Open Access Journal

Journal of Power Technologies 98 (1) (2018) 57–69

journal homepage:papers.itc.pw.edu.pl

Communication Assisted Fuzzy based Adaptive Protective Relaying Scheme for Microgrid

B.K.Chaitanya[a], Atul Kumar Soni[b], Anamika Yadav[1]

[a] *Research Scholar, Department of Electrical Engineering, National Institute of Technology Raipur, C.G., India*
[b] *PG Student, Department of Electrical Engineering, National Institute of Technology Raipur, C.G., India*
[c] *Assistant Professor, Department of Electrical Engineering, National Institute of Technology Raipur, C.G., India*

Abstract

This study proposes a communication assisted fuzzy based adaptive protective relaying scheme for fault detection, fault classification and faulty phase identification of microgrid along with a solution to isolate the microgrid from the utility grid by disconnecting the static-switch. Any fault in the utility grid causes the microgrid to be isolated from the utility grid whereas if there is a fault in the microgrid it continues to operate with the utility grid. An adaptive fuzzy inference system has been developed using a separate fuzzy rule base for the two modes of operation of microgrid, i.e. islanded mode or grid connected mode. The Central Grid Status Communication System (CGSCU) is considered which monitors the status of PCC and sends a command signal to the relays so that the relay settings are updated with new rules for any transition in the mode of the microgrid. The fundamental phasor amplitude and zero sequence component of current signals are used as input features, fault detection, fault classification and faulty phase identification. A standard microgrid model IEC 61850-7-420 was simulated using MATLAB/SIMULINK. The proposed method is tested for all types of faults by varying fault parameters and also for dynamic situations such as connection/disconnection of DGs and loads. The test results substantiate the effectiveness of the method.

Keywords: Fault Detection, Fault Classification, Fuzzy Inference System (FIS), Grid Connected Mode, Islanded Mode, Microgrid

1. Introduction

In the present scenario in order to meet increasing power demand the existing power network is integrated with a microgrid consisting of low voltage distributed generating units feeding local loads. This has increased the complexity of the system while improving the reliability. A microgrid consists of distributed generator (DG) units, such as, wind, fuel cell, photovoltaic cell, diesel generators etc., along with some local storage so as to achieve independent control of power over a particular area [1]. Major advantages of the microgrid include reduced transmission losses and greenhouse gas emissions [2]. Microgrids operate in two modes, either independently or connected to the grid. A microgrid connected to the utility grid constitutes 'grid connected mode' (GCM) and disconnection of it can be termed 'islanded mode' (IM). The power flow is affected upon a fault arising in the network [3], which in turn impacts the conventional relaying schemes that no longer provide support as regards microgrid protection.

There is very limited literature available in respect of microgrid protection in comparison with high voltage power system networks. A fault detection strategy based on monitoring the transient response of the inverter current waveform using a transient monitoring function (TMF) was proposed in [4] but it requires an extra auxiliary control system at the inverter. In [5], an S-transform based protection scheme using differential energy is proposed, which has been applied in the two modes of operation of microgrid but has the limitation of increased computation time. In [6], another differential energy based protection scheme was proposed using the Hilbert–Huang transform, which detects the fault instant to issue a trip decision without classifying the fault type. A data-mining based protection scheme for microgrid was presented in [7], [8] but it requires a greater number of features for training. In [9], a microgrid protection scheme that depends on evolutionary computation technique for relay coordination was used. In [10], a protection and relay coordination scheme using sequence components was implemented.

*Corresponding author: Anamika Yadav, ayadav.ele@nitrr.ac.in
Email addresses: bkchaitanya05@gmail.com (B.K.Chaitanya), atulsoni.mailbox@gmail.com (Atul Kumar Soni), ayadav.ele@nitrr.ac.in (Anamika Yadav)

Relay coordination makes the scheme more complex. A protection strategy based on microprocessor-based relays for low-voltage microgrids was presented in [11].

Some adaptive and communication based approaches have also been developed. In [12], an adaptive protection scheme was proposed which works effectively when the penetration level of DG is greater, but was not tested in the islanded mode of operation. In [13], a ring architecture network integrated with microgrid and an adaptive zonal protection scheme was described. In [14], an adaptive directional overcurrent relaying technique based on the positive-sequence (PSQ) and negative-sequence (NSQ) superimposed currents was proposed for microgrid protection. In [15], communication assisted digital relays were implemented for microgrid protection, using a differential current scheme which does not involve time synchronization. A communication strategy based differential protection scheme using symmetrical components was proposed in [16], for a microgrid operating only in islanded mode. In [17], a microgrid protection scheme using communication and coordination between relays and distributed generators was proposed which requires the relay settings to change for any change in the grid configuration. Another technique was based on fisher information, which measures the stability of electric signals, and was combined with wavelet analysis for faulty phase selection of a power distribution network [18]. The optimal planning and clustering of smart low-voltage distribution networks into autonomous microgrids within a greenfield area is discussed in [19] using an imperialist competitive algorithm.

After reviewing various schemes for microgrid protection, it is apparent that most researchers focused on fault detection only and did not consider fault classification or faulty phase selection. The communication system provides an additional advantage in microgrid protection, as it can be used in conjunction with the fuzzy rule base. In view of this, the main aim of this paper is not only to detect the presence of fault in both grid connected mode and islanded mode of operation of the microgrid, but also to classify the fault type and identify the faulty phase(s) of the microgrid. This paper deals with a communication assisted fuzzy based adaptive protective relaying scheme, in a microgrid which was studied on a standard IEC 61850-7-420 model [20]. The proposed methodology initially identifies the presence of fault, whether in the microgrid or utility grid. For a fault in the utility grid, the microgrid is disconnected from the utility grid and operates in islanded mode, while for a fault in the microgrid it continues to operate in grid connected mode and should be able to properly identify the fault type so as to eliminate the faulty phase by selective phase tripping. The fundamental phasor amplitudes and sequence components of the current signals are extracted, which are used as the input features for the protection scheme which detects the fault and faulty phase(s) rapidly and thereby enables a single pole tripping function in the case of a single line to ground fault without interrupting the unaffected phases.

2. Microgrid Model

A single line diagram of the microgrid system is shown in Fig. 1. The details of the microgrid system are considered as in [8]. It consists of a utility grid of rating 2,500 MVA, 120 kV and three DG units. The first DG unit (DG-1) is wind power based with capacity of 6 MW. The other two include photovoltaic cell based solar power DG units (DG-2 & DG-3) of 1 MW each. The system operating frequency is 60 Hz. Pi-section lines were used for the interconnections and loads were connected at the respective buses, as shown in the figure.

