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Rule base-Disturbance Estimation Based Fault Diagnosis for Grid Connected PV System

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Abstract*—*The paper contains a novel online fault diagnosis for distribution feeder with photovoltaic (PV) generation embedded. The aim of the research is to isolate and prevent system faults in Grid connected PV System. Firstly, a dynamic model of distribution feeder for fault diagnosis is built. Design of proposed fault diagnosis has two stages: firstly, an Equivalent Input Disturbance (EID) approach for the fault estimation is formulated; and Fuzzy knowledge base system is designed for analyzing the characteristics of the EID. The faults position can be located and the fault types can be identified. In this study Fault Diagnosis technique obtains fault detection, identification and halting the system. In the meantime graphical user interface (GUI) is opened when fault is detected. GUI shows the measurement value, fault time and fault type. This property gives some information about the system to the personnel. As seen from the simulation results, faults can be detected and identified as soon as fault appears. In summary, if the system has a fault diagnosis structure, system dangerous situations can be avoided.

Index Terms* —*Fault Detection, Distribution network, PV System, Fuzzy Logic, User Interface

I. INTRODUCTION

Renewable energy has recently shown remarkably rapid growth. A photovoltaic (PV) system, a kind of renewable energy, has become popular worldwide along with the progress in solar panel and power electronic converter technologies. Connecting a PV generator to a distribution network brings many benefits to both consumers and utilities. PVs generate power near load centers, reducing power transmission loss. Installing a large-scale PV system at the end of a distribution feeder changes the load flow situation for the whole power supply system. Specifically, the power flow changes direction when the PV system produces, rather than consumes, more electric power. Reversed power flow is a big problem for conventional protection devices in a distribution feeder. Installing a PV system changes the short-circuit fault current of the feeder, so the protection relay for short-circuit current needs to be reset. The level of the short-circuit fault current changes with variations in PV output due to the uncertainty of PV output. This makes conventional protection unsuitable. Various techniques are used to diagnose power distribution faults, e.g., expert systems, artificial neural networks, Petri net, rough set theory, multi agent technology, and optimization technique. Most of these methods are based on the integration of sensor information from a number of protective relays and circuit breakers used to identify fault types and locate fault locations. If mistaken breaker tripping is frequent, it is difficult to get correct results in fault diagnosis.

Fault diagnosis in power distribution feeders connected to PV systems has recently attracted much attention. There is always needed the scheme to change the location of protection device installation and to increase the number of protection devices. Model-based fault diagnosis methods have been widely used in many fields. They regard the failure of a system as a disturbance and faults are diagnosed by finding and analyzing disturbances.

In this study, a model-based fault diagnosis method for power distribution feeders with a PV system connected is proposed. The faults of system are estimated by an equivalent-input disturbance (EID) estimator and classified by Fuzzy logic. This method not only overcomes the shortage of conventional fault diagnosis methods but also avoid problems involving the installation of new devices and the modification of the protection system structure.

This paper is organized as follows: Section II explains modeling of power distribution feeders with a PV generator embedded. Section III describes proposed fault diagnosis method. Section IV presents simulation results proving the effectiveness of proposed method, and Section V presents concluding remarks.

II. DYNAMIC MODELING OF PV SYSTEM WITH DISTRIBUTION NETWORK

With a PV system connected, load consumers are simultaneously supplied power from the utility grid and the PV generator. Fig. 1 shows the block diagram of a node with a PV system connected and its equivalentcircuit. A PV system consisting of PV arrays and an inverter are connected to the node at point “a” and inject current into the network. One part of load consumption thus comes from PV system ($G2$), and the rest is supported by utility power ($G1$). A filter installed on the PV side eliminates high-frequency harmonic signals from the inverter. Compared to a PV generator, a utility power source is regarded as an infinite power that supplies sufficient power to the load. Due to a limited power supply, the PV generator is regarded as a controlled source. Its output current is limited and usually determined by weather.To ensure that the PV generator and utility source provide the power to the load simultaneously, PV output voltage is usually required to be the same as the voltage of the utility source. And the output voltage of PV generator always keeps the same with the reference voltage, the voltage of nodeU_f. $Z_f$is the equivalent impedance of electrical consumer. Generally, the utility power source is far from the consumer and connected by transmission line. $Z_1$is the equivalent impedance of the transmission line. During to the PV usually set up nearby the user, so the impedance of the transmission line between them can be ignored.

