

Fuzzy Logic based Adaptive Protection Scheme for Smart Microgrid

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Abstract—This study proposes a fuzzy based adaptive protective relaying scheme for fault detection and fault classification of microgrid. This scheme also isolates the microgrid from the utility grid by disconnecting the static-switch on detecting the presence of fault on utility grid. An adaptive fuzzy inference system module (AFIS-Module) has been developed using a separate fuzzy rule base for the two modes of operation of microgrid, i.e. islanded mode and grid connected mode. Centralized Communication unit monitors the status of Point of Common Coupling 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 components of current signals are used as input features for fault detection and fault classification. Using MATLAB/SIMULINK a standard microgrid model IEC 61850-7-420 was simulated. The proposed method is tested for all types of fault and results were obtained. The results showed a great level of effectiveness to accurately identify faults and trigger the opening of the right circuit breaker/s under different operation modes and other system disturbances.

Index Terms— Adaptive fuzzy inference system, Fault Detection, Fault Classification, Grid Connected Mode, Islanded Mode and Microgrid.

I. INTRODUCTION

A microgrid is a small-scale power grid that can operate autonomously or in conjunction with the area's main electrical grid. The Generating resources in a microgrid are fuel cells, wind, solar, or other energy sources. Microgrids can be operated either in a grid-connected mode or islanded mode to increase reliability and provide backup power during a utility outage. Microgrids dual configuration capability imposes challenges on the design of the protection system. Fault current magnitudes will vary depending on the microgrid operating mode [1]. Protection of the Micro-Grids needs dependable and reliable detection and classification of faults. Providing the operators with relatively accurate and reliable knowledge of fault classification will serve restoration efforts and improve power outage restoration, power quality, reliability and safety. One of the main challenging issues in the smart distribution systems and the Micro-Grids is the protection system. Especially, with the integration of distributed renewable energy resources, which leads to a bidirectional power flow, as well as, different fault current levels with the different operating modes (i.e. Grid connected mode and Islanded mode). Such issues may interrupt the operation of the protection relays and may result in several faults being misclassified or undetected. In addition, the fault current contribution from the distributed energy resources in the islanded mode may not reach the pick-up level for the protection device to detect the fault. As a result, all the aforementioned

concerns are considered as challenging problems for any fault detection in microgrid. In [3] a Differential relays with data mining algorithms were used to protect inverter based islanded microgrid, but the proposed method is implemented in islanded Microgrid only and did not consider grid connected mode. In [4] a central controller-based online method was used to calculate and update the settings of adaptive overcurrent relays when there is a change in the mode of the microgrid, but the scheme requires complex calculation each time when the microgrid changed its mode of operation. A differential energy based protection scheme and fault was detected using Hilbert-Huang transform in [6] without classifying fault type. In [7], 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. A multi-agent system was used to update the relay settings adaptively in [8], but this scheme considered various DG connection and disconnection scenario in grid-tied mode of operation only. Data mining was applied to extract the features and wavelet transform was used to detect different faults in the islanded microgrid in [10]. After reviewing various schemes for microgrid protection, it is obvious that most researchers focused on fault detection only and did not consider fault classification or faulty phase selection. The communication system can be used in conjunction with the fuzzy rule base which provides an additional advantage in microgrid protection. Therefore 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 phases of the microgrid. The problem has been formulated by designing microgrid using MATLAB/SIMULINK.

II. PROPOSED PROTECTIVE SCHEME

The proposed scheme retrieves the fault currents I_a , I_b and I_c at both ends of the respective feeders and features are estimated through DFT-preprocessor. These estimated features are given to AFIS Module for registering the fault status and to issue the tripping command to the respective faulty phases by selective phase tripping. Fig.1 shows the schematic diagram of the proposed protection scheme. Bus n and m are the buses present at two end of a faulted feeder.