3. Proposed Methodology

The complete flowchart of the proposed protective relaying scheme is shown in Fig. 2. The proposed methodology starts with identification of the fault, whether present in the microgrid or utility grid. For a fault in the utility grid, the microgrid is to be disconnected from the utility grid and must operate in islanded mode. And for a fault in the microgrid it should continue to operate in grid connected mode and should be able to correctly identify the fault type and faulty phase so as to enable selective phase tripping without affecting other healthy phases in the case of a single line to ground fault. The fundamental phasor amplitudes and sequence components of the current signals are extracted using the recursive DFT pre-processor and sequence analyzer respectively, which are used as the input features for the proposed fuzzy based protection scheme.

3.1. Design of Fuzzy Based Fault Identifier for Fault in Utility Grid/Microgrid (FIS-1)

The presence of a fault in the system is determined using the positive sequence phase angle (Φ) of current at bus-1 which determines whether the fault is present in the utility grid or microgrid. Φ_{low}, Φ_{medium} and Φ_{high} are the three ranges of phase angle which are selected using the triangular member function, which determines the presence of a fault in the utility grid or microgrid. In this study Mamdani type FIS was used. FIS-1 is designed for this task, showing $'0'$ for no fault, $'1'$ for a fault in the microgrid and $'-1'$ for a fault in the utility grid. The three rules used for the fault identifier are:

1. If phase angle is Φ_{low} then output is $'-1'$ (trip is TUG)
   (a) Fault is in utility grid, isolate microgrid from utility grid
2. If phase angle is Φ_{medium} then output is $'0'$ (trip is TN)
   (a) No fault in the system, continue to operate without disconnecting microgrid from utility grid
3. If phase angle is Φ_{high} then output is $'1'$ (trip is TN-GCM)
   (a) Fault is in microgrid, then identify the faulty phase by continuing to operate without disconnecting microgrid from utility grid.

