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Fault Detection in Modern Power Systems using Fuzzy Logic

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Abstract: *Meeting the evolving power consumption demands with reliability, environmental sustainability, and quality is increasingly challenging due to escalating electricity demands driven by population growth and industrialization. This paper explores fault detection and classification in modern electrical power systems, emphasizing the integration of renewable energy sources like solar PV. It presents a comprehensive study on fault identification using fuzzy logic techniques, focusing on an optimized IEEE 13-bus model integrated with solar PV. The objectives include designing and simulating the IEEE 13-bus model, integrating solar PV efficiently, designing a fuzzy logic-based fault identification system, and evaluating system performance under different fault conditions. The study showcases the effectiveness of the proposed fault identification approach in enhancing power system reliability.*

Keywords: *ault detection, fault classification, fuzzy logic, IEEE 13-bus system, solar PV integration, power system reliability.*

I. INTRODUCTION

Modern electrical power systems must meet constantly changing power consumption requirements with a satisfactory level of reliability, environmental friendliness and quality. Nevertheless, meeting these challenges has become progressively difficult owing to the increase in electricity demands caused by population and industrial growth. The International Energy Agency estimated that the global electricity demand in 2030 will be more than 50% higher than that in the present, for example, due to the massive implantation of the electric vehicle. In addition to this issue, the infrastructure investments required to support the growing global electricity demand will be massive because ageing power system components will have to be replaced. Thus, the usual practices aimed at balancing electricity supply and demand have to be examined closely. Electricity saved is worth more than electricity generated. For example, after accounting for transmission and distribution along line losses, one unit of electricity saved at the consumer side is worth 10% more of the unit saved at the generator side. In modern and deregulated power systems, distribution companies bid for electricity prices to maximize their profits.

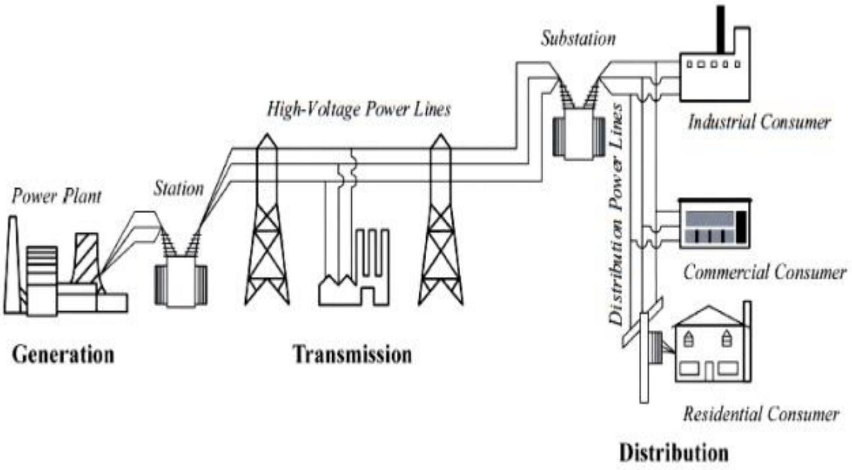


Figure 1 Electrical Power System

Electricity prices fluctuate in accordance with real-time electricity demands. Specifically, electricity prices increase as demand rises and vice versa. Prudent power system management is necessary to ensure the constant supply and trading of electricity [1].

A. Transmission Lines

Transmission lines are the conductors that serve as a path for transmitting (sending) electrical waves (energy) through them. These basically forms a connection between transmitter and receiver in order to permit signal transmission.

Transmission lines in microwave engineering are known as distributed parameter networks. As their voltage and current shows variation over its entire length. It enables the transfer of electrical signals by a pair of conducting wires that are separated from each other by a dielectric medium which is usually air.

Types of Transmission Line

Transmission lines are majorly classified into three categories:

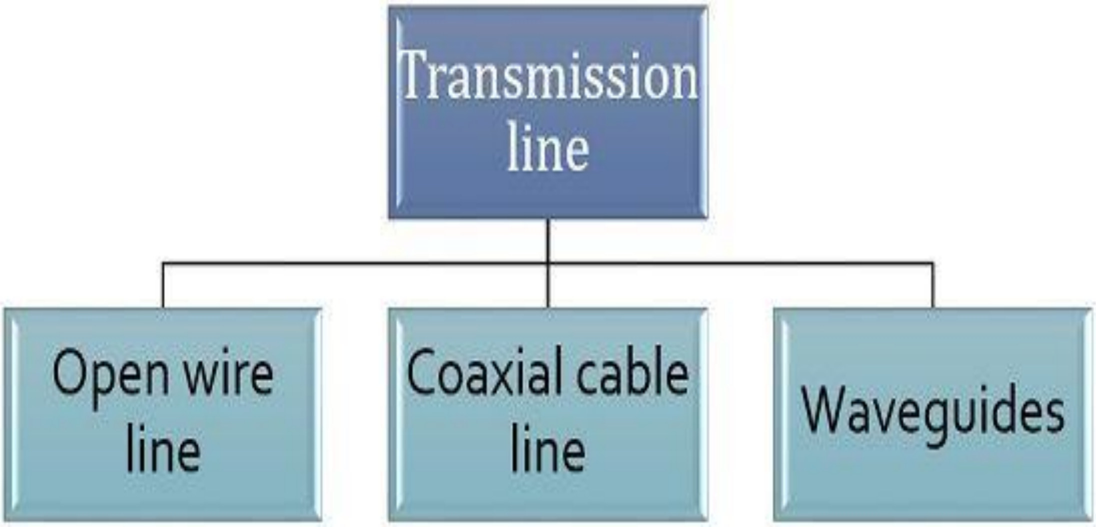


Figure 2 Types of Transmission Lines

Open-wire transmission line: These are the conductors having 2 lines (wires),that are separated by dielectric medium whose, one end connected to the source and other to the destination. These are low cost and simplest form of transmission line. But, their installation cost is somewhat higher as well as its maintenance sometimes becomes difficult due to the change in atmospheric conditions.

B. Faults in Electrical Networks

Electrical networks, machines and equipments are often subjected to various types of faults while they are in operation. When a fault occurs, the characteristic values (such as impedance) of the machines may change from existing values to different values till the fault is cleared.

There may be lot of probabilities of faults to appear in the power system network, including lighting, wind, tree falling on lines, apparatus failure, etc.A fault in an electric power system can be defined as , any abnormal condition of the system that involves the electrical failure of the equipment, such as , transformers, generators, busbars, etc. The fault inception also involves in insulation failures and conducting path failures which results short circuit and open circuit of conductors.