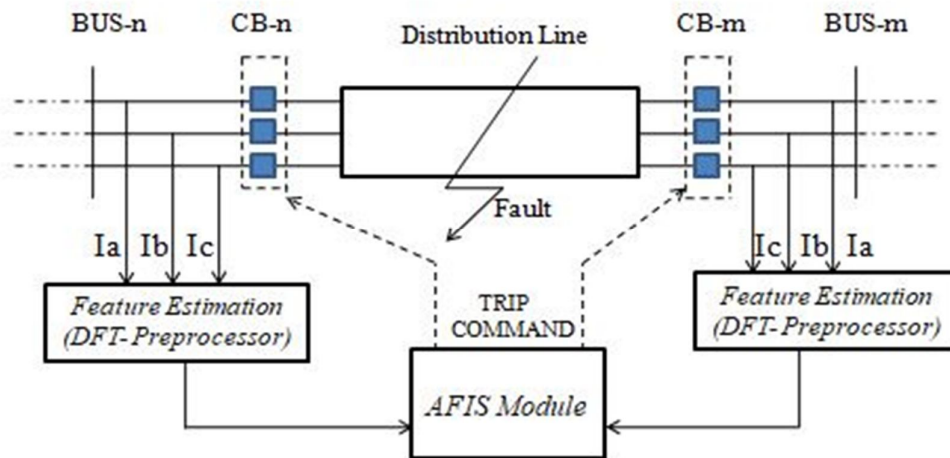


Figure 1. Operational flow of the proposed model

A. Pre-processor

This module computes the inputs for the AFIS module by using Discrete Fourier transform (DFT) to estimate the fundamental phasor, amplitude of three-phase current and sequence analyzer for extracting zero sequence component of the current signal.

B. Adaptive Fuzzy Inference System-Module

The 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 as shown in Fig.2. Each AFIS-Module consists of two fuzzy inference systems, where FIS-2 is specified for GCM (Grid connected

mode) and FIS-3 for IM (Islanded mode). 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 Centralized Communication Unit is used to update the fuzzy rules for relays to operate effectively by monitoring the status of PCC as to whether the utility grid is connected to or disconnected from the microgrid. This AFIS-Module will send a trip signal to the respective faulty phases by selective phase tripping.

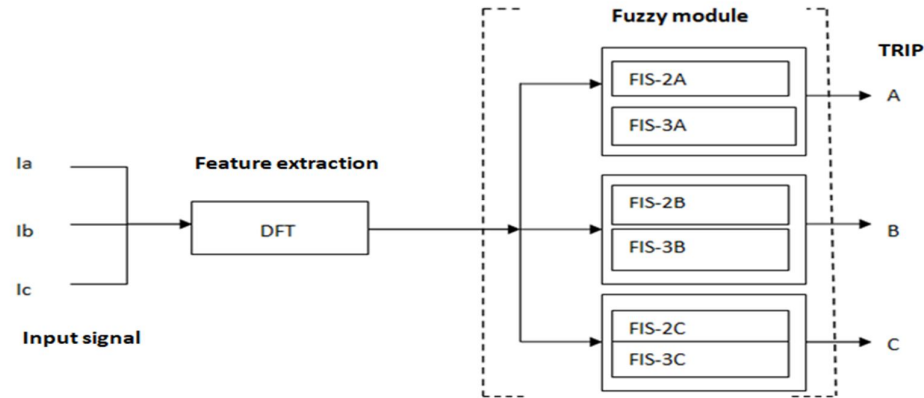


Figure 2. Adaptive Fuzzy Inference System-Module (AFIS-Module)

C. Algorithm developed for AFIS-module

Initially it is to be determined whether the fault is internal or external fault as shown in Fig.3. To detect the presence of fault certain features must be extracted from the network. The required features are fundamental phasor, amplitude and sequence components of current signal. The positive sequence phase angle was given as an input to the FIS-1. When the fault is present in the utility grid the microgrid must be disconnected from the utility grid through the static switch. When the fault is present in the microgrid (Islanded mode) then FIS-3 will be employed for detection and classification of faults. When the fault is present in the microgrid (grid connected mode) then FIS-2 will be employed for detection and classification of faults. This FIS-2 and FIS-3 will send a trip signal to the respective faulty phases by selective phase tripping.

