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An Efficient Fault Detection Algorithm for Micro-Grid

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This paper proposes an implementation procedure and performance testing of an algorithm comprise of Cumulative sum algorithm and power flow methods 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: *Micro-Grid, Fault Detection, Cumulative Sum Algorithm, Power Flows, Protection.*

1.0 INTRODUCTION

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. 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.

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

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 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

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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, micro-grids 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.

2.0 MICRO-GRID AND NEED OF PROTECTION

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 [1]. 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. Micro-grids have much littler environmental effects than conventional big thermal and hydro power plants. Using of micro-grids contributes reduction of gas emissions and it helps in extenuating the climate change. The most positive characteristics of micro-grids 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.

There is no universally consented standard definition for a micro-grid, but certain features are common in the existing micro-grids. A micro-grid 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 micro-grid inner load requirements. A micro-grid 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 micro-grid during a disruption [2].

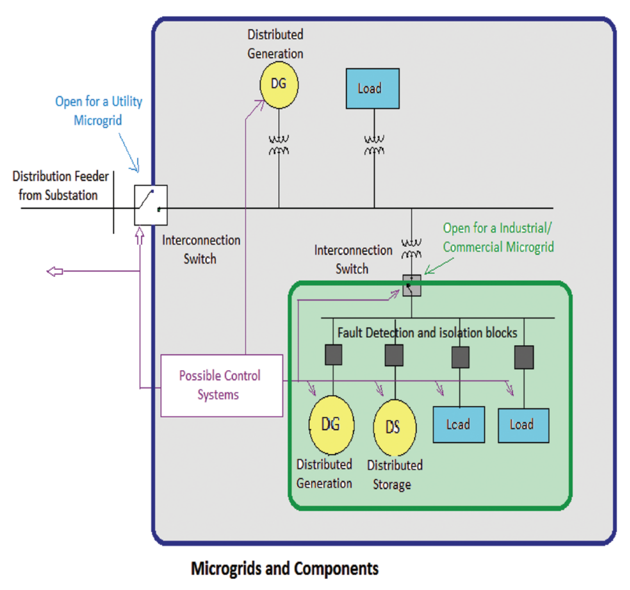

FIG. 1 TYPICAL MICRO-GRID CONFIGURATION [3]

A micro-grid 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 micro-grids 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 micro-grid configuration is shown in Figure 1.

The main feature of micro-grid system is its 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. 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. 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 [4-6].

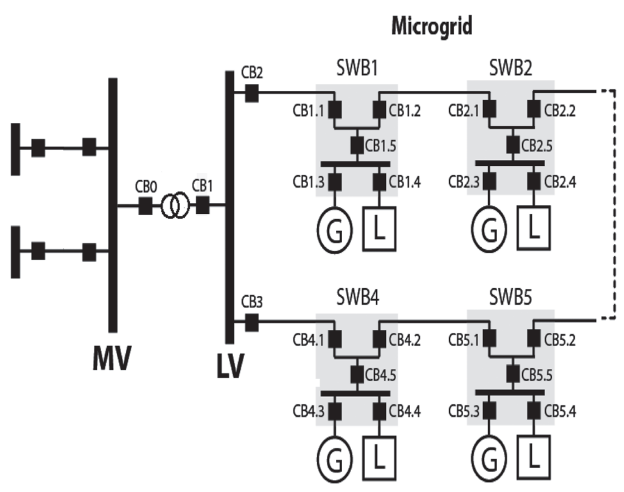

FIG. 2 PROTECTIVE SYSTEM FOR MICRO-GRIDS

Protection system in case of micro-grid as shown in Figure 2, must respond to both utility grid and micro-grid islanded faults

- Utility grid faults: protection isolates the micro-grid from the utility grid as rapidly as necessary to protect the micro-grid loads.
- Micro-grid faults: protection isolates the smallest possible section of the radial feeder to eliminate the fault.

Protection issues in Micro-grids

Connecting distributed generators to main grid like micro-grid, 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. 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 [7-8]:

1. loss of 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.

2. 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.