Under normal or safe operating conditions, the electric equipments in a power system network operate at normal voltage and current ratings. Once the fault takes place in a circuit or device, voltage and current values deviates from their nominal ranges. The faults in power system causes over current, under voltage, unbalance of the phases, reversed power and high voltage surges. This results in the interruption of the normal operation of the network, failure of equipments, electrical fires, etc. Usually power system networks are protected with switchgear protection equipments such as circuit breakers and relays in order to limit the loss of service due to the electrical failures.

Types of Faults

Electrical faults in three-phase power system mainly classified into two types, namely open and short circuit faults. Further, these faults can be symmetrical or unsymmetrical faults. Let us discuss these faults in detail.

1. Open Circuit Faults

These faults occur due to the failure of one or more conductors. The figure below illustrates the open circuit faults for single, two and three phases (or conductors) open condition.The most common causes of these faults include joint failures of cables and overhead lines, and failure of one or more phase of circuit breaker and also due to melting of a fuse or conductor in one or more phases.Open circuit faults are also called as series faults. These are unsymmetrical or unbalanced type of faults except three phase open fault.

2. Short Circuit Faults

A short circuit can be defined as an abnormal connection of very low impedance between two points of different potential, whether made intentionally or accidentally.These are the most common and severe kind of faults, resulting in the flow of abnormal high currents through the equipment or transmission lines. If these faults are allowed to persist even for a short period, it leads to the extensive damage to the equipment.

II. LITERATURE REVIEW

Jabir (2018): This review addresses the escalating electricity demand driven by industrialization and smart-grid transitions, necessitating enhanced grid adaptability. It discusses Demand-side Management (DSM) initiatives, techniques, and impacts, emphasizing their potential in bolstering grid reliability and financial performance.

Ali et al. (2017): Focusing on power system reliability assessment, this study reviews Monte Carlo simulation (MCS) and variance reduction techniques (VRTs). It elucidates MCS's flexibility and drawback in computational time, proposing effective methods for accelerating MCS for power system reliability assessment.

Rai et al. (2020): Introducing a fault detection approach using Convolutional Neural Networks (CNNs) for distributed networks with DGs, this study achieves high accuracy in fault classification. It outperforms conventional methods, demonstrating applicability in mixed transmission and distribution networks.

Veerasamy & Member (2021): This paper presents an LSTM-based approach for detecting High Impedance Faults (HIFs) in solar PV integrated systems. Achieving 91.21% accuracy, it surpasses traditional classifiers and demonstrates robustness through performance indices.

Belagoune et al. (2021): Introducing DL models based on DRNNs for Fault Region Identification, Fault Type Classification, and Fault Location Prediction, this study achieves superior detection and classification performance in multi-machine power systems compared to contemporary techniques.

Zhu et al. (2021): Proposing a method to identify critical transmission lines in power systems, this study constructs a topological model and derives indexes to assess line importance comprehensively. Simulation results verify the method's effectiveness in identifying critical transmission lines.

Liu et al. (2021): Presenting a fault diagnosis method for shipboard MVDC power systems, this study combines NA-MEMD and MI-LightGBM. Achieving high precision and efficiency, it outperforms existing methods, making it suitable for engineering applications.

Khalili et al. (2018): Focusing on transformers' condition assessment, this review explores Frequency Response Analysis (FRA) as a powerful diagnostic method. It discusses FRA's sensitivity to various transformer stresses and its significance in maintaining power network reliability.

III. OBJECTIVES

1. Design and simulation of an optimized IEEE 13 bus model in MATLAB/Simulink
2. To integrate the inverter-interfaced solar PV system to the IEEE 13 bus system in an efficient manner.
3. Designing of fuzzy based system for identification fault symmetrical and unsymmetrical faults in the IEEE 13 bus system
4. Evaluation of the system performance by analyzing the fault response time of the fuzzy rules at different fault conditions

IV. METHODOLOGY

The system taken for validation and testing of the proposed scheme is the IEEE 13-bus system [10]. The system comprises of generators, transformers, transmission lines and loads. The complex power of the lines is approximately hundreds of MVA each. The operating frequency of the test system is taken as 50Hz in this study. Main causes of faults in power systems are mainly due to human error, failure of insulation, flashovers or weather conditions. Such faults may involve all three phases' also known as symmetrical faults or may occur between any two phases or phase and ground and can be characterized as unsymmetrical fault. Other reasons of fault can be short circuit between live conductors or to earth. Two or more types of faults can occur consecutively sometimes. Along with various other aspects of power system study, calculation of fault plays a crucial part in functioning and design of a power system. Hence calculation of fault involves the investigation of the behaviour of the electrical power system under faulty conditions and its consequence on the systems current value. It can be observed that the current values for the faulted phases shoot up considerably upon occurrence of fault. Consequently current signals can prove to be effectively used in classification and identification of fault in the system which is utilized in our study for driving the FUZZY logic system. This chapter shall describe the MATLAB system modeling and fuzzy rules derived for fault identififcation the the IEEE 13 bus system in detail.

A. IEEE 13 bus system modeling in MATLAB

The IEEE 13 bus feeder is a small system that is used to test distribution systems. It operates
at 4.16kV, has 1 source, a regulator, a number of short unbalanced transmission lines, and shunt capacitors. The Figure 4.1 shows single line diagram of IEEE-13 bus system, in this diagram 1source, loads and 13 buses are connected. Different line lengths are connected in between the buses with the help of transmission line, this single diagram implemented in MATLAB by using Simulink tools. Some of the loads are connected 3phases and some of the loads are 2 phase and single phase. It provides an interactive graphical environment and a customizable set of block libraries that let this work design,

simulate, implement and test a variety of time-varying systems including power, communications, controls, signal processing, etc.

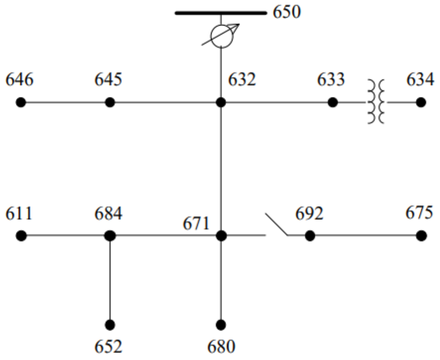


Figure 3: IEEE 13 bus system line diagram

B. Solar energy system

The high penetration of Renewable based energy resources in the modern electricity grid can provide many potential positive benefits through their integration but they can have many negative impacts on the network if power output and voltage at the Point of common coupling (PCC) is not properly regulated through controls.

