Fuzzy Expert System for Determining State of Solar Photo Voltaic Power Plant Based on Real-Time Data

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Fuzzy Expert System for Determining State of Solar Photo Voltaic Power Plant Based on Real-Time Data

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Abstract: This paper presents an implementation of fuzzy expert system for determining state of a solar plant in real-time, based on reliability, economy, and possible improper operations of the system components, using streaming real-time data of the solar plant. The reliability depends on the state of battery charge and the available backup time. The economy depends on the purchase of power from the utility supply. Improper operation of the system could be due to faulty or mal-operation of a component that could degrade the performance of plant. The proposed fuzzy expert system was developed for a 40 kWp Hybrid Solar power plant installed at Dayalbagh Educational Institute. The system determines the state of the plant in terms of reliability, economy, and possibility of improper operations under real-time conditions. In addition to reliability and economy being the key parameters, much focus has been placed on improper operations and corrective measures have been suggested.

Keywords: expert system; fuzzy logic; reliability; economy; improper operations

1. Introduction

An expert system is a software or system that mimics the human capability to make decisions using a knowledge base and specific rules. Fuzzy logic has been used in designing expert systems for various applications owing to its potential to deal with uncertainty and to store knowledge from experts in if-then type rules, which are very easy to design and visualize

Some of the fields in which fuzzy expert systems are used include medicine, power systems, the automobile industry, and home appliances. Dash et al. [1] presented a fuzzy expert system to classify power disturbances. Lee et al. [2] discussed an integrated fuzzy expert system for fault diagnosis in distribution networks. Chang et al.[3] presented an expert fuzzy system for the control of diabetes. Iqbal et al.[4] used a fuzzy expert system to optimize milling parameters to reduce production costs and increase output quality. Etik et al. [5] proposed a design for a controlled fuzzy expert system to improve room-operating conditions by taking humidity, heat, and particles as input and fresh air and fan circulation as output. A fuzzy expert system was presented [6] to make risk estimation more systematic and precise. Sallam et al.[7] suggested a fuzzy expert system for controlling voltage instability caused by load shedding. Kiartzis et al. [8] developed a fuzzy expert system for predicting future loads. Cao et al. [9] proposed a fuzzy-based system based on current customer needs, which acted as a personalized recommendation system. Zarkovi et al.[10] proposed a fuzzy controller to categorize the current conditions of a transformer to detect a specific type of fault. Almulla [11] designed an expert system for patients with diabetes based on the symptoms and location of the patient. The expert system works on the concept of backward and forward chaining. The Expert system warns the patient of an early stage of diabetes. Prabakaran et al.[12] investigated various factors responsible for the outbreak of COVID19 and suggests various methods to stop its spreading by using a fuzzy logic system. Berawi et al. [13] used Fuzzy Logic and Decision Tree in decision-making to prioritize earthquake victims according to their needs. Gupta et al. [14] proposed a fuzzy DEMATEL-ANP-TOPSIS technique to support the implementation of low carbon SCM. Zohedi et al [15] discussed the modeling of a remotely operated vehicle using single input fuzzy controller. The results show that SIFLC is the best technique, in comparison with Proportional, Integral, and Derivative (PID), Fuzzy Logic Controller (FLC). Choirunisa et al. [16] modeled an MR Damper with an Adaptive Neuro-Fuzzy Inference System using Gaussian and generalized bell membership functions. The results show Gaussian function is more accurate than the generalized bell membership function.