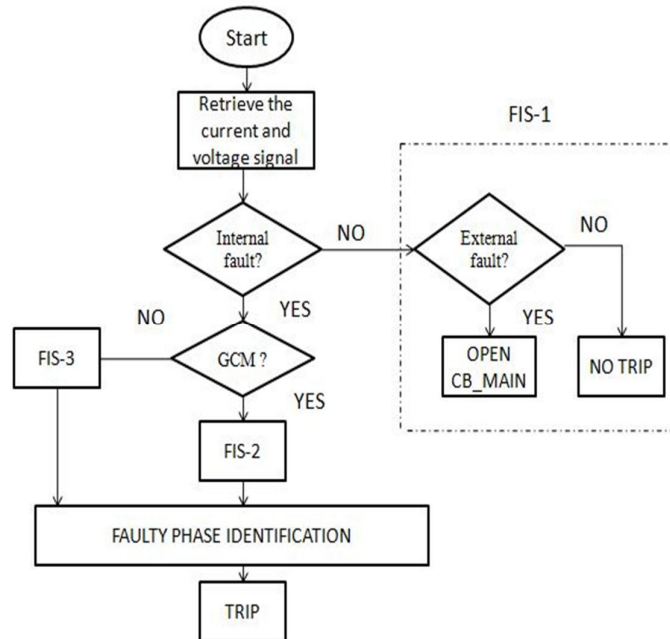


Figure 3. Flowchart of the proposed protective scheme

D. Test system

A single line diagram of the microgrid system is shown in Fig.3. It consists of a utility grid of rating 2,500 MVA, 120 kV and three DG units. The first DG unit (DG-1) is PMSG wind farm 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 60Hz. Pi-section lines were used for the interconnections and loads were connected at the respective buses, as shown in the Fig.4. The details of the IEC microgrid are given in [9]

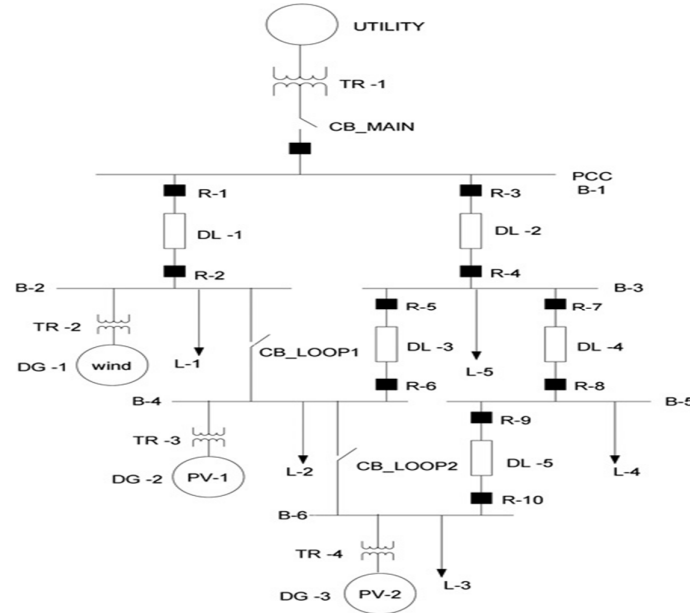


Figure 4. Schematic diagram of the microgrid according to IEC 61850-7-420.

E. Design of fuzzy based fault identifier for fault in utility grid (FIS-1)

The presence of a fault in the system is determined using the positive sequence phase angle of current at bus 1 which determines whether the fault is internal or external. Small, Medium and Large 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 Low for no fault, Medium for an internal fault and High for external fault in the utility grid. The fuzzy rules are given below:

1. If phase angle is *Small* then output is *internal fault* (Fault is in microgrid, then identify the faulty phase by continuing to operate without disconnecting microgrid from utility grid).
2. If phase angle is *Medium* then output is *no fault* (No fault in the system, continue to operate without disconnecting microgrid from utility grid)
3. If phase angle is *Large* then output is *external fault* (Fault is in utility grid, isolate microgrid from utility grid).

F. Design of fuzzy based fault identifier for fault in microgrid (FIS-2,3)

The fuzzy rules for grid-connected mode and islanded mode 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. 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. For a fault in section DL-1 the fundamental components of current signals at bus-1 (I1) and bus-2 (I2) are utilized to identify the faulty phase. Fuzzy rules are given below:

1. If I1 is low and I2 is low, then don't issue trip signal.
2. If I1 is medium and I2 is low, then don't issue trip signal.
3. If I1 is high and I2 is low, then issue trip signal.