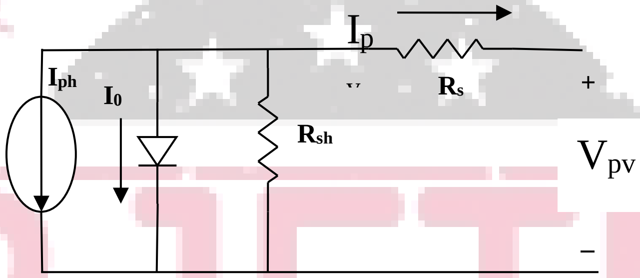


Figure 4: Solar cell circuit

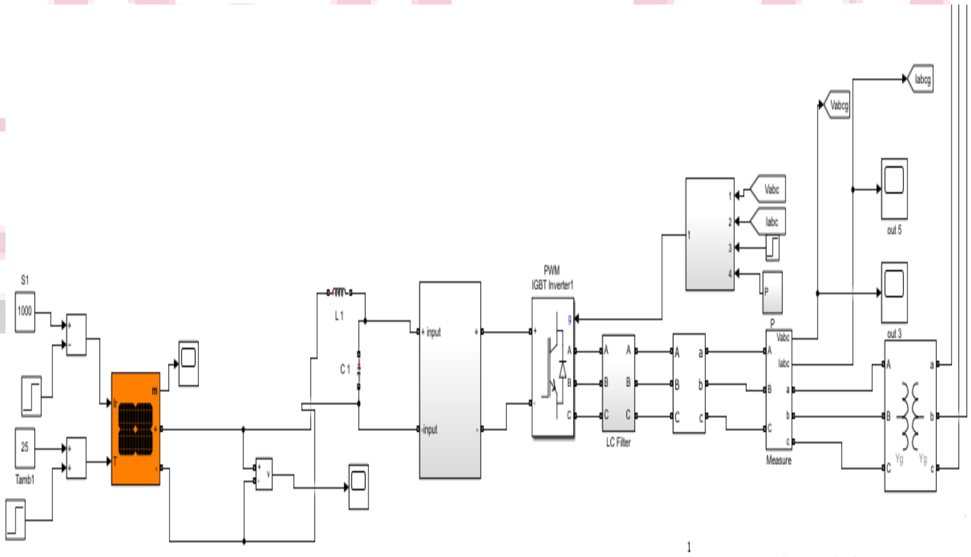


Figure. 5 MATLAB/SIMULINK model of solar system connected to IEEE 13 bus system

There are many Renewable energy technologies which generate the electrical voltage not in synchronism to the area they are integrated with or a grid. Hence, an intermediate power conversion stage is required in order to convert the power generated by these resources to the power with voltage magnitude and frequency in synchronism to the area they are intended to be connected with. The power electronics (PE) interface performs this task of connecting any type of resources to the grid by providing either DC - DC or DC - AC conversion stages. PE interfaces comprise of semiconductor switches with the devices like thyristors, diodes, and insulated gate bipolar transistors (IGBTs) or MOSFETs with proper control of the duty cycle of these switches to fulfill the desired objectives.

C. Design of fuzzy logic based systems for fault identification.

Fuzzy logic is a logic which deals with uncertainty by modelling the events. It deals with three entities:

i. Degree of accuracy /precision
ii. Uncertainty
iii. Vagueness (approximately equal)

In a narrow sense, fuzzy logic is a logical system, which is an extension of multi – valued logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In fuzzy logic, the truth of any statement becomes a matter of degree. Any statement can be fuzzy. The major advantage that fuzzy reasoning offers is the ability to reply to a yes-no question with a not-quite-yes-or-no answer.

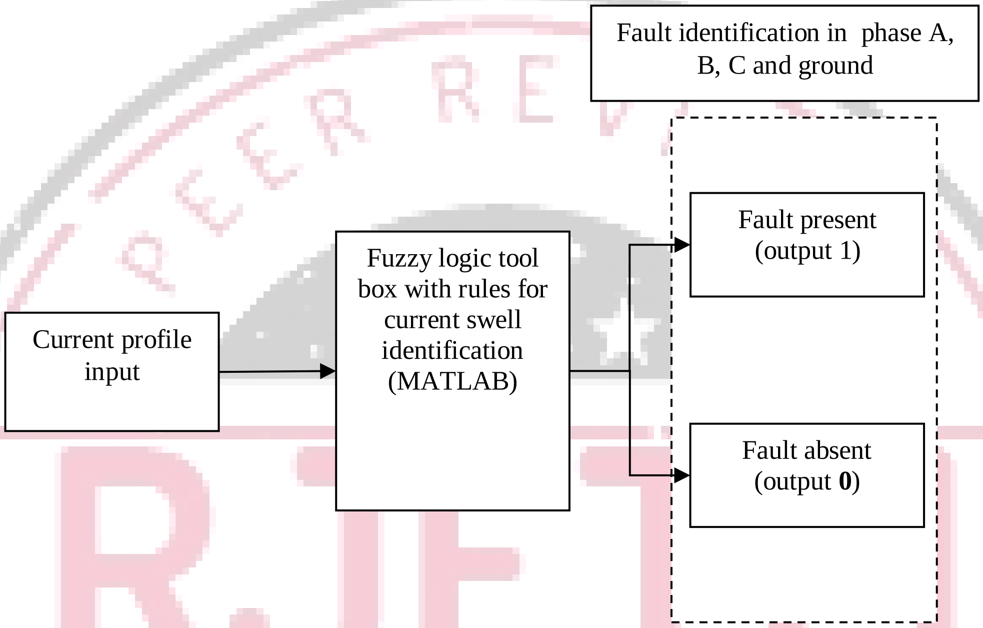


Figure 6: Block Diagram for fuzzy rules set

D. Fuzzy rules identifier for phase faults

For each input 2 triangular membership functions are chosen designated fca and nca. The membership function ranges for inputs are value between 0 to 1000. For nca the value ranges in between 0 to 615 and for fca the range is kept in between 620 to 10000. Figure 6 shows the membership functions of the inputs and Figure 7 shows the triangular membership functions of the outputs designated as na and fa.