3. Protective Disconnection of Generators

Distributed Generators in micro-grids 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 micro-grid, the protection system of generators should employ different time delay which assures the selectivity of the system.

4. Islanding mode of Micro-grid Operation

Micro-grid islanding operation through intentional islanding has to be studied as an alternative option which drastically increases the reliability of system because generators in micro-grid are capable to supply loads in it even if grid is disconnected.

5. Single-Phase Connection in Micro-grid

Some of the distributed generation units outputs single-phase power in micro-grid 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

The power output of distributed generators in micro-grids is 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 micro-grid during islanding mode of operation also has to be examined.

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 ensure a selective operation for all possible faults types. Therefore, it is essential to use a new advanced and simple fault detection algorithm to detect 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.

3.0 CUMULATIVE SUM ALGORITHM

The type of relay used earlier 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 used in the literature using Kalman filtering and the phasorestimation approach [9], [10], [13]. 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. The traditional fault detection algorithms mainly use the differential principle for detecting faults and because of this they are sensitive to noises or spikes or variation of parameters in the signal. In this algorithm unlike the moving sum technique, an integral approach is applied [11]. 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. A cumulative-sum (CUSUM)-based fault detector is being employed widely as a means for noticing abrupt changes in various fields [11]. As power signals (sinusoidal) alternate, the two-sided CUSUM algorithm is appropriately designed for the purpose of fault detection in power system. The performance of the above method in presence of noise, amplitude and frequency variation has been studied to find out the behaviour of the algorithm during transient disturbances in the system. The CUSUM method for fault detection uses the current samples (s_k) of any phase and prepares two complementary signals such as

$$s_k(1) = s_k \text{and} s_k(2) = -s_k. \quad ....(1)$$

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

$$g_k(1) = \max\left(g_{k-1}(1) + s_k(1) - v, \ 0\right) \quad ....(2)$$

$$g_k(2) = \max\left(g_{k-1}(2) + s_k(2) - v, \ 0\right) \quad ....(3)$$

Where g_k ( )represents the test statistics and υ is the drift parameter in it. A fault is registered if

$$g_k(1) > h \text{or} g_k(2) > h \quad ....(4)$$

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, provides the low-pass filtering effect and determines the performance of the fault detection algorithm. In general, the value of   is little more than amplitude of current signals. With an increased level in the current signal due to transient disturbances, if any $s_k > \upsilon$, the corresponding g_k starts growing. As observed from Figure 3, the g_k value increases by a factor of the difference between s_k and υ. 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 (4). The two-sided approach fits here as a power system signal (sinusoidal) alternates and is advantageous from the detection-speed point of view.

Behavior of cumulative sum fault detection algorithms is checked under four cases as:

- *Case 1 :* Normal Sinusoidal wave
  Amplitude : 1 A
  Frequency : 50 Hz.
  Sampling rate : 1000 Hz.
  ϑ : 1.0
- *Case 2 :* Amplitude deviation
  Amplitude_1 : 1 A
  Amplitude_2 : 2 A (after 100 ms)
- *Case 3 :* Frequency variation
  Frequency_1 : 50 Hz
  Frequency_2 : 52 Hz (after 100 ms)
- *Case 4 :* Noise
  Distortion : 10 %. (after 100 ms)

(red curve = input signal, blue and pink = g_k's, test statistics of cumulative sum algorithm)

From the simulation it is clear that cumulative sum output is zero during normal sinusoidal wave of the input signal. As the algorithm works on the sampled value at an instant it is immune to frequency variation and by selecting higher threshold value algorithm output is unaffected by noise. Suppose due to some disturbance the sampled value $s_k > \upsilon$, then the test statistics g_k will give an non-zero value and if this value $g_k > h$, fault is registered. This property of cumulative sum algorithm is very useful for detecting faults in the system.