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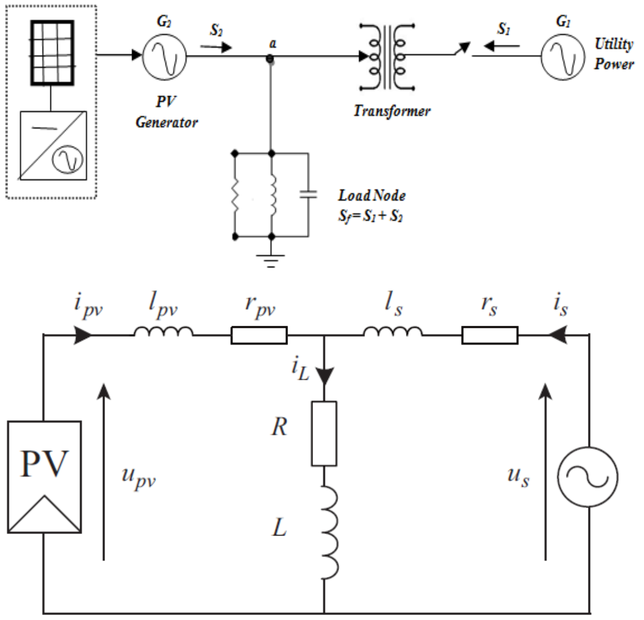

Fig.1. Block Diagram of grid connected PV System and its equivalent circuit

Then, according to the formula of impedance calculation we can get the equivalent impedance.

$Z_f = (U_f{}^2/S_f)^*$

Where, U_f is the voltage of node and S_f is the average power consumption of the node. For sinusoidal circuit, the equivalent impedance in two port network N is Z = R+jX. For the other parts of circuit, the network N can be equaled to a resistor and a reactance element in series. If the equivalent reactance X>0, the network N is inductive and can be equaled to an inductor. In opposite, if the equivalent reactance X<0, the network N is capacitive and can be equaled to a capacitance. If the X=0 the network N can be equaled to a resistor only. In electrical power system, the consumers are mainly inductive load, so we can use an inductance (L) to take place of the reactance X. Then we obtain:

$$Z_f = R_f + j\omega L_f \;\; ;Z_1 = R_1 + j\omega L_1$$

The utility power source as the infinite power, the output voltage U_0 remains unchanged. The output current of PV generator is i_{pv}, and R_1, L_1 are the equivalent resistor and reactance of transmission line between utility and load node respectively. R_f, L_f are the equivalent resistor and reactance of load node respectively. The system state equation is given below,

$$\dot{i}_1(t) = \frac{R_1 + R_f}{L_1 + L_f} i_1(t) + \left[\frac{-R_f}{L_1 + L_f} \; \frac{-L_f}{L_1 + L_f} \; \frac{1}{L_1 + L_f}\right] \begin{bmatrix} i_{pv}(t) \\ \dot{i}_{pv}(t) \\ u_0(t) \end{bmatrix}$$

$$u_f(t) = \left[\frac{-L_f R_1 + L_1 R_f}{L_1 + L_f}\right] i_1(t) + \left[\frac{L_1 R_f}{L_1 + L_f} \; \frac{L_1 L_f}{L_1 + L_f} \; \frac{L_f}{L_1 + L_f}\right] \begin{bmatrix} i_{pv}(t) \\ \dot{i}_{pv}(t) \\ u_0(t) \end{bmatrix}$$

III. PROPOSED FAULT DIAGNOSIS

The proposed Fault diagnosis system executes the tasks of failure detection and identification by ceaselessly monitoring the outputs of system. Under nominal conditions, these measurements follow predictable patterns within a tolerance influenced by the amount of uncertainties introduced by disturbances. Its tasks are fulfilled by EID approach when the fault occurrence varies from its predicted pattern. The initial step is to detect the abnormal system behaviour and estimate the order of magnitude of the fault. Then, it is classified by Fuzzy System. The proposed system is shown in Fig.2.

A. Disturbance Estimation

In this research work, the faults are regarded as disturbances of system and the EID estimation method is employed to obtain the disturbance. Then we can judge whether the fault occurs by analyzing the characteristic of the disturbance.