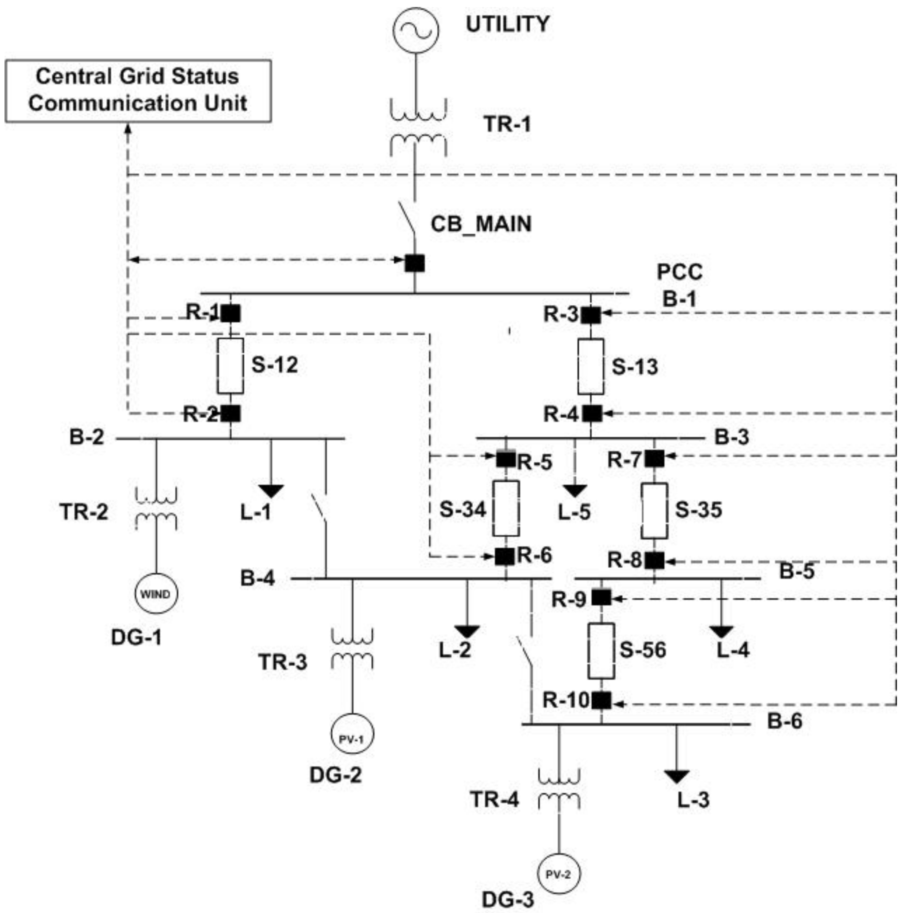

Figure 1: Schematic diagram of the microgrid according to IEC 61850-7-420

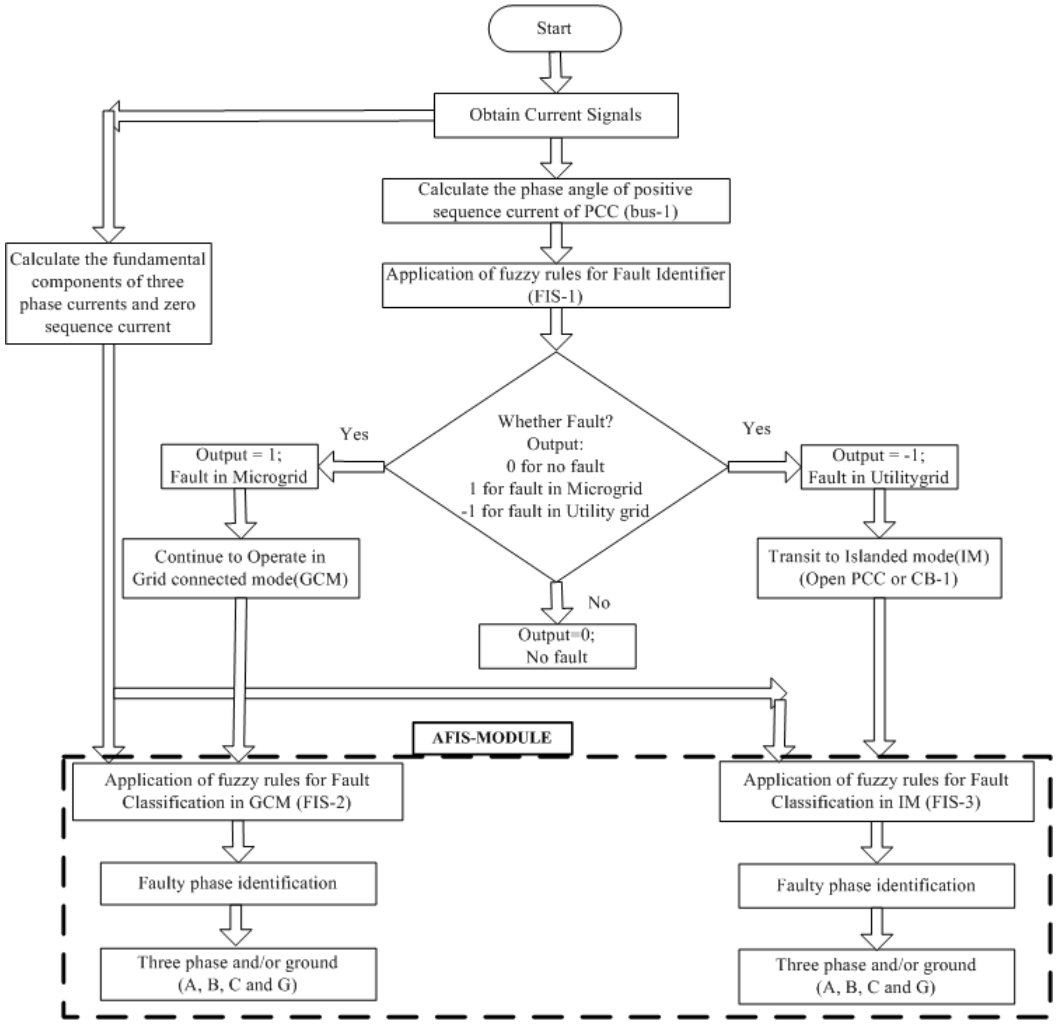

Figure 2: Flowchart of the proposed protective relaying scheme

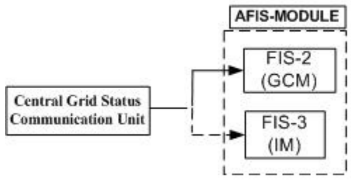

Figure 3: Central Grid Status Communication Unit (CGSCU) for AFIS-Module

For a fault in the utility grid, the microgrid is disconnected from the utility grid and should operate in IM and further identify the fault in the utility grid in order to restore the power and reconnect to the microgrid. For a fault in the microgrid, it can operate in GCM and further identify the faulty phase(s). For a fault in the microgrid in IM, an adaptive fuzzy module, which is explained in the next section, deals with the protective relaying of the microgrid.

3.2. Central Grid Status Communication Unit and Adaptive Fuzzy Inference System-Module

The characteristics of the fault currents are separate for the two modes of operation of the microgrid. In GCM the magnitude of currents in the system are high, due to the contribution from the utility grid, but in IM the disconnection of the utility grid reduces the magnitude of currents. This distinct characteristic of the fault currents in the two modes of microgrid demonstrates the need to design a separate fuzzy rule base, which is designed as an Adaptive Fuzzy Inference System-Module (AFIS-Module) to protect the microgrid. The AFIS-Module is placed in each section of the distribution lines. Each AFIS-Module consists of two fuzzy inference systems (FIS-2 & FIS-3), where FIS-2 is specified for GCM and FIS-3 for IM. Depending upon the mode of operation of the microgrid the fuzzy rule base FIS-2 is activated for GCM and FIS-3 for IM operation. The Central Grid Status Communication Unit (CGSCU) as illustrated in Fig. 3 is a processing unit used for communicating the status of the grid to update the fuzzy rules for relays to operate effectively.

CGSCU monitors the status of PCC as to whether the utility grid is connected to or disconnected from the microgrid. Depending on the status of PCC, CGSCU sends an interrupt to perform an update of the fuzzy rule base of relays with suitable settings (FIS-2 for GCM and FIS-3 for IM) for the purpose of issuing an accurate trip decision.

3.3. Design of Fuzzy Inference Systems (FIS-2 & FIS-3) for Faulty Phase Selection and Classification

Based on the output of FIS-1, CGSCU sends an interrupt to the relays to update the fuzzy rule base corresponding to the mode of operation of the microgrid. For the microgrid operating in GCM, FIS-2 is activated and for the islanded mode FIS-3 is activated. Each FIS includes separate rules for the detection of faulty phase(s) and ground fault detection, thereby classifying the type of fault. The fundamental components and zero sequence components of currents are employed to classify faults. A Mamdani type fuzzy logic designer with triangular membership functions was used.

The fuzzy rules are designed using fundamental components of individual phase currents to identify the faulty phase. Taking one phase as reference, the fuzzy rules were designed and the same rules considered for other phases in order to identify the faulty phase. Moreover, zero sequence current was used to detect whether the fault involves ground or not. The membership function of the input signal for phase selection is divided into three classes: low, medium and high while the output membership function is divided into two ranges: low and high. The fuzzy inference systems (FIS-2 and FIS-3) are separate for the two modes of operation of the microgrid, as explained hereunder.

3.4. Grid connected mode (FIS-2)

For a fault in section S-12 the fundamental components of current signals at bus-1 (I_{F-B1}) and bus-2 (I_{F-B2}) are utilized to identify the faulty phase.

1. . If I_{F-B1} is low and I_{F-B2} is low, then don't issue trip signal.
2. If I_{F-B1} is medium and I_{F-B2} is low, then don't issue trip signal.
3. If I_{F-B1} is high and I_{F-B2} is low, then issue trip signal.
4. If I_{F-B1} is low and I_{F-B2} is medium, then don't issue trip signal.
5. If I_{F-B1} is medium and I_{F-B2} is medium, then don't issue trip signal.
6. If I_{F-B1} is high and I_{F-B2} is medium, then issue trip signal.
7. If I_{F-B1} is low and I_{F-B2} is high, then issue trip signal.
8. If I_{F-B1} is medium and I_{F-B2} is high, then issue trip signal.
9. If I_{F-B1} is high and I_{F-B2} is high, then issue trip signal.

In a similar manner, the fuzzy rules for section S-13 use currents I_{F-B1} and I_{F-B3} while for section S-35 fuzzy rules use currents I_{F-B3} and I_{F-B5} as the aforementioned rules.

But the fuzzy rules for section S-34 use only the current signal of bus-3 (I_{F-B3}) as the other bus-4 is connected to the photovoltaic source causing very much less contribution to the fault current due to inverter operation. The rules are as follows:

1. If I_{F-B3} is low, then don't issue trip signal.
2. If I_{F-B3} is medium, then don't issue trip signal.
3. If I_{F-B3} is high, then issue trip signal.

The fuzzy rules for section S-56 are defined in a similar way and use only the current signal of bus-5 (I_{F-B5}) as bus-6 is also connected to the photovoltaic source causing very much less contribution to the fault current due to inverter operation.