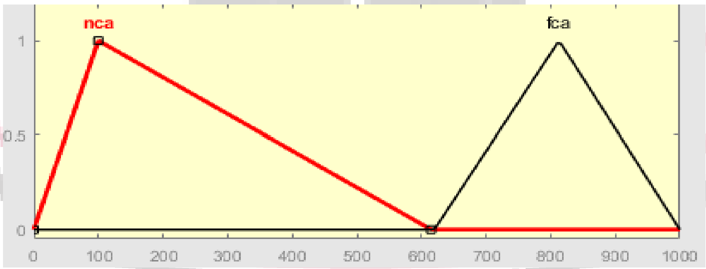


Figure 7: Input membership function

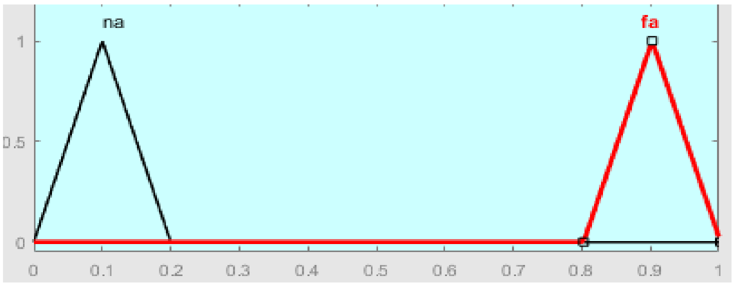


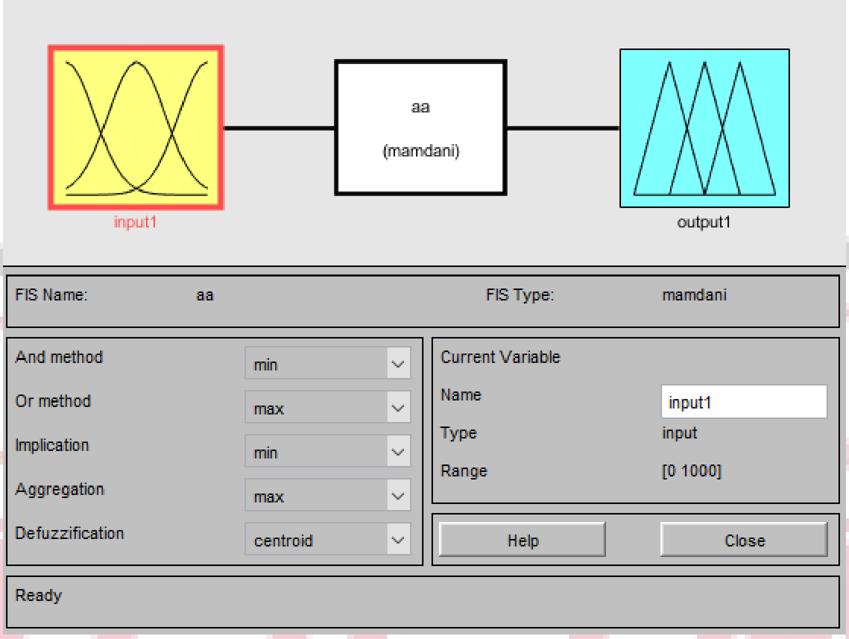
Figure 8: Output Membership Function

The output function na is decided to be in the rage 0 to 0.2 and fa is in between 0.8 to 1. The simulation concepts follows the rules as follows:

- If input is nca then, ouput is na
- Is input is fca then output is fa

The fuzzy output is then compared with the base value 0.5. The if the output is less than 0.5 then the fault is absent and if the output is more than 0.5 then fault is present in that phase.

Fuzzy rules identifier for ground faults



FIS Name: aa FIS Type: mamdani

And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid

Current Variable
Name: input1
Type: input
Range: [0 1000]

Ready

Figure. 9 Fuzzy rule Designing Block in MATLAB /SIMULINK

The possible involvement of ground in the fault is determined by the measurement of zero sequence current. The input universe of discourse is divided into two fuzzy sets with triangular membership functions, which after proper tuning attain unsymmetrical vertices. Similarly the output universe of discourse is divided into two symmetrical fuzzy sets with triangular membership functions.

For each input 2 triangular membership functions are chosen designated named as NGC and FGC. The membership function ranges for inputs are value in between 0 to 9 and that the range chosen for FGC is from 9.1 to 180 or more. The output variables are NG and FG chosen with the same range as in fuzzy classifier for the phase fault detection. The output function NG is decided to be in the rage 0 to 0.2 and FG is in between 0.8 to 1 The simulation concepts follows the rules as follows:

- If input is NGC then, ouput is NG
- Is input is FGC then output is FG

The fuzzy output is then compared with the base value 0.5. The if the output is less than 0.5 then the ground fault is absent and if the output is more than 0.5 then ground fault is present. Table shows the output variables for ground faults and phase faults along with the fuzzy rules to fine nature of faults in the IEEE 13 bus system.

Table 1 Rules for Identification of Faults in the Line

Fault/fuzzy outputs	FA (phase A)	NA1 (phase A)	FA2 (phase B)	NA2 (phase B)	FA3 (phase C)	NA3 (phase C)	FG	NG
LLLG	yes	-	yes	-	yes	-	yes	-
LLL	yes	-	yes	-	yes	-	-	yes
LG (Phase A& G)	yes	-	-	yes	-	yes	yes	-

LG (Phase B& G)	-	yes	yes	-	-	yes	yes	-
LG (Phase B& G)	-	yes	-	yes	yes	-	yes	-
LLG (Phase A& B& G)	yes	-	yes	-	-	yes	yes	-
LLG (Phase B& C& G)	-	yes	yes	-	yes	-	yes	-
LLG (Phase A& C& G)	yes	-	-	yes	yes	-	yes	-
LL (Phase A & B)	yes	-	yes	-	-	yes	-	yes
LL (Phase B & C)	-	yes	yes	-	yes	-	-	yes
LL (Phase A & C)	yes	-	-	yes	yes	-	-	yes