3.1. Definition of EID

The dynamic model for fault diagnosis previous section can be simplified as follow:

$\dot{x}_0 = Ax_0(t) + Bu(t)$

$y_0 = Cx_0(t) + Du(t)$

Where,$u(t) = \left[i_{pv}(t)\dot{i}_{pv}(t)u_0(t)\right]^T$,

$x_0(t) = i_1(t), and y_0(t) = u_f(t)$.*A*, *B*, *C*, *D* are the state space matrixes.

As mentioned above, the faults represent to be disturbances, then, we get the system plant with disturbances,

$\dot{x}_0 = Ax_0(t) + Bu(t) + B_d d(t)$

$\dot{y}_0 = Cx_0(t) + Du(t)$

If consideration that a disturbance is imposed only on the control input channel and structure an equivalent controlled system as shown in Fig.1, then the plant is given by

$\dot{x}_0 = Ax_0(t) + B[u(t) + d_e(t)]$

$\dot{y}_0 = Cx_0(t) + Du(t)$

An EID is defined as follows: Let the control input be$u(t) = 0$. Then, the output of the plant (6) for the disturbance $d(t)$is$y_0(t)$, and the output of the plant (7) for the disturbance $d_e(t)$ is$y(t)$. The disturbance $d_e(t)$ is called an EID of the disturbance$d(t)$if $y(t) = y_0(t)$ for all *t*≥0. For the system plant presented above, described in recent literatures, the following conditions guarantee that the EID exist objectively.

(1) (*A*, *B*, *C*) is controllable and observable.
(2) (*A*, *B*, *C*) has no zeros on the imaginary axis.

Considering the definition of EID, the fault from the point of view of system can be evaluated by analyzing the magnitude of EID. Then a method of estimating the EID will be present in following.

3.2 Estimation of EID

In Fig. 1, for the state observer

$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L[y(t) - \hat{y}(t)]$

Where,

$$\hat{y}(t) = C\hat{x}(t) + Du(t) y(t) = Cx(t) + Du(t)$$

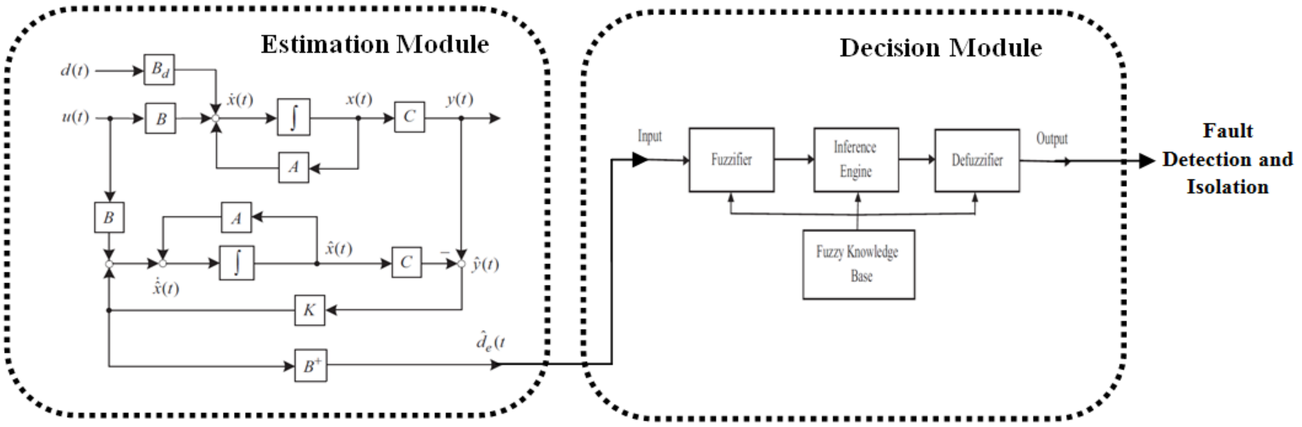

Fig.2. Block Diagram of Proposed Fault Detection and Isolation

Letting$\Delta x(t) = \hat{x}(t) - x(t)$, and substituting it into $\dot{\hat{x}}(t)$ yields

$$\dot{x}(t) = A\hat{x}(t) + Bu(t) + (Bd_e(t) + [\dot{\Delta x}(t) - A\Delta x(t)])$$