Table 1: Comparative Assessment

Authored by	Techniques used	Fault Detection	Fault Classification	Fault Phase Selection	Grid-connected mode	Islanded mode	Sampling Frequency	Operating Time	Fault type	FIA	Fault location
H Nikkhajoei et. al. [12]	Sequence components	Yes	No	No	Detects	Detects	-	2.5 cycles	LG, LL only	0°-360°	-
E Sortomme et. al. [10]	Communication assisted Differential currents	Yes	No	No	Detects	Detects	960Hz	1/8-1/4 cycle	LG only	-	At mid-point only
HH, Zeineldin et. al. [15]	Differential currents	Yes	No	No	Detects	Detects	-	3 cycles	-	0°-180°	-
S Kar et. al. [5]	S-Transform	Yes	No	No	Detects	Detects	1.2 kHz	4 cycles	10 types	0°-360°	0-20km
A Gururani et. al. [6]	Hilbert-Transform	Yes	No	No	Detects	Detects	1.2 kHz	2 cycles	10 types	0°-360°	0-20km
DP Mishra et. al. [7]	Combined Wavelet and Data Mining	Yes	Yes	No	Detects	Detects	6.66 kHz	1.5-2.5 cycles	10 types	0°-180°	At mid-point only
Proposed Scheme	Fuzzy based scheme	Yes	Yes	Yes	Detects	Detects	1.2 kHz	¼-1 cycle	10 types	0°-360°	2-18km

'Yes' = considered, 'No' = not considered, and '-' = not considered/mentioned

3.5. *Islanded Mode (FIS-3)*

The fuzzy rules which are framed to identify the faulty phase in section S-12 use only the current signal of bus-2 (I_{F-B2}) the currents at bus-1 are zero due to the disconnection of the utility grid. The fuzzy rules are defined as follows:

1. If I_{F-B2} is low then don't issue trip signal.
2. If I_{F-B2} is medium, then don't issue trip signal.
3. If I_{F-B2} is high, then issue trip signal.

Likewise, the fuzzy rules are defined for section S-13 using the current signal of bus-3 (I_{F-B3}) only. The fuzzy rules for section S-34 and S-56 use only the current signal of bus-3 (I_{F-B3}) and bus-5 (I_{F-B5}) respectively as bus-4 and bus-6 are connected to the photovoltaic sources which don't supply high currents as the inverters are included. For sections S-35 the current signals at bus-3 (I_{F-B3}) and bus-5 (I_{F-B5}) are utilized.

3.6. *Fuzzy Rules for Ground Fault Detection in both GCM and IM*

The zero sequence component of currents (I_0) at the respective buses of the particular sections are utilized to frame the fuzzy rules for ground fault detection for both grid connected as well as islanded modes. These ground fault detection rules are included in the fuzzy rule base of FIS-2 and FIS-3. Both the inputs and outputs are divided into two membership functions: low and high. The fuzzy rules are illustrated as follows:

1. If I_{0-B1} and I_{0-B2} and I_{0-B3} and I_{0-B4} and I_{0-B5} and I_{0-B6} are low, then ground is not involved in fault loop.
2. If eitherI_{0-B1} or I_{0-B2} or I_{0-B3} or I_{0-B4} or I_{0-B5} or I_{0-B6} is high, then it is a ground fault.

4. Simulation Results

The microgrid model was simulated in MATLAB/SIMULINK environment with a sampling frequency of 1.2 kHz at 60 Hz base frequency (20 samples per cycle). The fuzzy based adaptive relaying scheme was tested for a wide variety of operating conditions and fault situations which includes:

Dynamic operating conditions:

- Operating modes: Grid connected mode and islanded mode.
- When some DGs are out (e.g., DGpv out).
- Variations in system loads.

Fault situations:

- Faults on different distribution line sections: (S-12, S-13, S-34, S-35, S-56).
- Faults at different locations on distribution lines: (2 to 18kms of each distribution line).
- Different types of faults (LG, LL, LLG, and LLL).
- Variation in fault resistance: R_f = 0.01Ω, 2Ω.
- Variation in fault inception angle (0^0, 90^0).

The test results – with varying fault location, inception angle, resistance, type of fault in different line sections – are presented for fault detection and fault classification in Table 2 and Table 3 respectively. The test results shown in Table 2 indicate the results in GCM with varying fault parameters and it can be observed that the response time of the phase(s) involved and/or ground is less than one cycle in all the tested fault cases. The test results shown in Table 3 indicate in IM operation of the microgrid the proposed scheme requires less response time after the fault inception to detect the fault. The results are discussed in detail in the sections that follow.

Table 2: Test Results of Fuzzy Based Fault Detection and Classification in Grid Connected Mode

Faulty Section	Type of Fault	Fault Location (km)	Fault Inception Time (s)	Time at which faulty phase/ground is detected (s)			
				A	B	C	G
S-12	BG	3	1.625	-	1.634	-	1.627
	CG	5	1.65	-	-	1.663	1.652
	AB	7	1.675	1.684	1.685	-	-
	ABG	9	1.7	1.71	1.707	-	1.702
	BC	11	1.725	-	1.732	1.738	-
	CA	15	1.775	1.787	-	1.786	-
	CAG	17	1.775	1.782	-	1.781	1.777
	ABC	19	1.8	1.813	1.806	1.81	-
S-13	AG	1	1.6	1.613	-	-	1.603
	BG	3	1.625	-	1.634	-	1.627
	AB	7	1.675	1.684	1.684	-	-
	ABG	9	1.7	1.71	1.707	-	1.702
	BCG	13	1.725	-	1.757	1.761	1.753
	CA	15	1.775	1.787	-	1.786	-
	CAG	17	1.775	1.684	-	1.785	1.777
	ABC	19	1.8	1.808	1.806	1.809	-
S-34	AG	1	1.6	1.612	-	-	1.603
	BG	3	1.625	-	1.635	-	1.627
	AB	7	1.675	1.686	1.685	-	-
	ABG	9	1.7	1.712	1.71	-	1.702
	BC	11	1.725	-	1.739	1.738	-
	BCG	13	1.75	-	1.764	1.764	1.753
	CA	15	1.775	1.789	-	1.793	-
	ABC	19	1.8	1.813	1.814	1.814	-
S-35	AG	1	1.6	1.613	-	-	1.603
	BG	3	1.625	-	1.636	-	1.627
	AB	7	1.675	1.684	1.685	-	-
	ABG	9	1.7	1.71	1.708	-	1.703
	BCG	13	1.75	-	1.757	1.762	1.755
	CA	15	1.775	1.787	-	1.787	-
	CAG	17	1.775	1.785	-	1.787	1.778
	ABC	19	1.8	1.809	1.807	1.808	-
S-56	AG	1	1.6	1.617	-	-	1.604
	CG	5	1.65	-	-	1.663	1.652
	AB	7	1.675	1.684	1.684	-	-
	ABG	9	1.7	1.709	1.707	-	1.702
	BC	11	1.725	-	1.732	1.732	-
	CA	15	1.775	1.786	-	1.786	-
	CAG	17	1.775	1.784	-	1.782	1.778
	ABC	19	1.8	1.808	1.806	1.806	-

Table 3: Test Results of Fuzzy Based Fault Detection and Classification in Islanded Mode