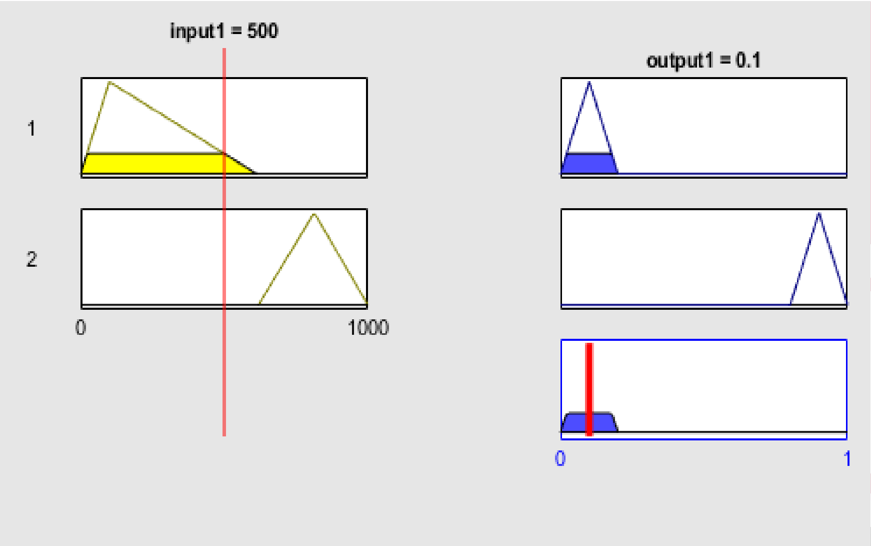


Figure 10 Fuzzy Rule Viewer Window for phase faults

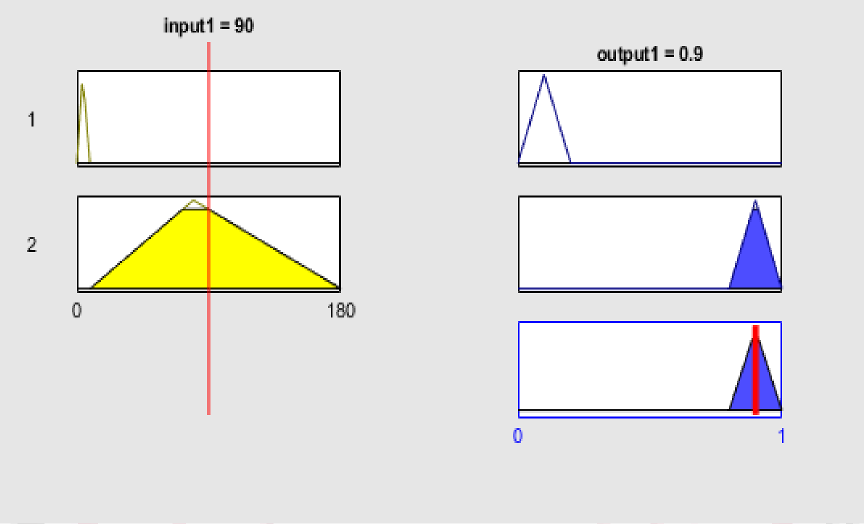


Figure 11 Fuzzy Rule Viewer Window for ground faults

V. RESULTS AND DISCUSSION

Fault detection techniques that can be used to detect accurately the fault and also differentiate between faulty and noisy signals are very important at any smart grid. Identification of faults (detection, classification, and determination of fault location) is the most important activity used in the safe relaying power stations. The malfunctioning of protective relay systems capable of detecting, diagnosing, distinguishing defective phases and avoid fault influences during the time of fault can have negative impacts on power grid systems. Thus, the method of fault detection should be done correctly as rapidly as possible for declining the duration abrupt and facilitate the return of electric service.

Under normal conditions, a power system operates under balanced conditions with all equipments carrying normal load currents and the bus voltages within the prescribed limits. This condition can be disrupted due to a fault in the system. A fault in a circuit is a failure that interferes with the normal flow of current. A short circuit fault occurs when the insulation of the system fails resulting in low impedance path either between phases or phase(s) to ground. This causes excessively high currents to flow in the circuit, requiring the operation of protective equipments to prevent damage to equipment.

Simulation results show that all types of faults can be successfully detected and the type of the fault can be recognized within one cycle time, thus confirming the suitability, quickness and appropriateness of the proposed protection scheme.

It is owing to the non-linear nature of the fault signals, which makes it difficult to detect, the proposed FIS-based fault identification and classification scheme successfully detect the symmetrical as well as unsymmetrical faults. The discussion is followed by the current waveform magnitude analysis and fuzzy rules identification for the detection of faults in different phases and ground. The analysis has is carried by the detecting faults of two types:

a) symmetrical fault

b) unsymmetrical fault.

The fault identification in all the types is done by the designed fuzzy rules in IEEE 13 bus system having solar energy system included in line. The conclusion points tends to evaluate the response time of the fault identification process by the FIS structure and is recorded for every type of fault in the system.

A. Symmetrical Faults Identification using Fuzzy system

These faults can be of two types:

(a) line to line to line to ground fault (LLLG fault) or

(b) line to line to line fault (LLL fault).

Since the three phases are equally affected, the system remains balanced. That is why, this fault is called a symmetrical or a balanced fault and the fault analysis is done on per phase basis. The behaviour of LLLG fault and LLL fault is identical due to the balanced nature of the fault. This is a very severe fault that can occur in a system and if Z^{-} f = 0, this is usually the most severe fault that can occur in a system. Fortunately, such faults occur infrequently and only about 5% of the system faults are three phase faults.