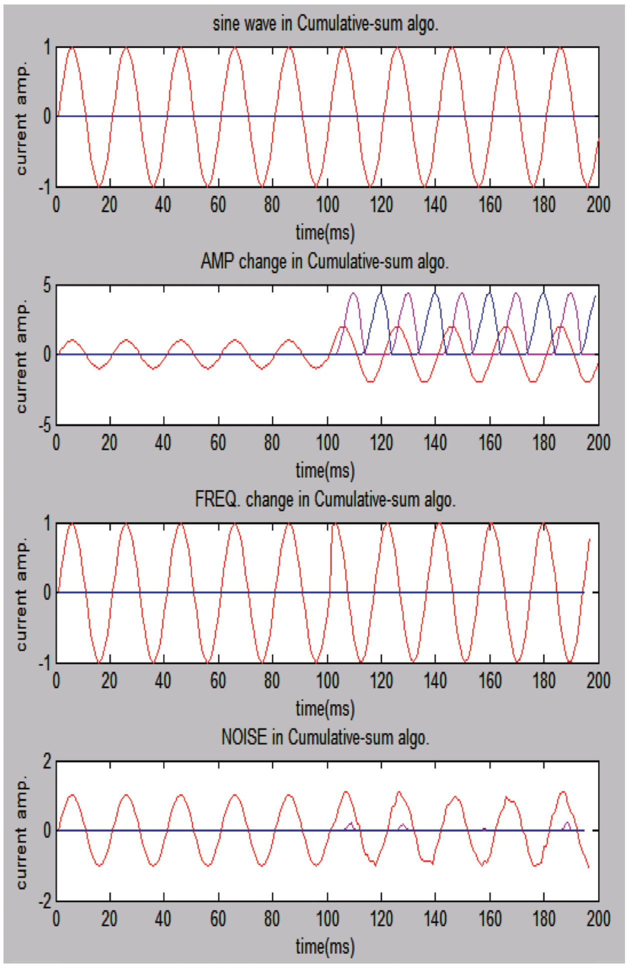

FIG. 3 CUMULATIVE SUM ALGORITHM SIMULATED RESULTS DURING (A) SINUSOIDAL WAVE, (B) AMPLITUDE CHANGE, (C) FREQUENCY VARIATION AND (D) NOISE

Cumulative Sum algorithm is 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.

4.0 IMPLEMENTATION OF PROPOSED ALGORITHM

The developed fault detection algorithm for micro-grids is constructed so that transient current disturbances are detected and defected region is isolated using circuit breaker. A tripping(fault detection) signal is initiated if a transient disturbance level is above the acceptable range. The flow chart of the proposed Fault Detection Algorithms is shown in Figure 4.

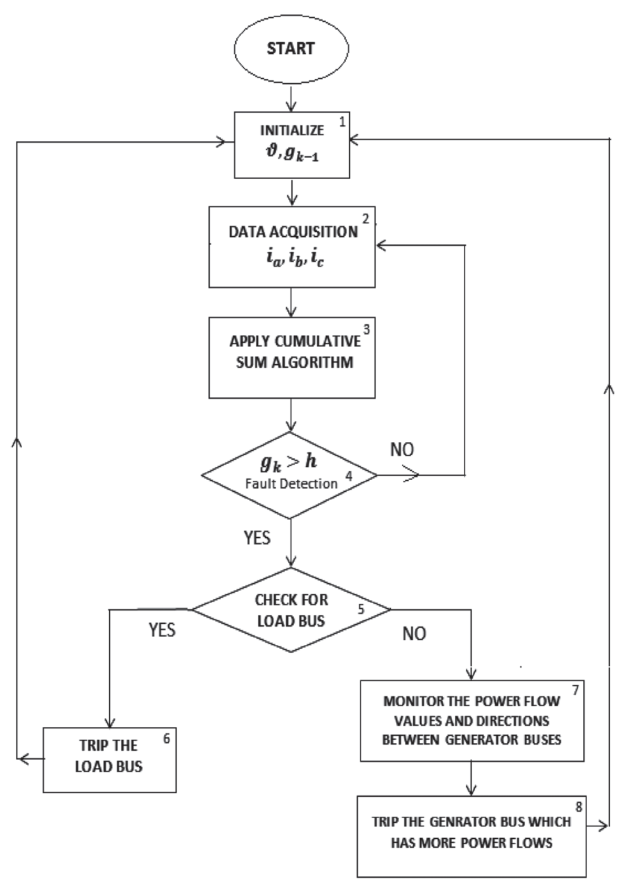

FIG. 4 FLOW CHART OF THE PROPOSED FAULT DETECTION ALGORITHM

The steps for detecting faults using proposed algorithm are:

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 all 3 input current phases.
4. Monitor the Fault Detection condition $g_k > h$ 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.