4. If I1 is low and I2 is medium, then don't issue trip signal.
5. If I1 is medium and I2 is medium, then don't issue trip signal.
6. If I1 is high and I2 is medium, then issue trip signal.
7. If I1 is low and I2 is high, then issue trip signal.
8. If I1 is medium and I2 is high, then issue trip signal.
9. If I1 is high and I2 is high, then issue trip signal.

The zero sequence component of currents (I_0) at the respective buses of the sections (DL-1, 2, 3, 4 and 5) are used 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 (Bus1) and I_0 (Bus2) and I_0 (Bus3) and I_0 (Bus4) and I_0 (Bus5) and I_0 (Bus6) are low, then ground is not involved in fault.
2. If either I_0 (Bus1) or I_0 (Bus2) or I_0 (Bus3) or I_0 (Bus4) or I_0 (Bus5) or I_0 (Bus6) is high, then it is a ground fault.

III. SIMULATION RESULTS

A detailed fault investigation for all locations in the microgrid under investigation is performed in MATLAB environment. The fault types contemplated in this study are single-line-to-ground fault, double-line-to-ground fault, line-to-line fault, and three-phase fault. The simulations are performed for both external and internal faults (islanded and grid-tied mode). The fuzzy based adaptive relaying scheme was tested for a wide variety of operating conditions and fault situations which includes external fault (fault on utility grid) and internal fault with both operating modes namely Grid connected mode and Islanded mode.

A. External fault Detection- Fault occurred in Utility grid

When there is no fault in the system the angle range is from -20 to -37 degree as shown in Fig.5. Therefore output of fuzzy based fault identifier shows '0' for no fault situation as shown in Fig.6.

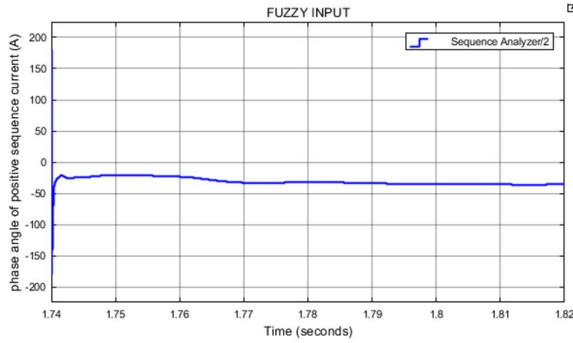


Figure 5. Input of fuzzy based fault identifier during no fault condition

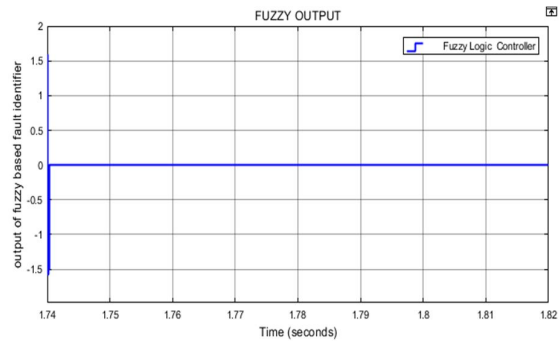


Figure 6. Output of fuzzy based fault identifier during no fault condition

When the fault was introduced at 1.8s (fault inception time) in microgrid, the positive sequence phase angle of the current starts increasing up to 150 degree. Fig. 7 shows the input of fuzzy based fault identifier for fault in the utility grid at bus-1. Fig.8. shows the output of the fuzzy based fault identifier shows '0' up to 1.8 s and after 1.8 s it starts increasing and reaches *high* i.e., fuzzy membership degree shows '+1.5' at 1.815 s, thus it takes 15 ms to detect the fault in the utility grid.

B. External fault Detection- Fault occurred in Microgrid

When the fault was introduced at 1.8s (fault inception time) in microgrid, the positive sequence phase angle of the current starts decreasing. Fig.9. shows the input of the fuzzy based fault identifier during fault in the microgrid at bus-1 at 1.8s. Fig.10. shows the output of the fuzzy based fault identifier. The output of the fuzzy based fault identifier shows '0' up to 1.8 s of time and starts decreasing after 1.8 s, and reaches *low* i.e., fuzzy membership degree shows '-1.5' at 1.806s time, which indicates a fault in the microgrid. Thus the proposed adaptive fuzzy inference protection scheme takes 8 ms to detect the fault.

