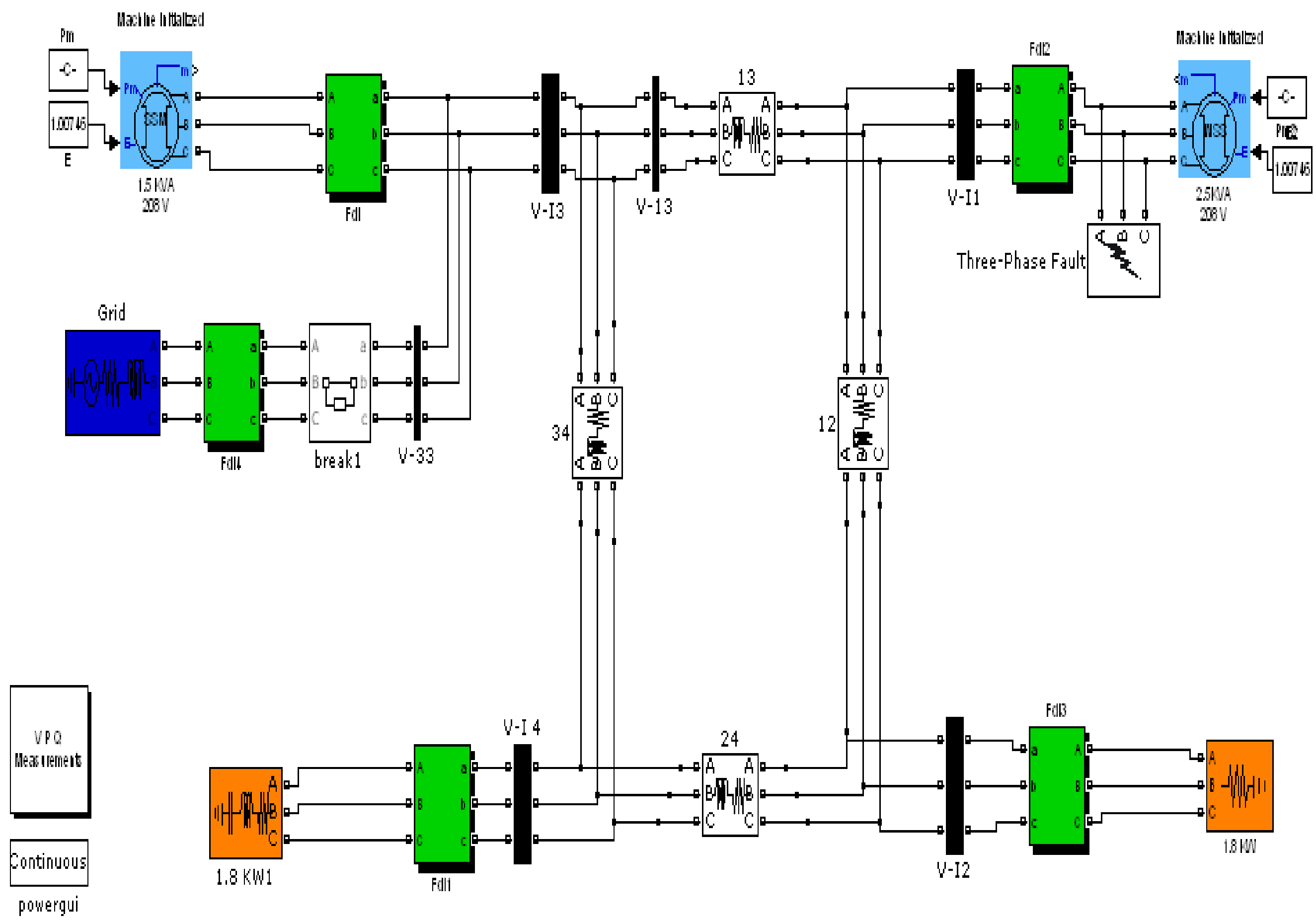

Fig. C.1: Simulation model of 4-bus load connected micro-grid system

APPENDIX D

3phase 5-bus micro-grid system

Fig. D.1 shows the simulation model of 5-bus micro-grid system.