In the proposed algorithm we first detect the fault in micro-grid system by using simple and fast fault detector algorithm i.e. Cumulative Sum Fault detector algorithm. But due to bidirectional power flow property of micro-grid, it is found that cumulative sum algorithm alone was inadequate so we use the concept of power flow method to detect exact location of faults in the system. By introducing delay in fault detection algorithm at generator buses and by monitoring the power flows between them, the selectivity of the protective system is improved.

The implementation of proposed fault detection algorithm was done in Simulink and the experimental performances for the algorithm which comprised of Cumulative-Sum and power flow method for Fault Detection were conducted on a laboratory test micro-grid model which composed of the following components [12], [14-16]

1. A 208 V, 60 Hz supply (the utility grid);
2. A 2.5 kVA, 4-pole, 208 V synchronous generator(Hydro Unit);
3. A 1.8 kVA, 4-pole, 208 V synchronous generator (Hydro Unit);
4. Two 1.8 kW Y-connected resistive loads;

The fault detection block is used at all 4 buses to detection transient disturbances in the system. The current through each bus were collected using current sensors.

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 Figure 5.

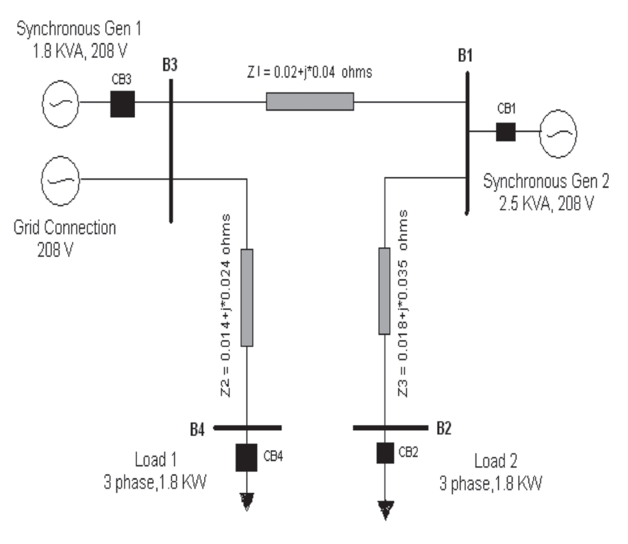

FIG. 5 4-BUS TEST MICRO-GRID SYSTEM

The step by step procedure for implementing the algorithm based on cumulative sum and power flow method for detecting faults was realized using simulinkSimPowerSystems tool box. Each fault detection block include current sensor which read samples at a sampling rate of 1 KHz from the current flowing through that bus. The output signals of current sensor were fed to cumulative sum algorithm which detects the presence of transient disturbances in the system. If due to presence of transients, the current amplitude goes above predefined threshold value, fault is registered by cumulative sum fault detection algorithm. The v value used in the above test micro-grid system is 28. so if current amplitude goes higher than 29 (h = 1) fault is detected.

In order to demonstrate the performance of the proposed fault detection algorithm comprises of cumulative sum and power flow method, several non-fault and fault transient disturbances were investigated. However, some of the test results are presented in this paper due to limits on the number of pages.

- Non-Fault Conditions: Grid connection
- Fault Conditions:
  - a - Single phase fault(SPG) at bus 4 in islanded mode
  - b - 3-phase fault at bus 2 in grid connection mode
  - c - Phase A-to-phase B fault at bus 1 in islanded mode

5.0 EXPERIMENTAL TEST RESULTS

A. *Grid disconnection and connection mode*

The main objective of this experimental test is to investigate the ability of the proposed algorithm-comprising of Cumulative Sum and power flow methods to identify and respond to non-fault transient disturbances. During test, the micro-grid test system is set to operate in islanded mode initially. As synchronous generator at bus 1 and 3 supplying power to loads at buses 2 and 4, utility grid is connected to islanded micro-grid system. The 3φ current signals for each buses are shown in Figure 6. It can be seen from Figure 6 that the utility grid connection to the islanded test micro-grid system creates transient disturbances in the 3φ current at all buses. These detected transient disturbances was a non-faulty one and are within the acceptable range so tripping is not required. The experimental results for the utility-grid connection demonstrate reliable and accurate identification and response to a non-fault transient disturbance in micro-grid system.