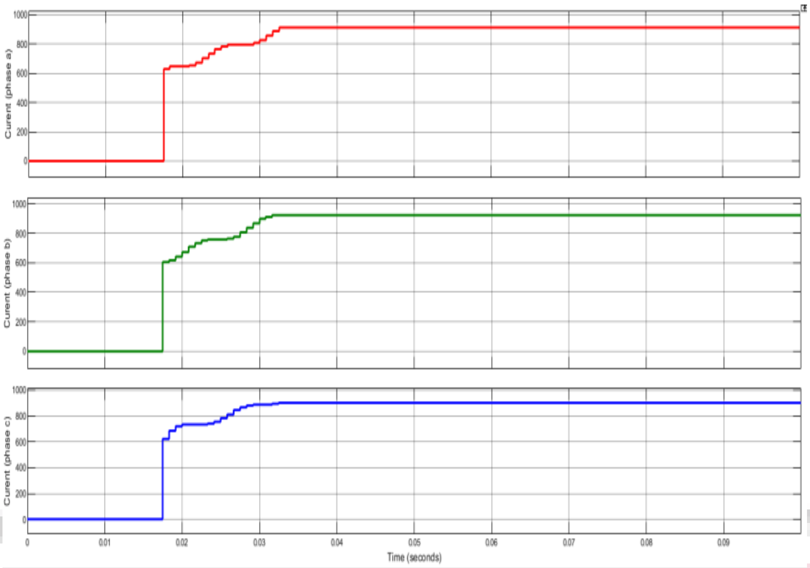


Figure 12: Current during LLL fault at the bus

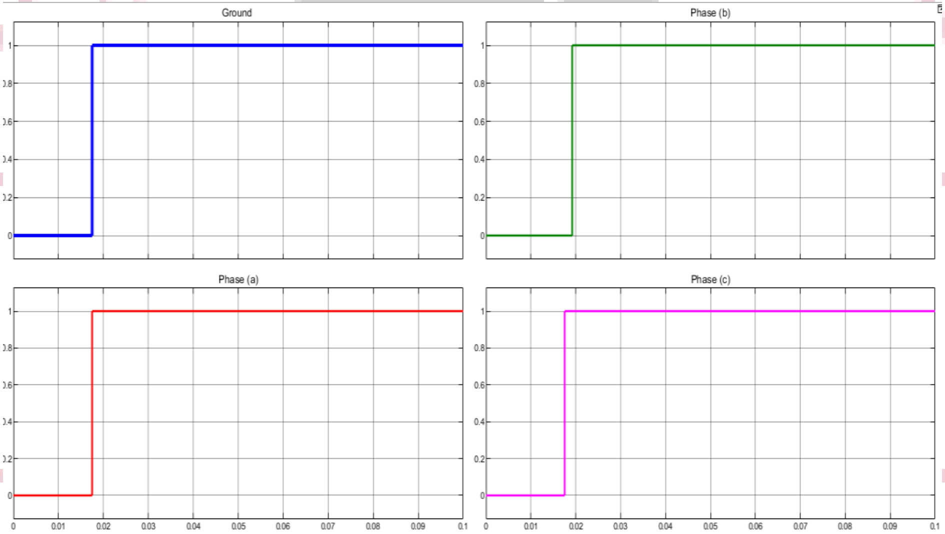


Figure 13: Fault identification window for LLLG fault

The figure 13 shows the current rise at the point where fault is created and the identification window respectively. All the outputs in the identification window of figure 6 have output 1 depicting symmetrical faults of LLLG type is present in the line.

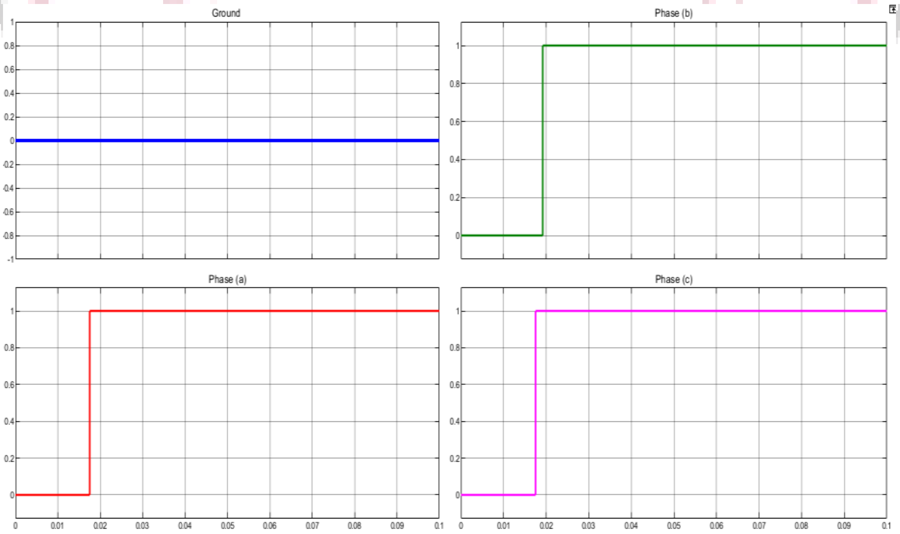


Figure 14: Fault identification window for LLL fault

The identification window in figure 14 seven shows the symmetrical fault type of LLL. The window has 1 output in all the phases but the ground window shows output as zero and hence the conclusion is drawn that the fault is present in all the three phases and ground fault is absent.

B. Unsymmetrical Faults Identification using Fuzzy system

Faults in which the balanced state of the network is disturbed are called unsymmetrical or unbalanced faults. The most common type of unbalanced fault in a system is a single line to ground fault (LG fault). Almost 60 to 75% of faults in a system are LG faults. The other types of unbalanced faults are line to line faults (LL faults) and double line to ground faults (LLG faults). About 15 to 25% faults are LLG faults and 5 to 15% are LL faults.

However when the model is being run for 0.2 seconds the unsymmetrical fault has been created to be switched on in 0.014 seconds. Fig shows the fault being created in the modeled IEEE 13 bus system with solar energy system integrated with it.

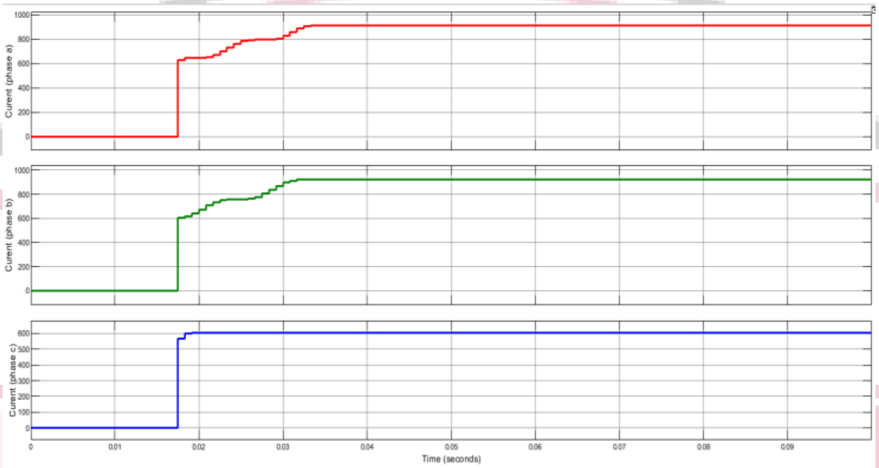


Figure 15: Current during LLG fault at phase (A,B) in the bus

The figure 15 shows that the fault is present only in phase A and B as the current waveform deviation is observed in these phases. The waveform of phase C shows constant behavior as it is not affected by the fault current in line.

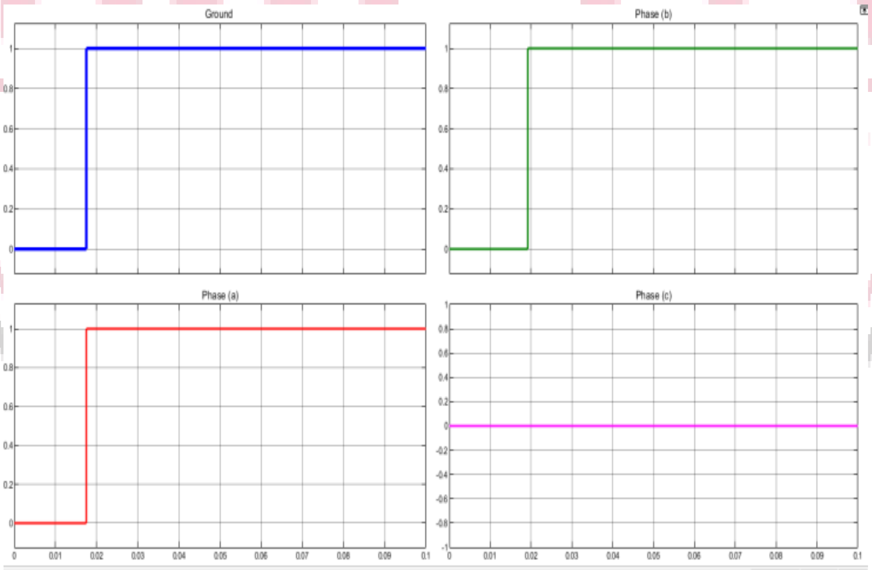


Figure 16: Fault identification window for LLG fault

The identification figure 16 has 1 as output in the ground window, phase A window and phase B window, the phase C window has 0 output. This shows that unsymmetrical fault of LLG type is present in the line in IEEE bus system with solar energy and only phases A and B are involved.