Faulty Section	Type of Fault	Fault Location (km)	Fault Inception Time (s)	Time at which faulty phase/ground is detected (s)			
				A	B	C	G
S-12	AG	1	1.6	1.605	-	-	1.602
	CG	5	1.65	-	-	1.655	1.652
	AB	7	1.675	1.680	1.681	-	-
	ABG	10	1.7	1.704	1.707	-	1.702
	BC	11	1.725	-	1.731	1.731	-
	BCG	12	1.75	-	1.757	1.754	1.752
	CAG	15	1.775	1.778	-	1.779	1.777
	ABC	17	1.8	1.804	1.807	1.804	-
S-13	AG	1	1.6	1.606	-	-	1.602
	CG	4	1.65	-	-	1.656	1.652
	AB	6	1.675	1.685	1.685	-	-
	ABG	7	1.7	1.706	1.708	-	1.702
	BCG	10	1.75	-	1.759	1.756	1.752
	CA	12	1.775	1.780	-	1.780	-
	ABC	16	1.8	1.805	1.808	1.805	-
S-34	AG	4	1.6	1.604	-	-	1.602
	BG	7	1.625	-	1.632	-	1.627
	AB	5	1.675	1.679	1.680	-	-
	ABG	6	1.7	1.704	1.707	-	1.702
	BC	8	1.725	-	1.732	1.731	-
	BCG	9	1.75	-	1.757	1.755	1.752
	CAG	11	1.775	1.779	-	1.780	1.777
	ABC	2	1.8	1.804	1.807	1.804	-
S-35	AG	1	1.6	1.606	-	-	1.602
	BG	2	1.625	-	1.633	-	1.627
	AB	5	1.675	1.685	1.685	-	-
	ABG	7	1.7	1.705	1.707	-	1.702
	BCG	10	1.75	-	1.758	1.755	1.752
	CA	12	1.775	1.780	-	1.780	-
	CAG	14	1.775	1.779	-	1.780	1.778
	ABC	16	1.8	1.805	1.809	1.807	-
S-56	AG	4	1.6	1.605	-	-	1.602
	BG	7	1.625	-	1.632	-	1.627
	ABG	6	1.7	1.704	1.707	-	1.702
	BCG	9	1.75	-	1.758	1.754	1.752
	CA	11	1.775	1.779	-	1.779	-
	CAG	13	1.775	1.778	-	1.779	1.778
	ABC	15	1.8	1.804	1.805	1.804	-

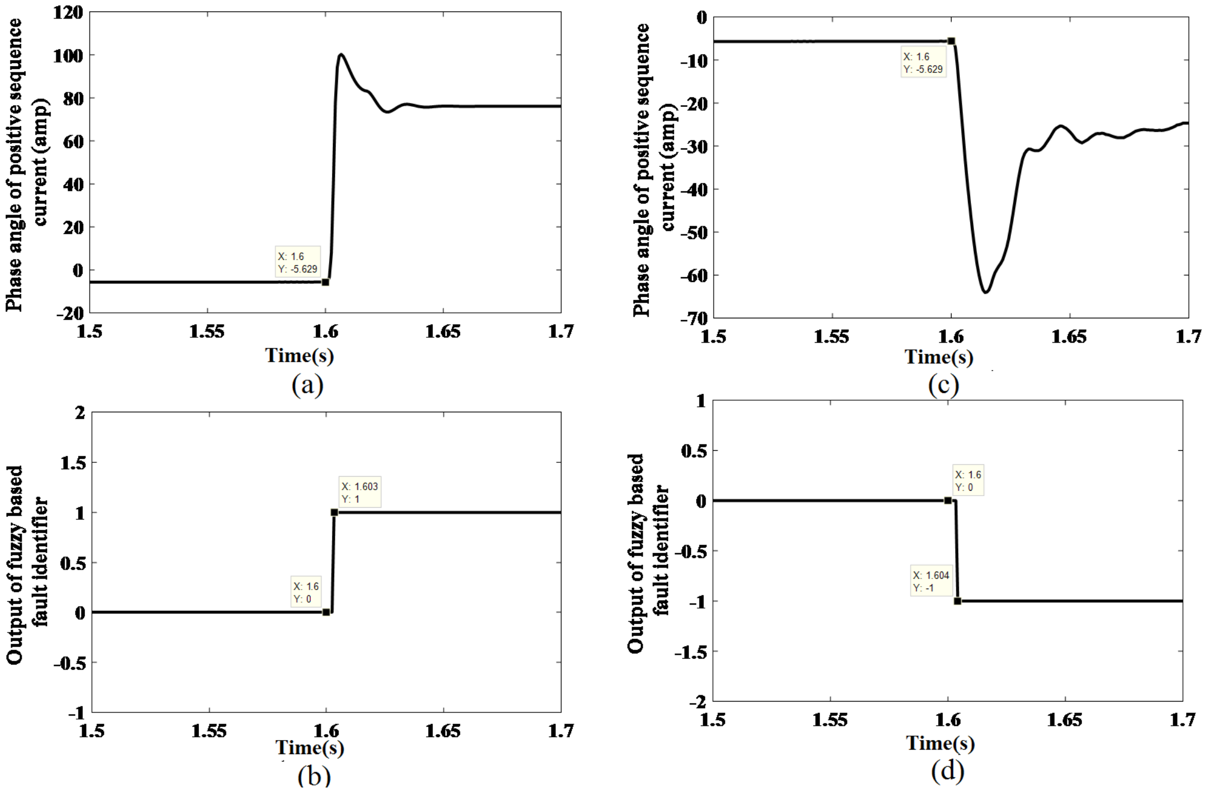

Figure 4: Performance of the fuzzy based fault identifier during AG fault at 1.6s (a) Input during fault in Microgrid (b) output fault in Microgrid (c) Input during fault in utility grid (d) output fault in utility grid

4.1. Performance of Fault Identifier for Fault in Utility Grid/Microgrid (FIS-1)

The fault identifier FIS-1 identifies the existence of fault in the utility grid or microgrid. The phase angle of positive sequence currents of PCC are given as inputs to the fault identifier. When the system is operating in normal condition, the output will always be zero. Upon the occurrence of fault in the system, the output tends to change to either +1 or -1 depending upon the presence of fault in either direction. Fig. 4(a) shows the input of the fuzzy based fault identifier during fault in the microgrid at 1 km from bus-1 at 1.6 s. The Fig. 4(b) shows the output of the fuzzy based detector and the output is '0' up to 1.6 s of time and starts to increase after 1.6 s, which displays a fault in the microgrid and reaches +1 at 1.603 s time, thus the proposed scheme takes 3 ms to detect the fault. Similarly, Fig. 4(c) and Fig. 4(d) show the input and output for an AG fault in the utility grid at 18 km from bus-1 at 1.6 s. The output of the fault detector is '0' up to 1.6 s and after 1.6 s it started decreasing and reached -1 at 1.604 s, thus it takes 4 ms to detect the fault in the microgrid.

4.2. Performance in the case of Grid Connected Mode

The performance of the proposed scheme was tested in grid connected mode for a number of fault cases in different line sections and it is observed that the fault current in this mode is high compared to the islanded mode of operation.