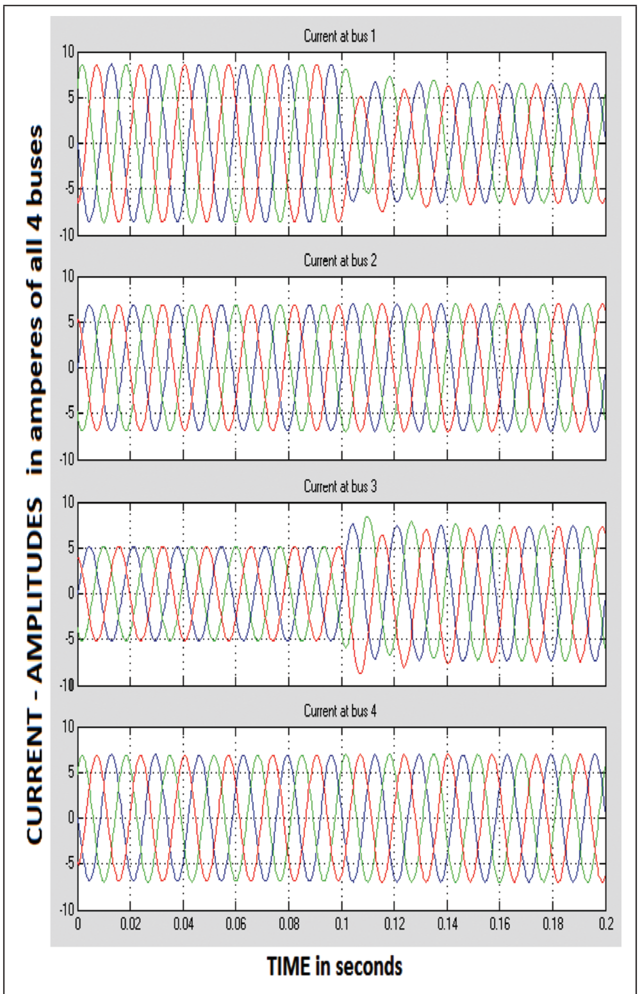

FIG. 6 GRID CONNECTION/DISCONNECTION

B. Single phse fault(SPG) at bus 4 in islanded mode

For this test, phase A-to-ground fault was created through activating a 1Ø controlled switch to connected phase A to ground point near bus 4 in islanded mode of operation of test micro-grid system. This test is conducted to demonstrate the ability of the proposed algorithm to detect, classify and respond to a single line-to-ground fault. Due to fault, it triggers higher level transient current at all generator buses and a 4th bus which is a load bus as shown in Figure 7. Here by introducing delay in fault detection algorithm block at all generator buses, fault detection block at load bus will detect the transient current faster so that the defected region was tripped quickly to avoid further damage to the system. Delay introduction helps to improve the selectivity of the protective system. From Figure 7, we can see that the proposed algorithm had successfully detected, classified and tripped the load bus 4 to maintain the stability in the system.