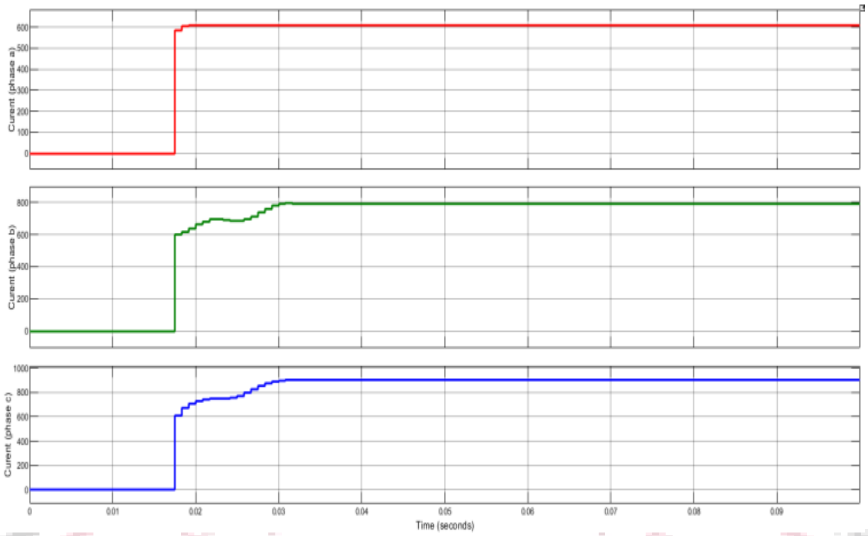


Figure 1: Current during LL fault at phase (B,C) in the bus

The current outputs in the IEEE 13 bus system with unsymmetrical fault at phases B and C is represented in figure 17. The waveform of phase A shows constant behavior as it is not affected by the fault current in system as it is created at B and C only.

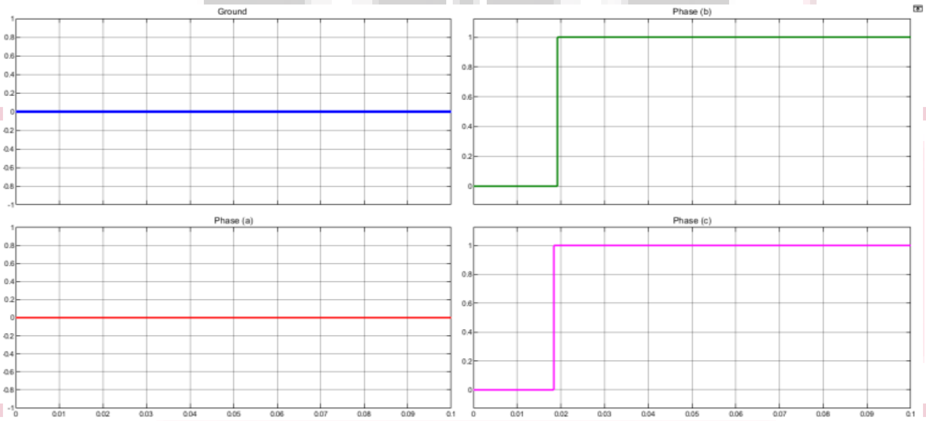


Figure 18: Fault identification window for LL fault

The identification figure 18 has 1 as output in the phase b window and phase C window, the phase A window and ground window has 0 output. This shows that unsymmetrical fault of LL type is present in the line in IEEE bus system with solar energy and only phases B and C are involved

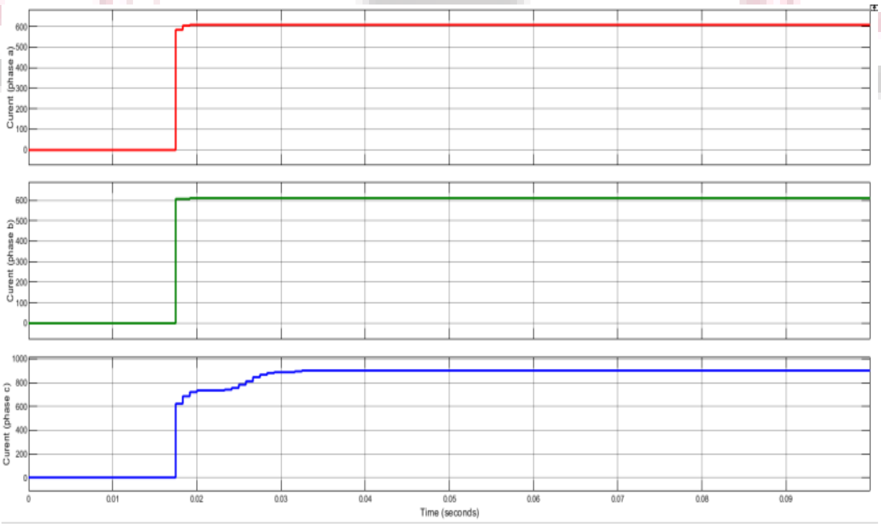


Figure 19: Current during LG fault at phase (C) in the bus

The figure 19 depicts the output current when the fault is created at the phase C with ground. The output current waveforms shows rise in the fault current only at phase C.