Contribution of fuzzy logic in the domain of solar energy includes Flores et al.[17] proposed a fuzzy predictive controller that optimizes constant outlet oil temperature with multi-objective problems considering the given goals and constraints. Chaabene et al.[18] designed a fuzzy algorithm that determines the optimal connection mode to domestic appliances between the grid and PVP, thereby providing an efficient mechanism to save energy. Yang et al.[19] described a control strategy to maximize the advantages of the SPV using variable universe fuzzy control for MPPT control. Zarkovic et al.[20] proposed a fuzzy expert system to optimize energy consumption and storage to maximize the gain from the microgrid. Rizwan et al.[21] presented a fuzzy-logic approach for predicting SPV system output using the mean duration of sunshine per hour, temperature, latitude, longitude, altitude, and months of the year as input parameters. El-Bidairi et al.[22] presented a fuzzy expert system for multi-objective energy management and optimal battery sizing based on a fuzzy-logic grey wolf optimizer. Thomas et al. [23] proposed a fuzzy-based self-adaptive virtual synchronous machine scheme in which the inertia value was calculated using fuzzy rules to handle frequency fluctuations in the microgrid. Mostafaeipour et al. [24] presented a study to identify challenges in the growth of solar energy using the fuzzy worst-best method to identify the criteria hindering the development of solar energy. Akhtar et al. [25] proposed three different techniques for reliability assessment:- the alternative model-creating technique (AMCT), two parameter-based alpha model techniques (TPBAMT), and fuzzy fault tree-based techniques (HDFFTBT) with fuzzy logic-based inverter control for reliability assessment. To illustrate the effectiveness of the suggested technique, risk analysis was performed. Hoedi [26] proposed a monitoring system for Solar Photo voltaic plants using hardware and IoT, at a very low price for an On-grid PV system in urban areas.

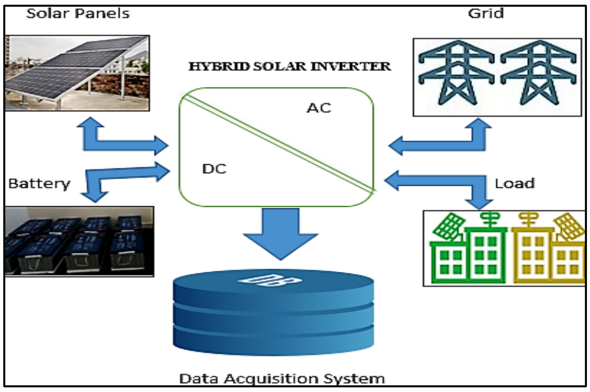

Fig 1. Interactive Microgrid at DEI

This paper presents the implementation of a real-time fuzzy expert system that provides the current state of the Solar Photo Voltaic power plant in terms of good, medium, low-reliability economy and the possibility of improper operation that will help us to take corrective measures well in advance. This study was conducted at the Dayalbagh Educational Institute, Agra where eight distributed SPV power plants with storage are located in different departments within the university campus. For this study, a 40 kWp power plant deployed at the Arts faculty was considered. Data acquisition software is designed as a client that collects data streams from inverters, displays them in real-time, and maintains a database. The historic data of previous years was taken as a reference for designing the fuzzy parameters.

2. Fuzzy Expert System for Solar PV Plant

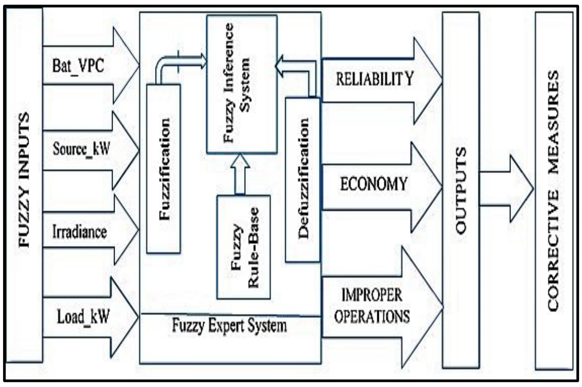

Fig 2. Proposed Fuzzy Expert System

The proposed expert system (Fig 2) uses a fuzzy model to draw inferences from real-time data streams available from the centralized communication center of the smart microgrid at Dayalbagh Educational Institute. An additional feature fuzzy expert system also indicates any malfunction in system components through fuzzy inferences. The streaming data from the inverter are fed to the fuzzy expert system, which determines whether the present state of operation is good or bad in terms of reliability economy associated with improper operations.