Assume that there exists a control input

$[\dot{\Delta x}(t) - A\Delta x(t)] = B\Delta d(t)$

Letting the estimate of the EID be

$\widehat{d_e}(t) = d_e(t) + \Delta d(t)$

So allows us to express the plant as

$$\hat{x} = A\hat{x}(t) + B[u(t) + \widehat{d_e}(t)]$$

Above Equations mean that, if we take the state of the plant with an EID to be$\hat{x}(t)$, which is exactly the state of the observer, then the difference between the state of the plant and that of the observer is equivalent to the difference between the exact value and the estimate of the EID. $B\widehat{d_e}(t)$ yields,

$$B\widehat{d_e}(t) = LC\,[x(t) - \hat{x}(t)]$$

According to $\widehat{d_e}(t)$,

$$\widehat{d_e}(t) = B^{+}LC\,[x(t) - \hat{x}(t)]$$

Where, $\widehat{d_e}(t)$is the estimation of EID and

$B^{+} = (B.B^{T})^{-1}B^{T}$

The estimation of$d_e(t)$, denoted as $\widehat{d_e}(t)$can be used to reflect the characteristic of $d(t)$and diagnose the fault of system.

B. Fuzzy Decision Making

Fuzzy decision making is integrated in two basic steps. The preparations of the fault dictionary for different models are identified faults in the first step.

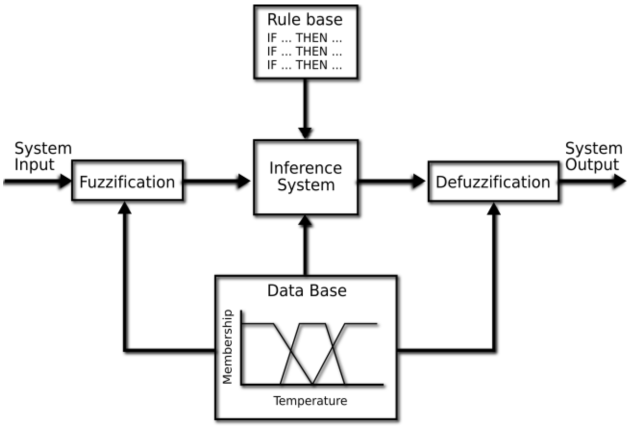

Fig.3. Block Diagram of Fuzzy fault Classifier

In the second step, implementation of the fuzzy classifier for the fault classification is done. The fault dictionary is prepared by tabulating estimates for each fault model. The fault dictionary contains the residues $d_{e1}(t), d_{e2}(t), d_{e3}(t)$[V]. The estimates for different faults are shown in Fig.5.The crisp input is given to the fuzzifier, which converts it to a linguistic variable by using the membership functions stored in the fuzzy knowledge base. Inference engine gets the fuzzy input and converts into fuzzy output using IF–THEN rules. Fuzzy output of the inference engine is converted to crisp using membership functions by Defuzzifier as shown in Fig.3. Five commonly used defuzzification methods are Center of Area, Modified Center of Area, Center of Sums, Center of Maximum and Mean of Maximum. The Mamdani method is widely used and accepted for capturing expert knowledge [8]. It allows describing the expertise in a more human like manner. These fuzzy models are characterized by having fuzzy propositions as antecedents and consequences.

IV. RESULTS AND DISCUSSION

A. Model Parameters

In this work, the voltage supplied to the load is 4160V and the impedance of transmission line is Z=0.3 + j0.6 [Ω/m] for utility power source. The state space description of the node as follow:

$A = (-255)$; $B = (-247.1 \quad -0.472 \quad 27.78)$

$C = (4.554)$; $D = (-4.696 \quad 0.00897 \quad 0.4722)$

For the system above, an optimal observer gain L was

$J_L = \int_0^{\infty}\{\rho x_L^T(t)Q_L x_L(t) + u_L^T(t)u_L(t)\}dt$

Where, $\rho = 10^6$ and $Q_L = 1$; The parameter yield: $L = 946$

B. Disturbance Models

Different types of faults can interrupt the healthy operation of the power system. Some of the major Electrical faults are phase fault, open circuit fault, overload, real power deficit, etc. In this simulation, the faults are considered as disturbances of system. In order to verify the effectiveness of the method, the disturbances are introduced it to fault diagnosis model, then, employ the method to judge whether the diagnosis result is right. In general, the faults can be represented as two kinds, one of which is the load magnitude over the permitted range but power factor basically unchanged, the other of which is the

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power factor below the allowed threshold. Meanwhile, we noticed that the normal load variation, due to the changing Demand for consumer, also can be treated as a kind of disturbance but not fault. The three kinds of disturbances are shown as Fig.4.