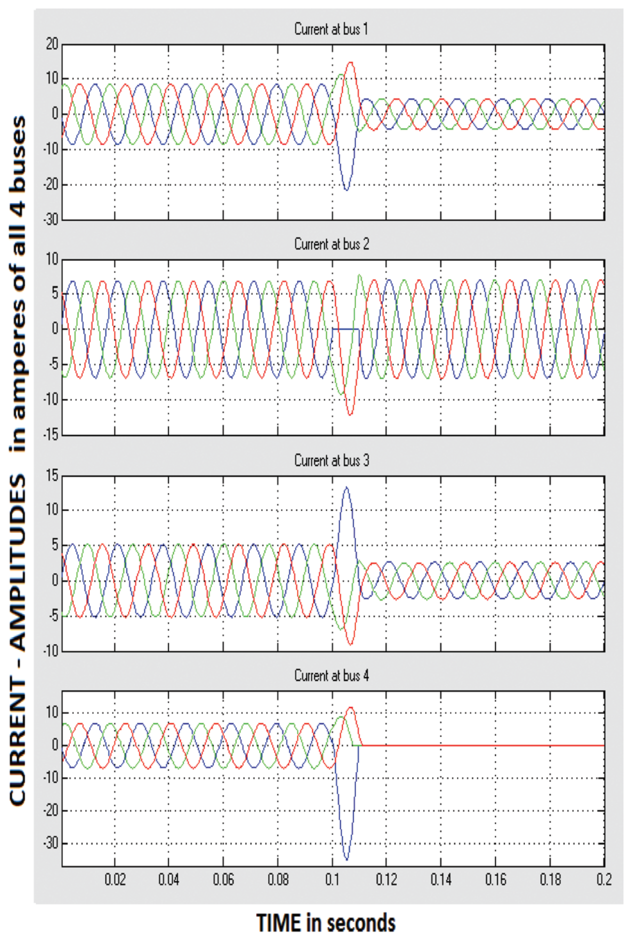

FIG. 7 SPG FAULT AT BUS 4 IN ISLANDED MODE

C. 3-phase fault at bus 2 in grid connection mode

The 3φ-to-ground fault at terminals of the load at Bus 2 was performed for purposes of investigating the responses of the proposed algorithm to a high level fault current in the grid connected mode. The loads at Buses 2 and 4 were being supplied by the generators at bus1 and 3 when a 3Ø–to-ground fault was connected to the ground at Bus 2. The detected 3Ø current signals for each protective device near all buses are shown in Figure 8.

The experimental output given in Figure 8 shows encouraging performances of the proposed algorithm comprising of cumulative sum and power flow method in terms of coordination, speed and accuracy. These results show that fault is detected at load bus 2 first due to delay introduction in all generator buses to improve selectivity of system. The fault detected signal at buses 1, 3 and 4 kept their trip signal unchanged(high). The fault at bus 2 triggered high transient current levels at all buses but transient current at bus 2 had higher value beyond the acceptable threshold value, so bus 2 region is tripped to kept micro-grid system in operating status.

D. Phase A-to-phase B fault at bus 1 in islanded mode

The line-to-line fault on the terminals of the generator Bus1 was performed in order to investigate the responses of proposed algorithm for detecting faults to an asymmetrical fault within the domain of the micro-grid in islanded mode of operation. As the generator buses 1 and 3 units were supplying the loads at Buses 2 and 4 and delivering power to the utility grid, phase A was suddenly connected to phase B (through a solid-state switch) on the terminals of the generator at bus 1. Figure 9 shows the fault detected 3Ø current signal for each buses for this experimental test.

One can see from Figure 9 that the line-to-line fault at the terminal of synchronous generator triggered high leveled transient disturbances in 3Ø current at all generator buses. By using the power flow method we found out the exact location of fault in the micro-grid system as due to fault the power flows was high near defected region.