Feature Selection - The feature selection for deciding input variables for the fuzzy expert system was performed by obtaining correlation coefficients through a correlation matrix by applying Pearson's coefficient formula to the data collected through the data acquisition system. The correlation matrix provides a basis for determining the relationship between various parameters. Parameters whose correlation coefficient is equal to one are not considered for redundancy because each parameter having a value of r is equal to 1 will be the same.

The formula for computing the Pearson's coefficient of correlation r between x and y is as follows:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{(n-1)\sigma_x \sigma_y}$$

Where: x¯ and y¯ are the respective means of x and y, n is the population size.

$\sigma_x = \sqrt{\frac{\sum(x_i - \bar{x})^2}{(n-1)}}$ is the standard deviation(S.D.) of x.,

$\sigma_y = \sqrt{\frac{\Sigma(y_i - \bar{y})^2}{(n-1)}}$ is the standard deviation(S.D.) of y.

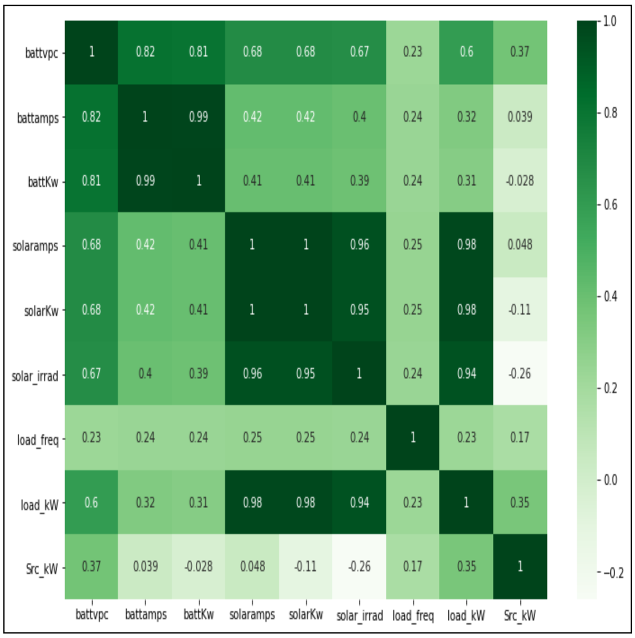

Fig 3. Correlation Matrix

The correlation diagram above shows various correlation coefficient along with various inverter parameters. solaramps, solarkW, solar_irrad, solaramps, solarkW, load_kW, battamps, and battkW are strongly connected because their value is greater than threshold value 90, we can select only one of them and drop the others. However, because Src_kW, solar_irrad, and load_kW are not related we have to consider all three of them. The final features selected were Src_kW, solar_irrad, battvpc, load_kW which are the input parameters for the fuzzy expert system.

2.1 Input Parameters

The historic data stored through Data Acquisition Software was analyzed to calculate the data range for each input parameter, that is, Src_Kw, solar_irrad, battvpc, and load_kW. The range of all input parameters is selected from the max and min values computed over previous years.

Table 1. Various SPV parameters along with their range

PARAMETERS	RANGE
Battery VPC	1.5V-2.3V
Irradiation	0-1300 W/m2
Load_kW	0kW-30kW
Source_kW	-28kW to + 35kW

The proposed fuzzy expert system consists of four linguistic inputs i.e Battery VPC (voltage per cell), Load_kW, Irradiance, Source_kW, and three linguistic outputs i.e. Reliability, Economy, and Improper Operation. The input variables i.e. Battery VPC, Load_kW, and Irradiance are described by the fuzzy terms high, medium, and low whereas Source_kW takes the value as very negative, negative, zero, positive, and very positive. The fuzzy variables are expressed in terms of membership functions. The membership functions convert the degree of fuzziness in the interval [0, 1]. For this study, triangular-shaped membership functions are considered. A triangular function is defined by a lower limit a, an upper limit b, and a value m, where a < m < b.