An ABG fault is considered in the line section-34 (S-34) at 9kms from bus-3 at 1.6 s fault inception time, and the test results are depicted in Fig. 5. Fig. 5(a) shows the fundamental components of current signals of bus-3, which are the inputs to the fuzzy based fault classifier. Fig. 5(b) shows the output of the fuzzy based fault detector which is low (0) prior to the fault inception at 1.6 s, thereafter it goes high (1) after 1.61 s, thus the fault is detected 10ms after inception of the fault. Subsequently, Fig. 5(c) shows the output of the fuzzy based fault classifier in which phases A, B go high (1) after 11ms while C remains low (0) and G goes high (1) after 4ms, confirming that the fault type is LLG fault involving A, B phases and ground. Thus, the proposed scheme rapidly detects the fault and identifies the faulty phase.

4.3. Performance in the case of Islanded Mode

The proposed scheme was evaluated in islanded mode of operation and is explained in this section. As the magnitude of current at various buses is very small compared to the grid connected mode, the protection task in this mode is taken care of by using the fuzzy based adaptive fault classifier (i.e. FIS-3). For an ABC fault in islanded mode in section-13 (S-13) at 18 kms from bus-1 at 8 s, Fig. 6 demonstrates the results of the proposed scheme. Fig. 6 (a) shows the fundamental components of current signals of bus-3, which are the only inputs of FIS-3 as the magnitudes of the current signals of bus-1 are zero for the islanded mode as the utility

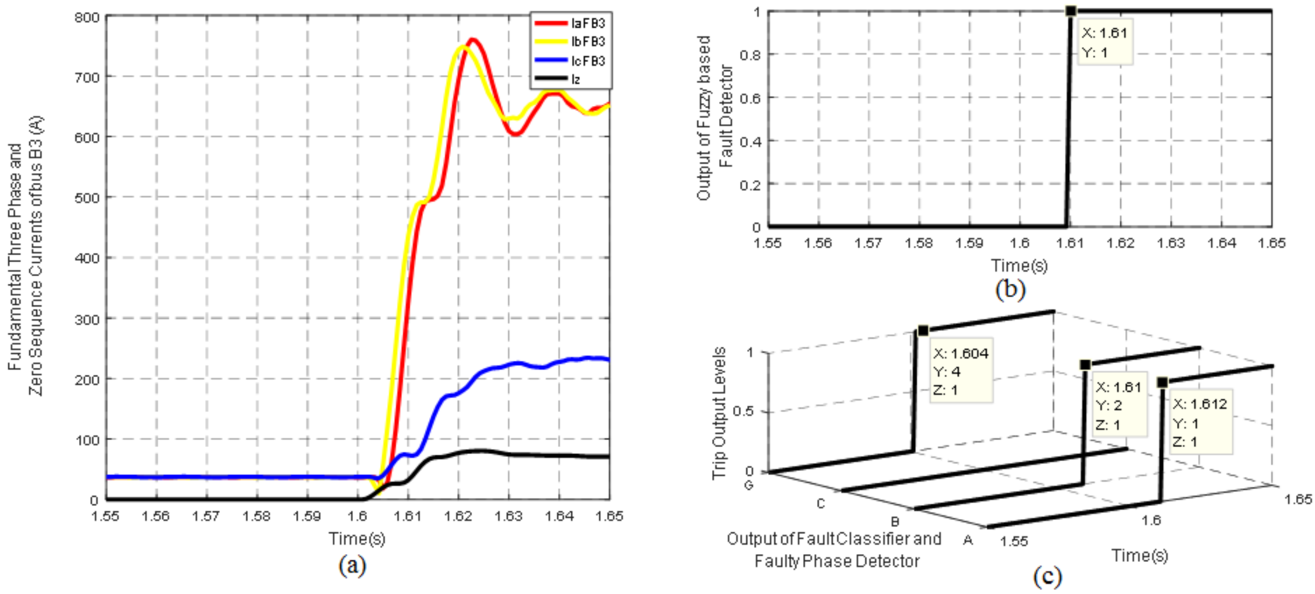

Figure 5: Test result of ABG fault in section S-34 at 9kms with R_F = 0.01Ω, t_i = 1.6s in GCM (a) Fundamental three phase currents and zero sequence currents of bus-3 (b) Fault detection (c) Fault classification

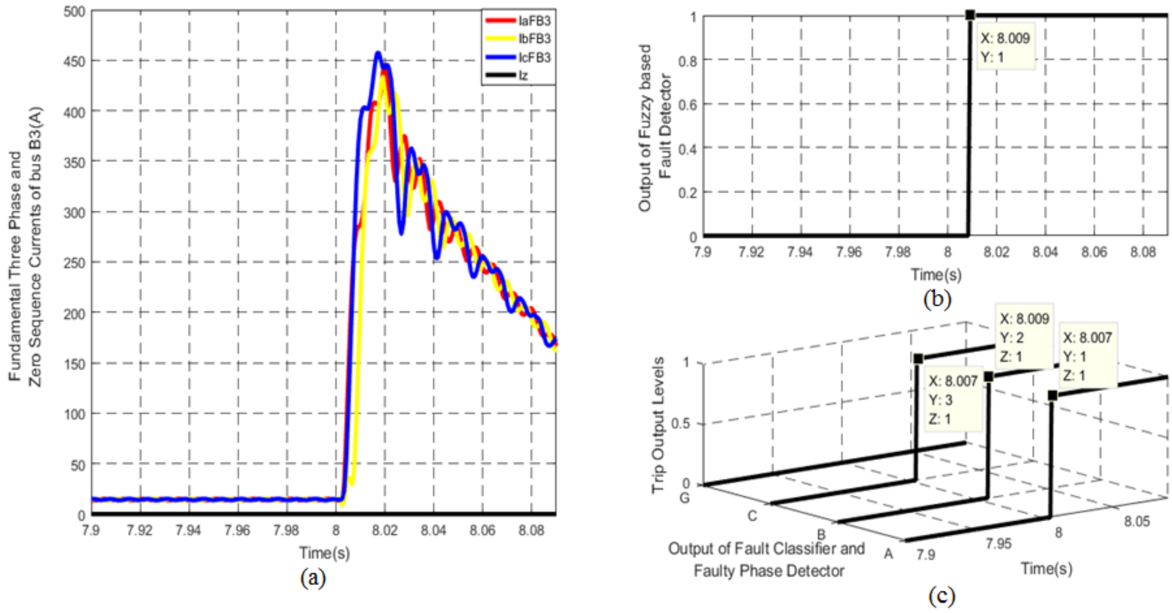

Figure 6: Test result of ABC fault in section S-13 at 18kms with R_F = 2Ω, t_i = 8s in IM (a) Fundamental three phase currents and zero sequence currents of bus-3 (b) Fault detection (c) Fault classification

grid is disconnected. Fig. 6(b) exemplifies the output of the fuzzy based fault detector, which rises from 0 to 1 (high) after 8.009 s. Thus, the fault detection time is 9ms in this case. Fig. 6(c) depicts the four outputs of fault classification, i.e., phases A, B, C which become high (1) after 8.007 s, 8.009 s, 8.009 s respectively and G remains low (0), which confirms that the fault type is a three phase fault, i.e., ABC fault. Thus, the proposed scheme correctly identifies the far end fault in section-13 within 9 ms.