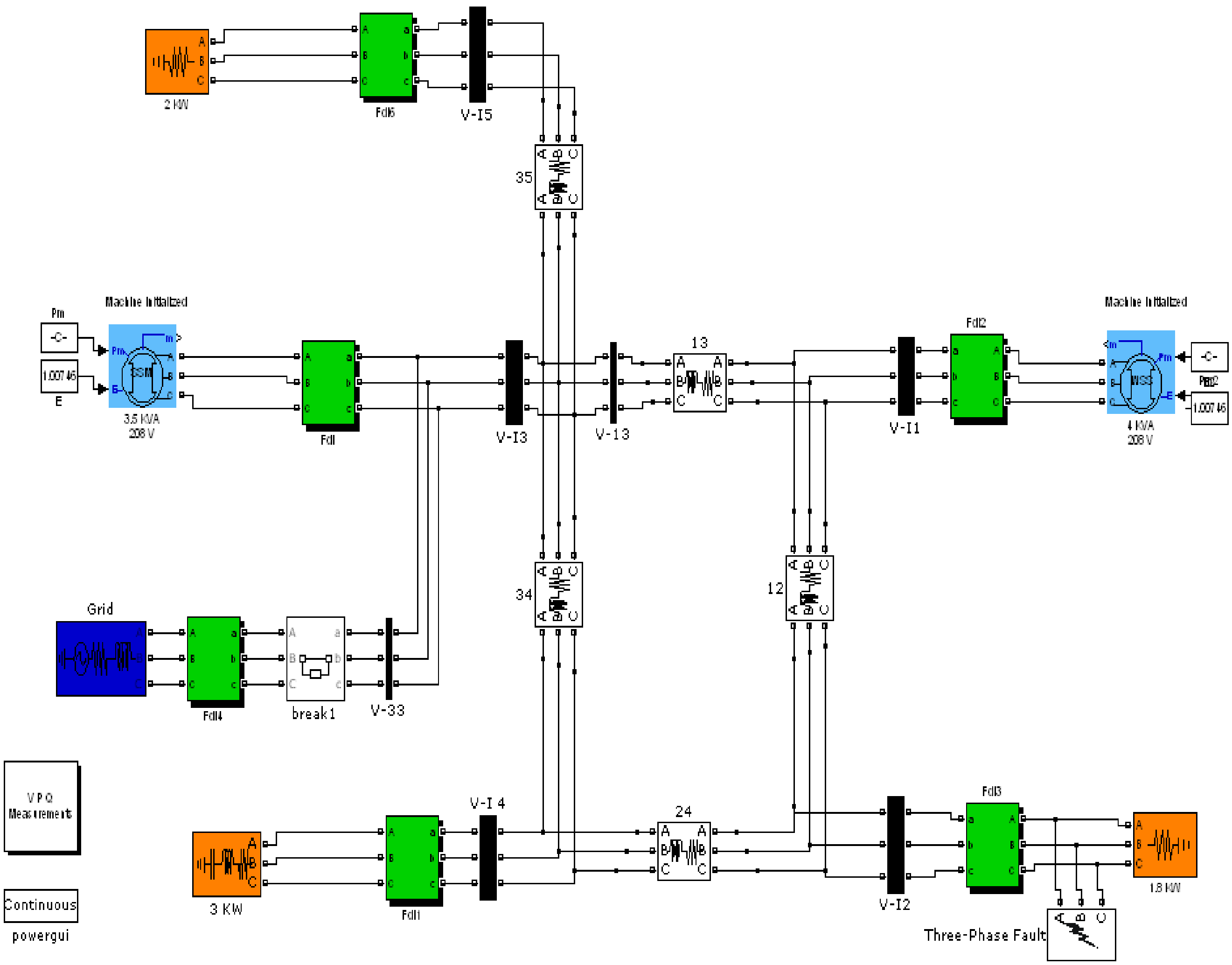

Fig. D.1: Simulation model of 5-bus micro-grid system

Table D.1 : Data of the equipment used in Simulation of 5-bus microgrid system

Equipment	Data
1st synchronous machine (Blue colour)	Nominal power- 3.5 KW line to line voltage- 208V Frequency – 60 Hz Mechanical input- Pm, mechanical power
2nd synchronous machine (Blue colour)	Nominal power- 4 KW line to line voltage- 208V Frequency – 60 Hz Mechanical input- Pm, mechanical power
Grid (Violet colour)	voltage- 208 V Frequency- 60 Hz Internal connection- Yg 3φ short circuit level at base voltage- 10e3V
Load 1 (orange colour)	Nominal phase to phase voltage- 208 V Nominal frequency- 60 Hz Active power- 3.0e3 W Configuration- Y grounded
Load 2 (orange colour)	Nominal phase to phase voltage- 208 V Nominal frequency- 60 Hz Active power- 1.8e3 W Configuration- Y grounded
Load 3 (orange colour)	Nominal phase to phase voltage- 208 V Nominal frequency- 60 Hz Active power- 2.0e3 W Configuration- Y grounded
Connecting wires	RL type

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