$$f(x): X \longrightarrow [0,1]$$

$$f(x) = \begin{cases} 0, & x \le a, x \ge b \\ \frac{(x-a)}{(m-a)}, & a < x \le m \\ \frac{(b-x)}{(b-m)}, & m < x < b \end{cases}$$

The four input variables are as follows:

Battery VPC- The battery voltage per cell (VPC) indicates the health of a battery i.e. how much it is charged, fully charged battery will contribute to high reliability and high economy. The range of Battery VPC is between 1.5V to 2.3V. The mathematical and graphical representation is shown in fig (4) where $f_l(x)$ =low, $f_m(x)$ =medium and $f_h(x)$ =high.

$$f_l(x) = \begin{cases} 0, & x \le 1.529, x \ge 1.917 \\ \frac{(x-1.529)}{(1.745-1.529)}, & 1.529 < x \le 1.745 \\ \frac{(1.917-x)}{(1.917-1.745)}, & 1.745 < x < 1.917 \end{cases}$$

$$f_m(x) = \begin{cases} 0, & x \le 1.838, x \ge 2.096 \\ \frac{(x-1.838)}{(1.966-1.838)}, & 1.838 < x \le 1.966 \\ \frac{(2.096-x)}{(2.096-1.966)}, & 1.966 < x < 2.096 \end{cases}$$

$$f_h(x) = \begin{cases} 0, & x \le 2.048, x \ge 2.392 \\ \frac{(x-2.048)}{(2.22-2.048)}, & 2.048 < x \le 2.22 \\ \frac{(2.392-x)}{(2.392-2.22)}, & 2.22 < x < 2.392 \end{cases}$$

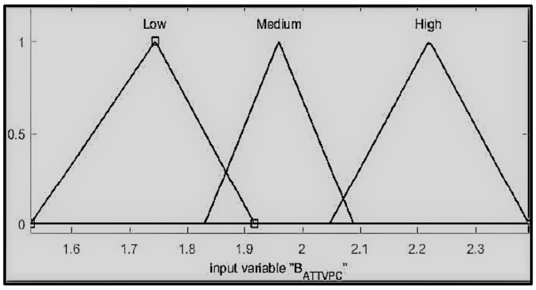

Fig 4. MFs for Batt_VPC

Source_Kw defines the power import from the grid (positive value) or power export to the grid (negative values). Therefore the value is "-ve" power is supplied to the grid which means the economy is good and if its value is "+ve" power is taken from the grid i.e. low economy. The range of Source_kW is between -27.7 to 34.0 kW. Mathematical and graphical representations are shown in fig (5) where $f_{vn}(x)$ =very negative, $f_n(x)$ =negative, $f_z(x)$ =zero and $f_p(x)$ =positive and $f_{vp}(x)$ =very positive

$$f_{vn} = \begin{cases} 0, \quad x \le -40.04, x \ge -15.5 \\ \dfrac{(x - -40.04)}{(-27.64 - -40.04)}, 9.53 < x \le -27.64 \\ \dfrac{(-15.5 - x)}{(-15.5 - -27.64)}, -27.64 < x < -15.5 \end{cases}$$

$$f_n(x) = \begin{cases} 0, \quad x \le -17.38, x \ge -4.255 \\ \dfrac{(x - -17.38)}{(-10.01 - -17.38)}, -17.38 < x \le -10.01 \\ \dfrac{(-4.255 - x)}{(-4.255 - -10.01)}, -10.01 < x < -4.255 \end{cases}$$

$$f_z(x) = \begin{cases} 0, \quad x \le -5.15, x \ge 5.065 \\ \dfrac{(x - -5.15)}{(0.758 - -5.15)}, [-5.15 < x \le 0.758 \\ \dfrac{(5.065 - x)}{(5.065 - 0.758)}, 0.758 < x < 5.065 \end{cases}$$