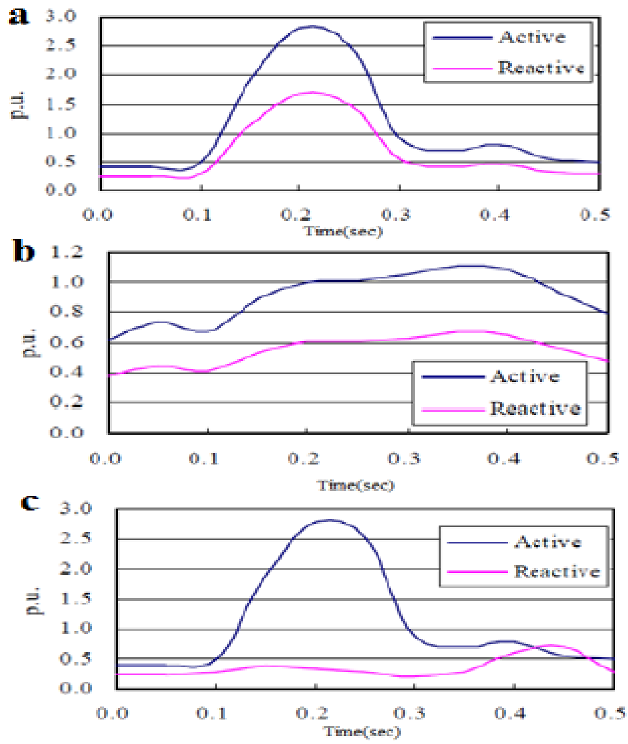

Fig.4. Disturbance profile – a) Normal Load b) Amplitude type c) Phase type

C. Rule base Inference Engine

The estimates extracted for fault diagnosis is considered as the fuzzy system input. In the proposed approach only two inputs considered. Number of membership function for input signature depends upon the number of predefined fault models. Three fault models are defined namely Amplitude fault (AF), Phase fault (PF). Fault Free (NL) case is also noted. Hence the total number of input membership function is three. Fig.6. shows the possible appearance of the input membership functions. Once the membership functions are defined for both the inputs and the output of the fuzzy system, they are connected with IF-THEN rules. The procedure of defuzzification combines the consequence of the activated rules by means of the center of the area method. The output of the fuzzy system is the fault index which is used for maintenance. Since there are three inputs membership functions and hence four IF– THEN rules are designed. The rule structure for all fault models are given as

If Input $_0$ is NL AND Input $_1$ is NL Then Output is Fault Index 0

If Input $_0$ is AF AND Input $_1$ is AF Then Output is Fault Index 1

If Input $_0$ is PF AND Input $_1$ is PF Then Output is Fault Index 2

C. Graphical User Interface

Additionally GUI is added to the system as a tool. Fault diagnosis tool consist of measurement value graphic, fault alarm, fault type and fault time. When the fault is detected user interface appears and gives the warning about the fault and the details like fault type, fault time and measurement value.