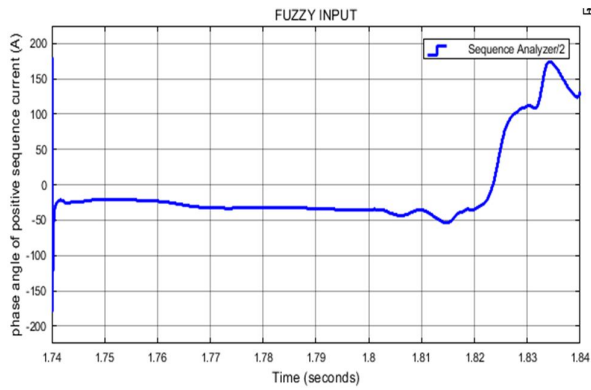


Figure 7. Input of fuzzy based fault identifier for fault in utility grid

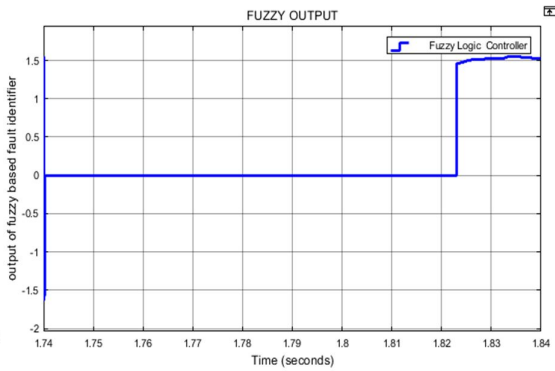


Figure 8. Output of fuzzy based fault identifier for fault in utility grid

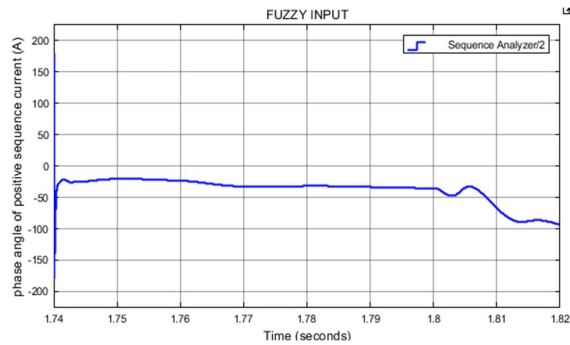


Figure 9. Input of fuzzy based fault identifier for fault in microgrid

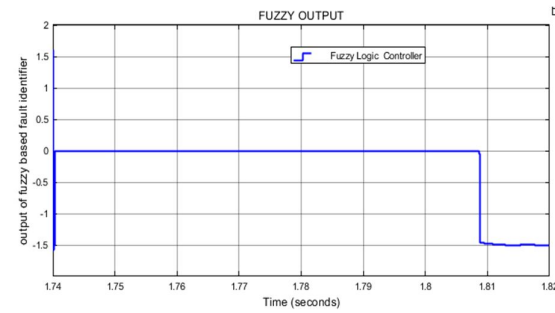


Figure 10. Output of fuzzy based fault identifier for fault in microgrid

C. Internal fault Detection- Fault occurred in microgrid operated in Grid Connected Mode

The proposed scheme was tested in grid connected mode for number of fault cases and observed that the fault current in this mode is high as compared to islanded mode. Consider the three phase fault occurred at 1.75s (fault inception time) on the distribution line (DL-3) of the microgrid. Fig.11. shows the fundamental component of three phase current of bus-3 which is during the occurrence of three phase fault. This fundamental component of three phase current was preprocessed using DFT and given as input to the fuzzy based fault identifier (FIS-2) during ABC fault in the microgrid.