$$f_p(x) = \begin{cases} 0, \quad x \le 3.34, x \ge 13.3 \\ \dfrac{(x - 3.34)}{(8.996 - 3.34)}, 3.34 < x \le 8.996 \\ \dfrac{(13.3 - x)}{(13.3 - 8.996)}, 8.996 < x < 13.3 \end{cases}$$

$$f_{vp}(x) = \begin{cases} 0, \quad x \le 11.98, x \ge 34.58 \\ \dfrac{(x - 11.98)}{(22.18 - 11.98)}, 11.98 < x \le 22.18 \\ \dfrac{(34.58 - x)}{(34.58 - 22.18)}, 8.996 < x < 34.58 \end{cases}$$

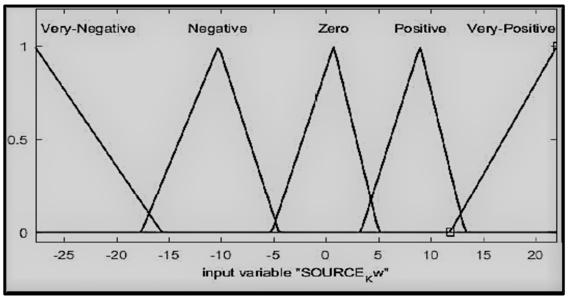

Fig 5. MFs for Input "Source_kW"

Irradiance refers to the amount of sunlight incident on the solar panel. The higher the irradiance value, the higher the solar power generation. Zero value signifies that there is no sunlight; therefore, no solar power generation occurs. The irradiance range is between 0 and 1300 W/m2 but the data acquisition system shows the value between 0 and 132 W/m2 as it has been scaled by one-tenth of its original value. The mathematical and graphical representation is shown in fig (6) where $f_l(x)$ =low, $f_m(x)$ =medium and $f_h(x)$ =high.

$$f_l(x) = \begin{cases} 0, \quad x \le 0, \\ \dfrac{(x - 0)}{44}, 0 < x \le 44 \\ 1, x \ge 44 \end{cases}$$

$$f_m(x) = \begin{cases} 0, \ x \le 42.4, x \ge 89.7 \\ \frac{(x-42.4)}{(65.6-42.4)}, 42.4 < x \le 65.6 \\ \frac{(89.7-x)}{(89.7-65.6)}, 65.6 < x < 89.7 \end{cases}$$

$$f_h(x) = \begin{cases} 0, \ x \le 88, \\ \frac{(x-88)}{132-88}, 88 < x \le 132 \\ 1, x \ge 132 \end{cases}$$

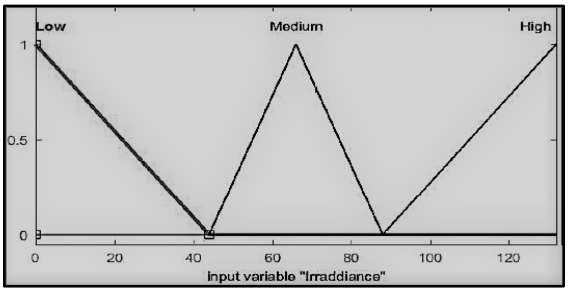

Fig 6. MFs for Input "Irradiance"

Load_kW signifies the load of a building or a unit. A high load implies high power consumption. The range for Load_kW was between 1kW and 30kW. The mathematical and graphical representation is shown in fig. (7) where $f_l(x)$=low, $f_m(x)$=medium and $f_h(x)$=high.