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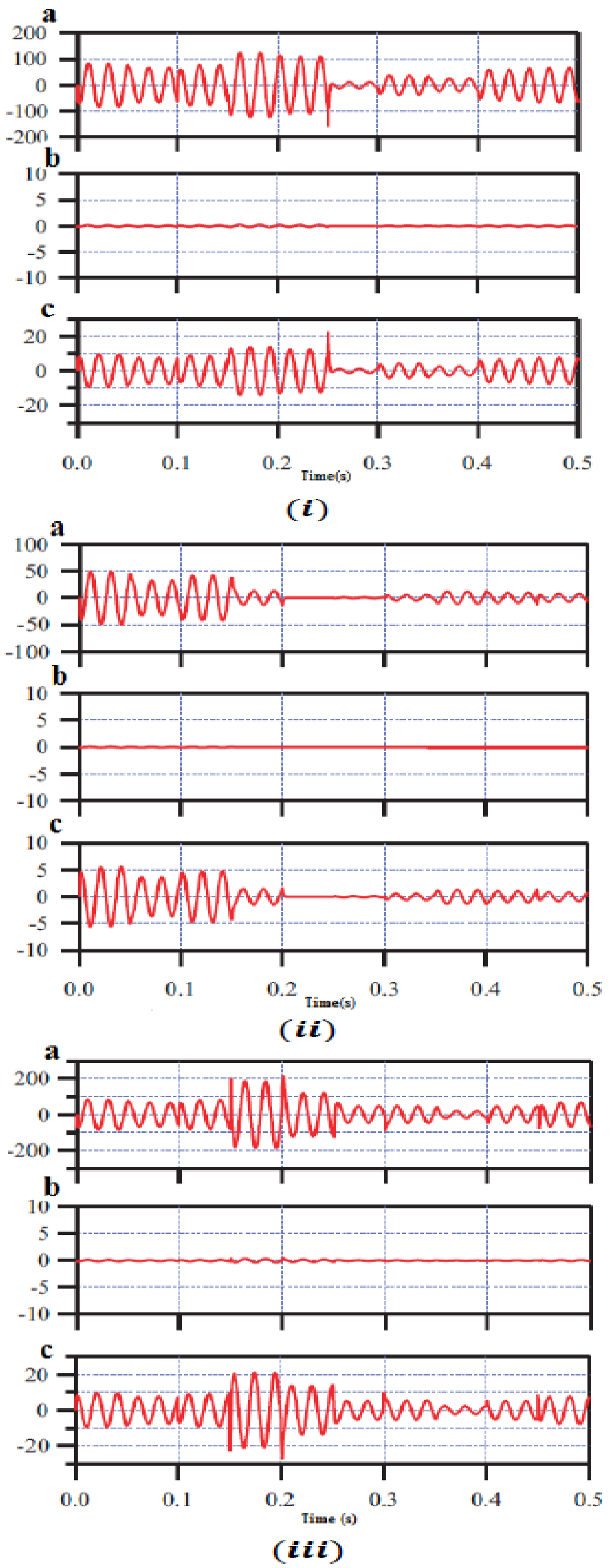

Fig.5. Estimates of system when (i) Normal Load Variation (ii) Amplitude type (iii) Phase type fault (a) de1 t [V] (b) de2 t [V] (c)de3 t [V]

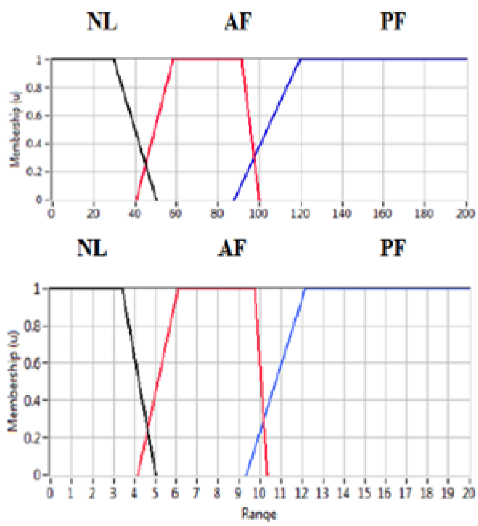

Fig.6. Possible fuzzy input membership functions

If fault diagnosis technique was not applied to the system, system would maintain to work but not at the reference point. Fault diagnosis tool has been designed to simplify the work of the operator, monitoring the performance of the system.

IV. CONCLUSION

This paper addresses an online fault diagnosis with fuzzy cluster and EID estimator for distribution feeder. Firstly, a dynamic model for diagnosis was set up; secondly the faults of system were obtained by an EID estimator and classified by fuzzy logic. The existing methods rely on a large number of information of sensors; the proposed method only uses the information of input voltage and current for fault diagnosis. Therefore, it can overcome the impact on the relay and breaker. The proposed method integrates fault diagnosis with PV embedded preliminary. Additionally the fault is diagnosed with GUI which includes the fault time, fault type, measurement value as a graphical. Simulation results are satisfactory because faults are detected and identified in a short period of time which is important as much as fault diagnosis. In the further research, the detail of this method, such as the design of fault type, the nonlinear loads and the exactly setting of threshold for EIDs, need to be considered.

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