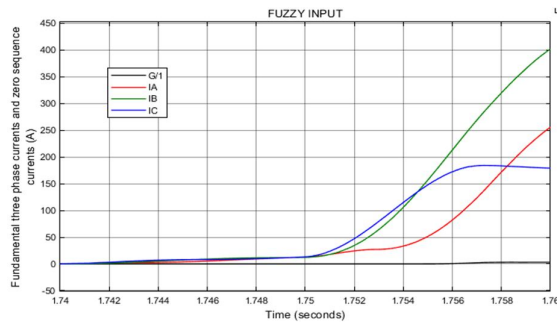


Figure 11. Fundamental three phase currents and zero sequence currents at bus-3

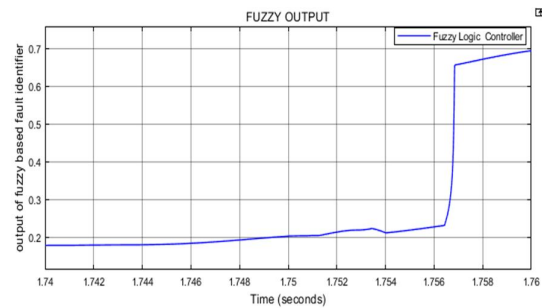


Figure 12. Output of fuzzy based fault identifier for fault in phase-a

Figs.12, 13 and 14 depict the three outputs of fault classification, i.e., phases A, B and C. Here the fuzzy based fault identifier which become high i.e., fuzzy membership degree shows 0.6 after 5.939s, 3.395s and 3.904s

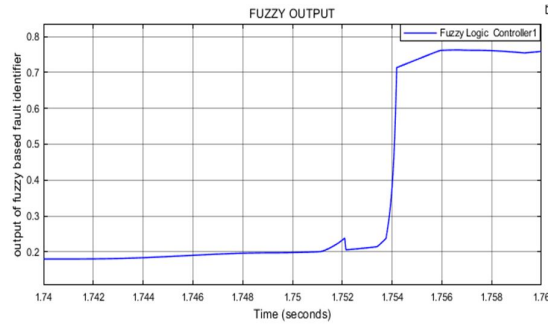


Figure 13. Output of fuzzy based fault identifier for fault in phase-b

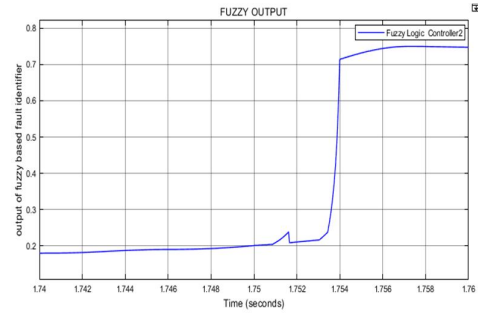


Figure 14. Output of fuzzy based fault identifier for fault in phase-c

respectively and fuzzy ground identifier remains low i.e., fuzzy membership degree shows 0, which confirms that the fault type is a three phase fault, i.e., ABC fault.

D. Internal fault Detection- Fault occurred in microgrid operated in Islanded Mode

The proposed scheme was tested in islanded mode for number of fault cases and observed that the fault current in this mode is low as compared to grid connected mode. Consider the three phase fault occurred at 1.75s (fault inception time) on the distribution line (DL-3) of the microgrid. Fig.15. shows the fundamental component of three phase current of