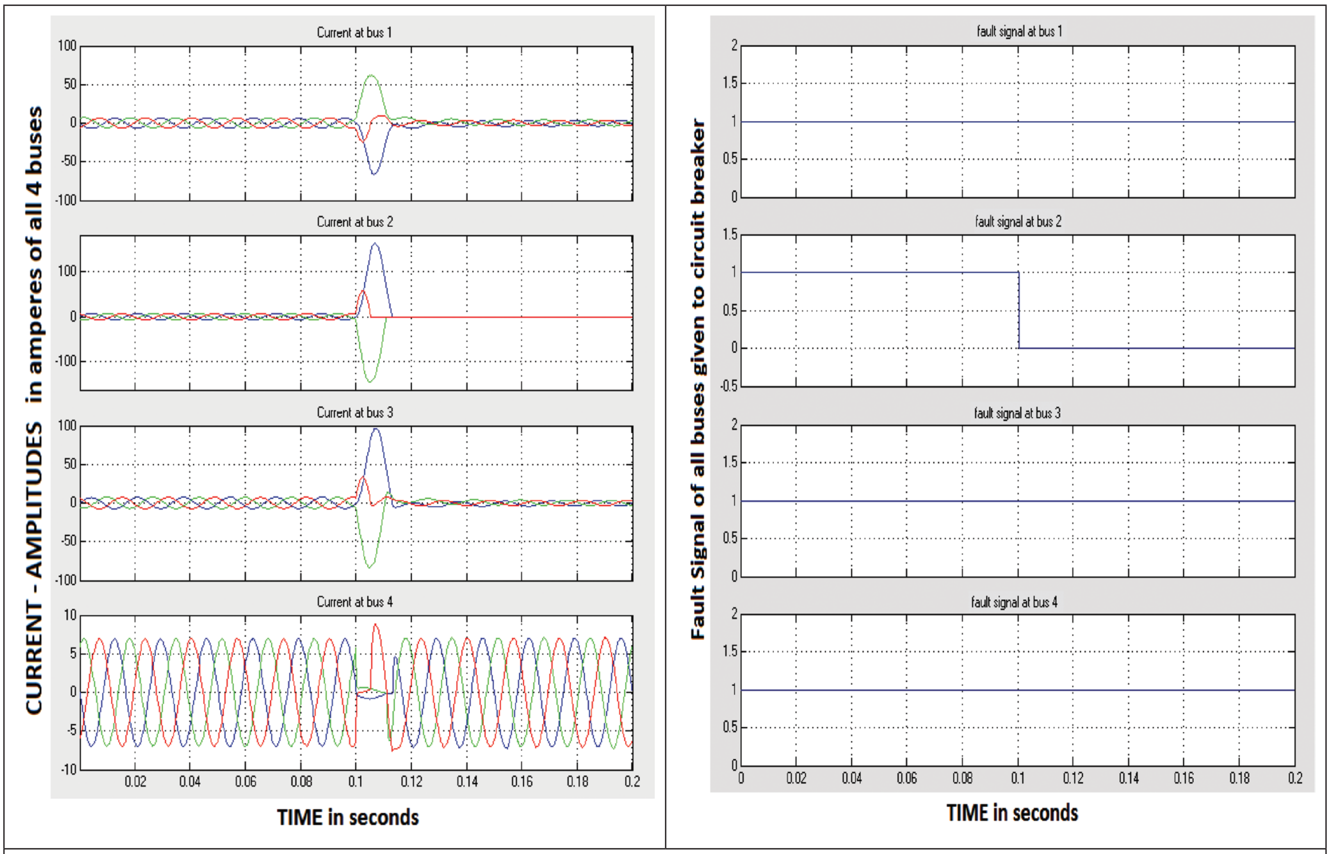

FIG. 8 EXPERIMENTAL RESPONSES OF PROPOSED FAULT DETECTION ALGORITHM WHEN 3Ø FAULT WAS OCCUR NEAR BUS 2 (A)3Ø FAULT AT BUS 2 IN GRID CONNECTED MODE AND (B) FAULT DETECTED SIGNAL AT ALL BUSES