4.4. Performance in the case of Disconnection of DG unit

The performance of the proposed scheme was tested for the disconnection of DG-2 (PV-1) of 1MW at bus-4 at time instant t = 1.7 s which should not have any impact on the proposed protection scheme. The test results are depicted in Fig. 7 wherein Fig. 7(a) and Fig. 7(b) show the fundamental components of the current signals of bus-4 and bus-2 respectively, as these two buses are nearer to DG-2 which is most influenced by disconnection of the DG unit. Subsequently, Fig. 7(c) shows the output of the fault detector, which remains low (0) throughout the simulation time.

Further, Fig. 7(d) shows the output of the fuzzy based fault classifier, which also remains low (0) and unaffected, confirming that there is no fault in the system. Thus, it concludes that the proposed scheme is reliable and robust in the case of disconnection of DGs as well.

4.5. Performance in the case of Load Variation

The performance of the proposed scheme has also been tested for sudden load variation, by adding a load-4 of 1 MW, 0.2 MVAR at bus-5 at 1.6 s, which correspond to change in currents at bus-3 and bus-5. In this the performance of the proposed scheme is exemplified in Fig. 8. The Fig. 8(a) and Fig. 8(b), showcase the fundamental components of current signals of bus-3 and bus-5 respectively wherein there is sudden change in all the three phase currents after 1.6 s. Subsequently Fig. 8(c) and Fig. 8(d) show the outputs of fuzzy based fault detector and fault classifier respectively which remains low (0) and unaffected. Thus the results substantiate that, the proposed scheme is not affected by variation in load.

5. Comparison with Existing Schemes

The proposed fuzzy based protective relaying scheme for the microgrid was compared with the recently reported protection schemes for the microgrid. A comparison of different protection schemes with respect to different parameters and conditions is shown in tabular form in Table 3. It can be seen that most of the techniques [5, 6, 10, 12, 15] deal with only fault detection. Only one scheme [7] classifies the fault, but it does not identify the faulted phase; also its response time and sampling frequency are high and consider fault at the midpoint of the line only. Further, the proposed scheme detects the fault rapidly compared to the other techniques. Moreover, the reliability of the proposed scheme is not affected by change in the operating mode of the microgrid; it detects the fault and also identifies the fault type/faulty phases rapidly during grid connected and islanded modes of operation of the microgrid.

6. Conclusion

Only very limited research papers are available that deal with protection of the microgrid and they are limited to only the issue of fault detection. This paper presents new fault detection, fault classification and faulty phase identification schemes for the microgrid. The technique is based on fundamental current signals of all the terminals of the microgrid. The performance of the proposed technique was evaluated by simulating a standard microgrid model IEC 61850-7-420 using a MATLAB software package. The results clearly indicate that the presented technique is able to detect the fault correctly, even when the fault is near the terminal points. At the same time, it is capable of identifying the faulted phase and the type of fault. The proposed scheme also identifies whether the fault is present in the utility grid or in the microgrid so that the PCC disconnects the microgrid. The response time is within the ¼-1 cycle even in the presence of the wide variation in system and fault parameters. In the final analysis, a comparison of the proposed fuzzy inference system based protective relaying scheme with the existing technique shows its superiority. The complete protection scheme is very simple and is feasible for practical implementation, in contrast to other training based and conventional protection schemes.

References

[1] Y. Li, F. Nejabatkhah, Overview of control, integration and energy management of microgrids, J. Mod. Power Sys. Clean Energy 2(3) (2014) 212–222.

[2] B. S. Hartono, Y. Budiyanto, R. Setitabudy, Review of microgrid technology, in: International Conference on QiR, 2013.

[3] N. D. Hatziargyriou, A. P. S. Meliopoulos, Distributed energy sources: Technical challenges, in: IEEE Power Engineering Society Winter Meeting, 2002.

[4] I. Sadeghkhani, M. E. H. Golshan, A. M. Sani, J. M. Guerrero, A. Ketabi, Transient monitoring function–based fault detection for inverter-interfaced microgrids, IEEE Transactions on Smart Grid-doi:10.1109/TSG.2016.2606519.

[5] S. Kar, S. R. Samantaray, Time-frequency transform-based differential scheme for microgrid protection, IET Generation, Transmission & Distribution 8 (2) (2014) 310–320.

[6] A. Gururani, S. R. Mohanty, J. C. Mohanta, Microgrid protection using hilbert–huang transform based-differential scheme, IET Generation, Transmission & Distribution 10 (15) (2016) 3707–3716.

[7] D. P. Mishra, S. R. Samantaray, G. Joos, A combined wavelet and data-mining based intelligent protection scheme for microgrid, IEEE Transactions on Smart Grid 7 (5) (2016) 2295 – 2304.

[8] S. Kar, S. R. Samantaray, M. D. Zadeh, Data-mining model based intelligent differential microgrid protection scheme, IEEE Systems Journal 11 (2) (2017) 1161 – 1169.

[9] W. K. A. Najy, H. H. Zeineldin, W. L. Woon, Optimal protection coordination for microgrids with grid-connected and islanded capability, IEEE Transactions On Industrial Electronics 60 (4) (2013) 1668 – 1677.

[10] E. Sortomme, S. S. Venkata, J. Mitra, Microgrid protection using communication-assisted digital relays, IEEE Trans. Power Deliv 25 (4) (2010) 2789–2796.