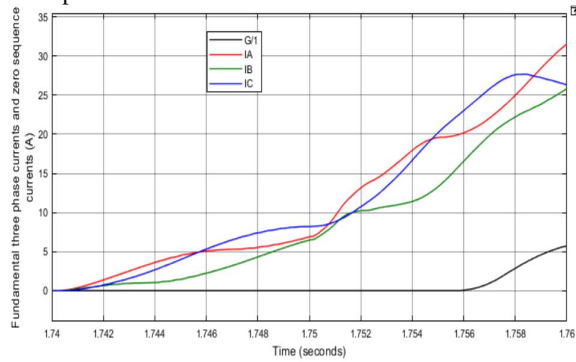


Figure 15. Fundamental three phase currents and zero sequence currents at bus-3

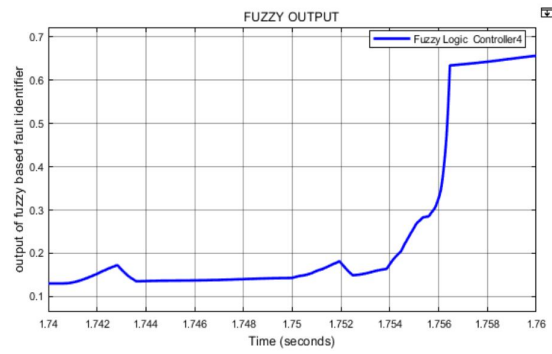


Figure 16. Output of fuzzy based fault identifier for fault in phase-a

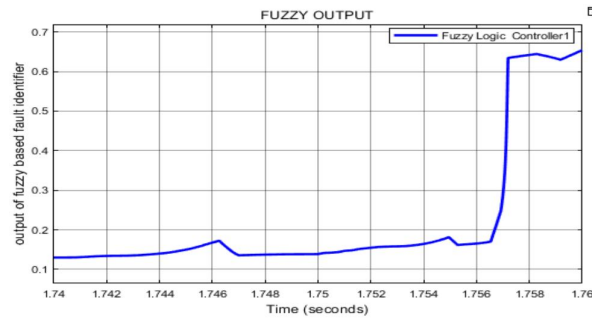


Figure 17. Output of fuzzy based fault identifier for fault in phase-b

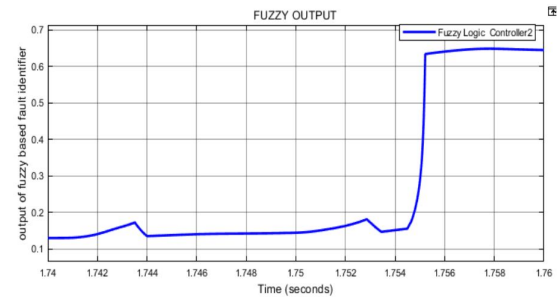


Figure 18. Output of fuzzy based fault identifier for fault in phase-c

Figs.16, 17 and 18 depict the three outputs of fault classification, i.e., phases A, B and C. Here the fuzzy based fault identifier which become high i.e., fuzzy membership degree shows 0.6 after 2.231s, 4.922s and 3.004s respectively and fuzzy ground identifier remains low i.e., fuzzy membership degree shows 0, which confirms that

the fault type is a three phase fault, i.e., ABC fault. The test results shown in Table I. indicates the proposed scheme requires less response time less than 1/4 cycle in all the tested fault cases.

TABLE I. TEST RESULTS OF FUZZY BASED FAULT DETECTION AND CLASSIFICATION IN GRID CONNECTED MODE AND ISLANDED MODE

Lines	Fault	Grid-Connected Mode				Islanded Mode			
		Time taken to detect fault in ms							
		A	B	C	G	A	B	C	G
DL-1	AG	5.802	-	-	4.051	1.652	-	-	1.000
	BG	-	3.679	-	1.311	-	1.874	-	1.512
	CG	-	-	3.239	1.057	-	-	3.219	1.771
	AB	4.589	4.286	-	-	5.000	5.974	-	-
	AC	6.859	-	6.409	-	4.082	-	4.145	-
	BCG	-	5.802	3.678	4.051	-	1.856	4.354	1.262
	ACG	5.959	-	3.943	1.311	1.997	-	4.354	1.262
	ABC	5.123	3.623	3.474	-	2.710	5.059	3.963	
DL-2	AG	5.802	-	-	4.051	2.857	-	-	3.454
	BG	-	3.679	-	1.311	-	3.454	-	2.280
	CG	-	-	3.239	1.057	-	-	2.000	2.280
	AB	4.589	4.286	-	-	1.683	2.162	-	-
	AC	6.859	-	6.409	-	1.937	-	1.693	-
	BCG	-	3.504	3.219	3.992	-	1.988	1.830	1.341
	ACG	5.959	-	3.943	1.311	1.311	-	2.867	1.459
	ABC	5.311	3.623	3.474	-	6.292	4.271	3.777	-
DL-3	AG	5.683	-	-	4.041	2.016	-	-	1.458
	BG	-	3.904	-	1.986	-	4.804	-	2.025
	CG	-	-	3.845	1.321	-	-	2.808	2.030
	AB	4.374	4.295	-	-	5.382	3.826	-	-
	BCG	-	3.454	4.002	4.354	-	2.828	2.202	1.458
	ACG	6.585	-	4.765	1.986	2.250	-	3.258	1.227
	ABC	5.939	3.395	3.904	-	2.231	4.922	3.004	-
DL-4	AG	4.012	-	-	2.021	1.018	-	-	1.262
	CG	-	-	2.926	1.164	-	5.215	-	5.000
	AB	3.082	4.648	-	-	5.969	5.998	-	-
	AC	6.000	-	2.143	-	3.542	-	3.493	-
	BCG	-	3.591	3.337	4.139	-	3.458	3.258	1.595
	ACG	5.801	-	3.278	1.741	2.720	-	4.746	2.096
	ABC	5.057	3.278	3.043	-	1.272	2.000	1.536	-
DL-5	AG	5.370	-	-	4.432	1.703	-	-	1.380
	BG	-	4.100	-	2.182	-	-	2.358	1.595
	AB	5.352	5.117	-	-	2.877	2.162	-	-
	BC	-	3.748	3.862	-		3.190	2.143	-
	BCG	-	3.630	3.864	4.139	-	2.534	2.143	1.595
	ABG	5.802	4.112	-	1.982	4.796	3.395	-	4.980
	ABC	5.605	4.041	3.865	-	2.270	4.726	3.160	-