$$f_l(x) = \begin{cases} 0, \quad x \le 0, \\ \dfrac{(x - 0)}{9.8}, 0 < x \le 9.8 \\ 1, x \ge 9.8 \end{cases}$$

$$f_m(x) = \begin{cases} 0, \quad x \le 9.53, x \ge 20.2 \\ \dfrac{(x - 9.53)}{(14.8 - 9.53)}, 9.53 < x \le 14.8 \\ \dfrac{(20.2 - x)}{(20.2 - 14.8)}, 14.8 < x < 20.2 \end{cases}$$

$$f_h(x) = \begin{cases} 0, \ x \le 19.7, \\ \frac{(x-19.7)}{132-88}, 19.7 < x \le 29.8 \\ 1, x \ge 29.8 \end{cases}$$

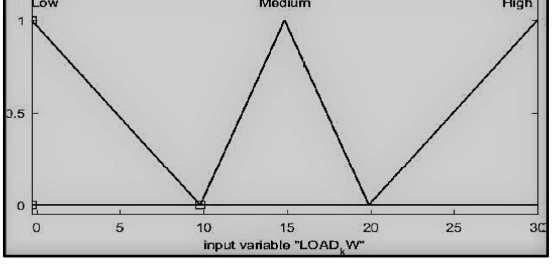

Fig 7. MFs for Input "Load_kW"

2.2. Output Parameters

The output of the fuzzy expert system consists of three output indices, that is, i.e. reliability, economy, and improper operations having three linguistic values -low, medium, and high defined over the universe of discourse.

Reliability indicates the ability of a system to cater to load even in the absence of a utility source. This depends on the available charge of the battery. A fully charged battery implies that reliability is high.

Economy refers to how effectively available resources are utilized to meet our requirements with minimum time and money. This depends on irradiance and load. High irradiance and low load conditions will result in more electricity export i.e. good economy whereas low irradiance and high load will lead to more import of electricity from the grid i.e. lower economy.

Improper operations can disturb the normal operation of any system. Improper operations can be due to hardware problems, software settings, connectivity issues, and so on. Common improper operations in an SPV plant can be due to dusty panels, shadows over panels, faulty connectors, and improper software settings of the inverter.

The output of fuzzy logic, that is, all three variables, is further classified into three categories based on universal discourse. If the value ranges between 0 and .30 then it is classified as "LOW", if the value is 0.31 and 0.60 then it is classified as "MEDIUM" and "HIGH" if the value is greater than 0.60. The objective of classification is to make the output more understandable, as the results are in linguistic form rather than numerical value.

In the case of "High" and "Medium" improper operations, the possible problem of the cause is also suggested, this feature of the expert system makes it unique in its type.

2.3. Rule Base

The rule base represents knowledge on which decisions are made. In fuzzy systems, the rule base is represented by simple rules (if- then) statements. In this study, these rules were framed by a team of expert who has been indigenously monitoring SPV plants since 2010. These rules were framed, based on the practical experience of these experts. Some of the basic facts, shared by the team of expert, by which rules were framed includes:

- When the battery is low - no export of electricity to the grid.
- High irradiance and low load – export of electricity to the grid.
- Irradiance (Solar) will be preferred over the grid to cater to load and battery charging.

These rules are verified using case studies based on historical data. In this study, the Fuzzy Inference system is composed of 135 rules using the Mamdani model.

These rules can be read as (for Rule1): If "Battery_VPC is low" and "Source_Kw is very positive" and "Load_kW is low", "Irradiance is low" then "Reliability is low", and "Economy is low" and "Improper Operation is medium".

Careful observation of the above rules shows almost 50 percent of the rules show improper operation which should be properly handled to guarantee smooth operation of the plant. The rule base is represented in Table 2 where RNO represents Rule Number, VPC represents Battvpc, Rad represents Irradiance, Rel represents Reliability, Eco represents Economy and IO represents Improper Operations. H stands for high, M stands for medium, L stands for low, VN stands for Very Negative, VP stands for Very Positive, P stands for Positive, Z stands for Zero and N stands for Negative P stands for Positive, Z stands for Zero and N stands for Negative.