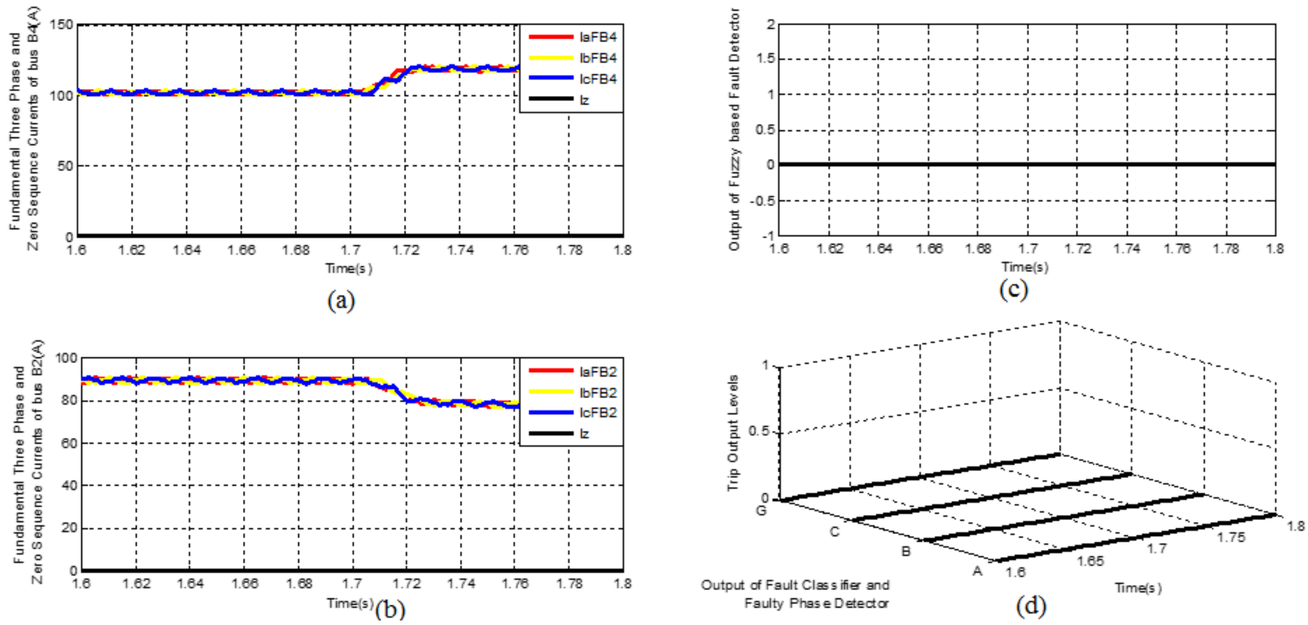

Figure 7: Test results for the disconnection of DG-2 (solar power PV-1) at time instant t = 1.7s in GCM (a) Fundamental three phase currents and zero sequence currents of bus-4 (b) Fundamental three phase currents and zero sequence currents of bus-2 (c) Output of fault detection (d) Output of fault classification

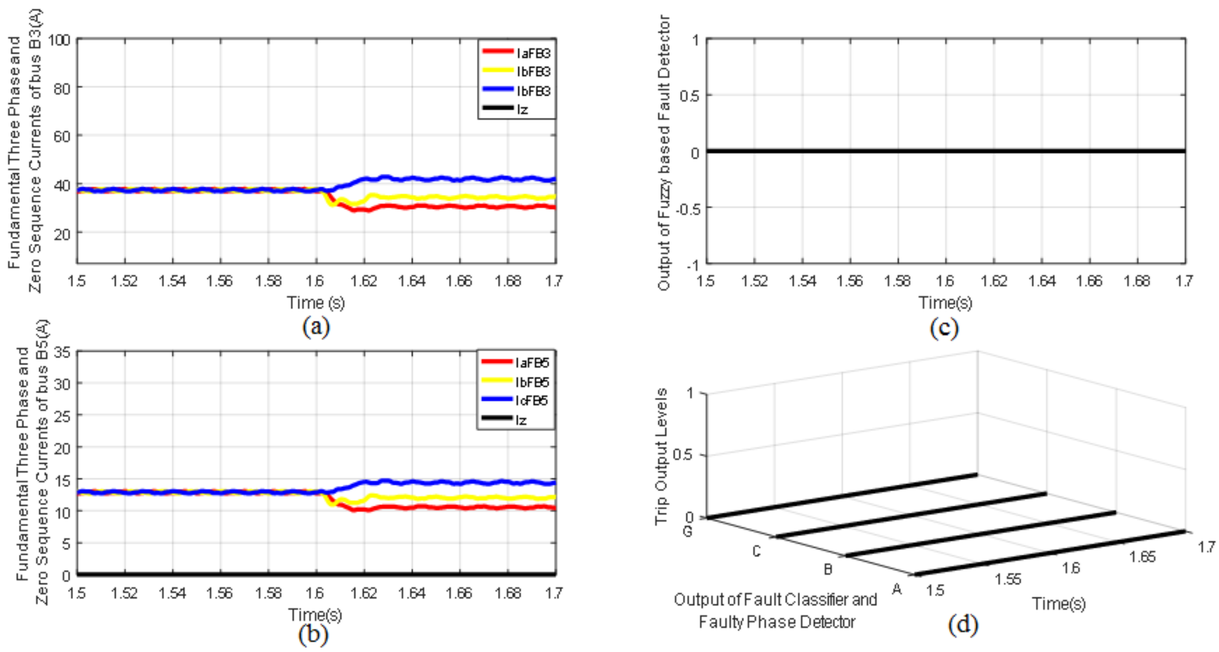

Figure 8: Test result in case of sudden increase in load-4 at bus-5 (a) Fundamental three phase currents and zero sequence currents of bus-3 (b) Fundamental three phase currents and zero sequence currents of bus-5 (c) Output of fault detection (d) Output of fault classification

[11] M. A. Zamani, T. S. Sidhu, A. Yazdani, A protection strategy and microprocessor-based relay for low-voltage microgrids, IEEE Transactions On Power Delivery 26 (3) (2011) 1873–1883.
[12] H. Nikkhajoei, R. H. Lasseter, Microgrid protection, in: IEEE PES General Meeting, 2007, pp. 24–28.
[13] U. Orji, C. Schantz, S. B. Leeb, J. L. Kirtley, B. Sievenpiper, K. Gerhard, T. McCoy, Adaptive zonal protection for ring microgrids, IEEE Transactions on Smart Grid 8 (4) (2017) 1843–1851.
[14] H. Muda, P. Jena, Superimposed adaptive sequence current based microgrid protection: A new technique, IEEE Transactions on Power Delivery 32 (2) (2017) 757–767.
[15] H. H. Zeineldin, E. F. El-Saadany, M. M. A. Salama, Distributed generation microgrid operation: control and protection, in: Proc. Power Syst. Conf, 2006, p. 105–112.
[16] E. Casagrande, W. L. Woon, H. H. Zeineldin, D. Svetinovic, A differential sequence component protection scheme for microgrids with inverter-based distributed generators, IEEE Transactions On Smart Grid 5 (1) (2014) 29–37.
[17] T. S. Ustun, C. Ozansoy, A. Zayegh, Fault current coefficient and time delay assignment for microgrid protection system with central protection unit, IEEE Transactions On Power Systems 28 (2) (2013) 598–606.
[18] S. Cai, G. Liu, Study on application of fisher information * for power system fault detection, Journal of Power Technologies (2016) 692–701.
[19] S. Mojtahedzadeh, S. N. Ravadanegh, M. R. Haghifam, A framework for optimal clustering of a greenfield distribution network area into multiple autonomous microgrids, Journal of Power Technologies 96 (4) (2016) 219–228.
[20] T. S. Ustun, C. Ozansoy, A. Zayegh, Modeling of a centralized microgrid protection system and distributed energy resources according to iec 61850–7-420, IEEE Trans. Power Syst. 27 (3) (2012) 1560–1567.