IV. CONCLUSIONS

This study presents fuzzy based fault detection, fault classification and faulty phase identification schemes for the microgrid. The technique is based on the features extracted from fundamental current signals of all the terminals of the microgrid. The results clearly indicate that the presented technique is able to detect the fault correctly. 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 for this proposed method is less than $\frac{1}{4}$ cycle whereas the response time achieved in the paper [5] is within $\frac{1}{4}$ to 1 cycle. Therefore comparatively this proposed method is more effective and response is faster even in the presence of the wide variation in system and fault parameters. 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] Waleed K. A. Najy, H. H. Zeineldin and Wei Lee Woon "Optimal Protection Coordination for Microgrids With Grid-Connected and Islanded Capability", IEEE Transactions on Industrial Electronics, Volume: 60, Issue: 4, April 2013; 1668 – 1677.
- [2] S. Cai, G. Liu, "Study on application of fisher information for power system fault detection", Journal of Power Technologies 2016; 692–701.
- [3] Casagrande E, Woon WL, Zeineldin HH, Svetinovic D. "A differential sequence component protection scheme for microgrids with inverter-based distributed generators". IEEE Transactions on Smart Grid 2014; 5:29–37.
- [4] Coffele F, Booth C, Dysko A. "An adaptive overcurrent protection scheme for distribution networks". IEEE Transaction Power Delivery 2015; 30:561-8.
- [5] B.K.Chaitanyaa, Atul Kumar Sonib, Anamika Yadav. "Communication Assisted Fuzzy based Adaptive Protective Relaying Scheme for Microgrid". Journal of Power Technologies 2018; 10:536–45.
- [6] Gururani A, Mohanty SR, Mohanta JC. "Microgrid protection using Hilbert-Huang transform based-differential scheme". IET Generation Transmission Distribution 2016; 10:3707–16.
- [7] Kar S, Samantaray SR. "A Fuzzy Rule Base Approach for Intelligent Protection of microgrids" Electric Power Components and systems 2015; 8:310–20.
- [8] Liu Z, Su C, Hoidalén HK, Chen Z. "A multiagent system-based protection and control scheme for distribution system with distributed-generation integration". IEEE Transaction Power Delivery 2017; 32:536–45.
- [9] 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.
- [10] Mishra DP, Samantaray SR, Joos G. "A combined wavelet and data-mining based intelligent protection scheme for microgrid". IEEE Transaction on Smart Grid 2016; 7:2295–304.
- [11] H. Muda, P. Jena, "Superimposed adaptive sequence current based microgrid protection: A new technique", IEEE Trans. on Power Delivery 2017; 757–767.
- [12] H. Nikkhajoei, R.H. Lasseter, "Microgrid protection", in: IEEE PES General Meeting, 2007, pp. 24–28.
- [13] A. Oudalov and Antonio Fidigatti, "Adaptive Network Protection in Microgrids," in International Journal of Distributed Energy Resources, vol.5, pp. 201-225, 2009.
- [14] . B.K. Panigrahi, P K. Ray, P.K. Rout, A. Mohanty and K. Pal. "Detection and classification of faults in a microgrid using wavelet neural network". Journal of Information & Optimization Sciences 2017; 24:50–45.
- [15] A. Rahmati and R. Adhami, "A Fault Detection and Classification Technique Based on Sequential Components," IEEE Trans. Ind. Appl., vol. 50, no. 6, pp.4202-4209, Dec. 2014.
- [16] 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 2013; 598–606.