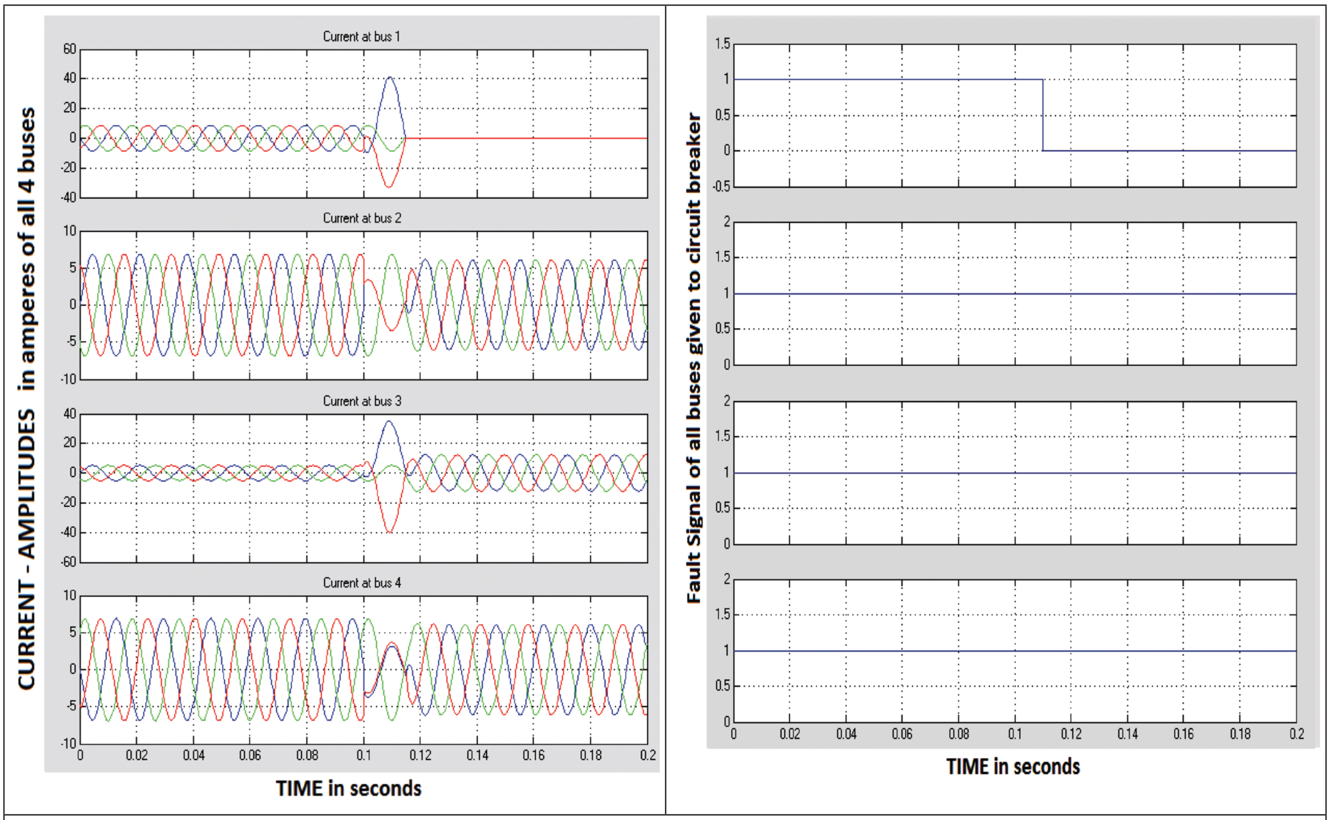

FIG. 9 EXPERIMENTAL RESPONSES OF PROPOSED FAULT DETECTION ALGORITHM WHEN PHASE A-TO-PHASE B FAULT OCCURRED NEAR BUS 1(A)PHASE A-TO-PHASE B FAULT AT BUS 1 IN ISLANDED MODE AND (B) FAULT DETECTED SIGNAL AT ALL BUSES

In this case, the power flows in opposite direction as in normal steady state condition which suggested that fault is near bus 1. As we used delay for improving selectivity of protective system, the output tripped signal given to circuit breaker near generator bus 1 was showing some time lag.

6.0 CONCLUSION

This paper has presented the development and experimental performances of a new simple and fast algorithm for detecting faults in micro-grid systems. The proposed algorithm comprises of cumulative sum and power flow method for fault detection. Cumulative sum based fault detection method alone is insufficient for detecting faults in a looped system like micro-grid, power flows concept is used along with it for exact detection of fault location in micro-grid systems.

It is found that a fault at any bus creates transient disturbances in currents flowing in all buses. The faults at load bus can be easily detected by using cumulative-sum fault detection algorithm and introducing delay in fault detection block at generator bus to improve selectivity of system. And fault at generator bus has been detected by using the concept of Power Flows. By monitoring theta (θ) value i.e. power flows through all generator buses we can find the actual location of faults in micro-grid (looped) system.

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