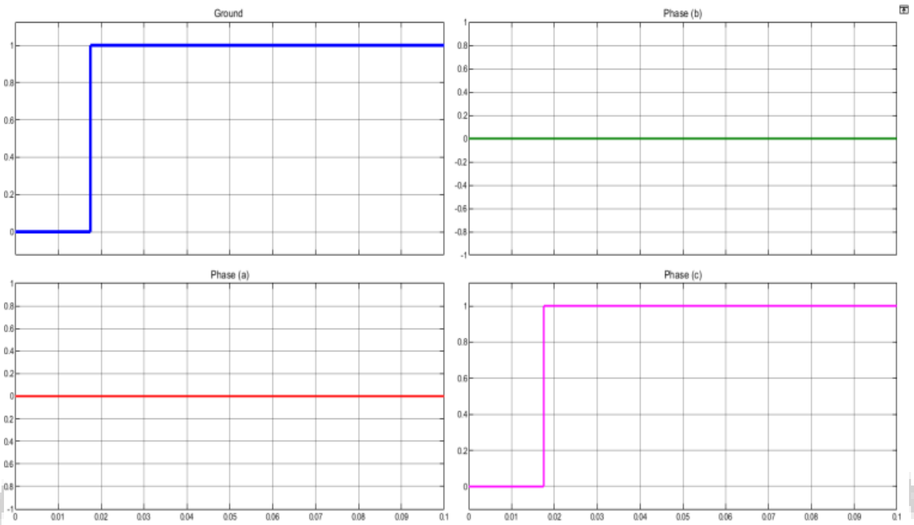


Figure 20: Fault identification window for LG fault

The figure 20 is the fault identification window that shows 1 output in the ground window and phase C window. The output for the phase A and B windows is 0.

Further the work is extended to identify the FIS response time of the implemented fuzzy rule in identifying all the types of faults for different fault resistance which is presented in table 2 and 3

The table represents the time required for fault identification of all types when the fault resistance is kept 10 and the fault inception time is varied.

Table 2: FIS response time with fault resistance 10

Fault Type	Fault Inception Time(sec)	Fault Resistance (Ω)	FIS Response Time			
			A	B	C	G
AB	0.05	10	0.0525	0.055		
AC	0.06	10	0.0641	0.0666		
BC	0.068	10		0.07	0.0708	
AG	0.075	10	0.0755			0.08
BG	0.08	10		0.085		0.0825
CG	0.085	10			0.0908	0.0866
ABC	0.09	10	0.0925	0.0933	0.0925	

The outputs drawn from the table concludes the following key points:

- when the fault type is AB (LL fault) and the inception time is kept to be 0.05 sec the FIS rules responded to the fault created, at 0.055 seconds for phase B and 0.0525 for phase A.
- when the fault type is AC (LL fault) and the inception time is kept to be 0.06 sec the FIS rules responded to the fault at 0.0641 seconds for phase A and 0.0666 for phase C.
- when the fault type is BC (LL fault) and the inception time is kept to be 0.068 sec the FIS rules responded to the fault at 0.07 seconds for phase B and 0.0708 for phase C.
- when the fault type is AG (LG fault) and the inception time is kept to be 0.075 sec the FIS rules responded to the fault at 0.0755 seconds for phase A and ground fault was detected at 0.08 sec

- when the fault type is BG (LG fault) and the inception time is kept to be 0.8 sec the FIS rules responded to the fault at 0.085 seconds for phase A and ground fault was detected at 0.0825 sec
- when the fault type is CG (LG fault) and the inception time is kept to be 0.85 sec the FIS rules responded to the fault at 0.0908 seconds for phase A and ground fault was detected at 0.0866 sec
- when the fault type is ABC (LLL symmetrical fault) and the inception time is kept to be 0.9 sec the FIS rules responded to the fault at 0.0925 seconds for phase A, 0.0933 seconds for phase B, 0.0925 seconds for phase C.

Now the Response time in the fault creation block is varied along with the fault resistance in it. The outcomes from the fuzzy logic system with respect to its response time is recorded and represented in table 5.2

Table 3: FIS response Time with fault variable resistance

Fault Type	Fault Inception Time(sec)	Fault Resistance(Ω)	FIS Response Time			
			A	B	C	G
AG	0.09	20	0.0966			0.0919
BG	0.08	25		0.0858		0.0825
CG	0.065	40			0.0683	0.065
AB	0.085	30	0.0891	0.0875		
AC	0.07	80	0.075		0.0858	
BC	0.06	55		0.07	0.0683	
ABC	0.05	70	0.0575	0.0541	0.0561	

The Results summarized in the table 5.3 provide us the following key conclusions during analysis of both symmetrical and unsymmetrical faults:

- When AG (LG fault) is created in the IEEE 13 bus system at the fault inception time of 0.09 seconds keeping the fault resistance 20 ohms, the FIS response time for phase A came to be 0.0966 sec and ground fault was detected at 0.0919
- When BG (LG fault) is created in the IEEE 13 bus system at the fault inception time of 0.08 seconds keeping the fault resistance 25 ohms, the FIS response time for phase B came to be 0.0858 sec and ground fault was detected at 0.0825 sec.
- When CG (LG fault) is created in the IEEE 13 bus system at the fault inception time of 0.065 seconds keeping the fault resistance 40 ohms, the FIS response time for phase C came to be 0.0683sec and ground fault was detected at 0.065 sec.
- When AB (LL fault) is created in the IEEE 13 bus system at the fault inception time of 0.085 seconds keeping the fault resistance 30 ohms, the FIS response time for phase A came to be 0.0891 sec and for phase B it was detected at 0.0875 sec.
- When AC (LL fault) is created in the IEEE 13 bus system at the fault inception time of 0.07 seconds keeping the fault resistance 80 ohms, the FIS response time for phase A came to be 0.075 sec and for phase C it was detected at 0.0858 sec.
- When BC (LL fault) is created in the IEEE 13 bus system at the fault inception time of 0.06 seconds keeping the fault resistance 55 ohms, the FIS response time for phase B came to be 0.07 sec and for phase C it was detected at 0.0683 sec.
- When ABC (LLL symmetrical fault) is created in the IEEE 13 bus system at the fault inception time of 0.05 seconds keeping the fault resistance 70 ohms, the FIS response time for phase A came to be 0.0575 sec, phase B came to be 0.0541and for phase C it was detected at 0.0561 sec.

V. CONCLUSION

This study presents a robust approach to fault detection and classification in modern electrical power systems, particularly focusing on the integration of solar PV in the IEEE 13-bus system. By designing and simulating an optimized IEEE 13-bus model and integrating solar PV efficiently, the study establishes a foundation for reliable power system operation. The proposed fuzzy logic-based fault identification system demonstrates high accuracy in detecting and classifying various fault types, including symmetrical and unsymmetrical faults. Simulation results validate the effectiveness of the proposed approach, showcasing rapid fault identification within one cycle time. The study underscores the importance of accurate fault detection for ensuring power system resilience and reliability, especially in the context of increasing renewable energy integration. Overall, the proposed methodology offers a promising solution for enhancing power system reliability in modern electrical grids.

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