Table 2. Showing various Fuzzy Rules for Expert System

	INPUT				OUTPUT		
R NO	VPC	Rad	Load	Source	Rel	Eco	IO
1	L	L	L	VP	L	L	M
2	L	L	L	P	L	L	L
3	L	L	L	Z	L	M	M
4	L	L	L	N	L	H	H
5	L	L	L	VN	L	H	H
6	L	L	M	VP	L	L	L
7	L	L	M	P	L	L	L
8	L	L	M	Z	L	L	H
9	L	L	M	N	L	H	H
10	L	L	M	VN	L	H	H
11	L	L	H	VP	L	L	L
12	L	L	H	P	L	L	L
13	L	L	H	Z	L	M	H
14	L	L	H	N	L	M	H
15	L	L	H	VN	L	M	H
16	L	M	L	VP	M	L	L
17	L	M	L	P	M	M	L
18	L	M	L	Z	M	M	L
19	L	M	L	N	M	H	H
20	L	M	L	VN	M	H	H
21	L	M	M	VP	L	L	M
22	L	M	M	P	M	L	L
23	L	M	M	Z	M	M	L
24	L	M	M	N	M	H	H
25	L	M	M	VN	M	H	H
26	L	M	H	VP	M	L	L
27	L	M	H	P	L	L	L
28	L	M	H	Z	L	L	H
29	L	M	H	N	L	M	H
30	L	M	H	VN	L	H	H
31	L	H	L	VP	M	M	H
32	L	H	L	P	M	M	M
33	L	H	L	Z	M	M	L
34	L	H	L	N	M	H	L
35	L	H	L	VN	M	H	L
36	L	H	M	VP	M	L	H
37	L	H	M	P	M	L	M
38	L	H	M	Z	M	M	L
39	L	H	M	N	M	H	M
40	L	H	M	VN	M	H	M
41	L	H	H	VP	M	L	L
42	L	H	H	P	M	L	L
43	L	H	H	Z	M	M	H
44	L	H	H	N	M	H	H
45	L	H	H	VN	M	H	H
46	M	L	L	VP	M	L	L
47	M	L	L	P	M	L	L
48	M	L	L	Z	M	M	M
49	M	L	L	N	M	H	H
50	M	L	L	VN	M	H	H
51	M	L	M	VP	M	L	L
52	M	L	M	P	M	L	L
53	M	L	M	Z	M	M	H
54	M	L	M	N	M	H	H
55	M	L	M	VN	M	H	H
56	M	L	H	VP	M	L	L
57	M	L	H	P	M	L	L
58	M	L	H	Z	M	M	M
59	M	L	H	N	M	H	H
60	M	L	H	VN	M	H	H
61	M	M	L	VP	M	L	H
62	M	M	L	P	M	L	M
63	M	M	L	Z	M	M	L
64	M	M	L	N	M	H	M
65	M	M	L	VN	M	H	H
66	M	M	M	VP	M	L	M
67	M	M	M	P	M	L	L
68	M	M	M	Z	M	M	M

Table 2 continued

	INPUT				OUTPUT		
R NO	VPC	Rad	Load	Source	Rel	Eco	IO
69	M	M	M	N	M	H	M
70	M	M	M	VN	M	H	H
71	M	M	H	VP	M	L	L
72	M	M	H	P	M	L	L
73	M	M	H	Z	M	M	H
74	M	M	H	N	M	H	H
75	M	M	H	VN	M	H	H
76	M	H	L	VP	M	L	H
77	M	H	L	P	M	L	M
78	M	H	L	Z	M	M	L
79	M	H	L	N	M	H	M
80	M	H	L	VN	M	H	M
81	M	H	M	VP	M	L	M
82	M	H	M	P	M	L	L
83	M	H	M	Z	M	M	L
84	M	H	M	N	M	H	M
85	M	H	M	VN	M	H	H
86	M	H	H	VP	M	L	M
87	M	H	H	P	M	L	L
88	M	H	H	Z	M	M	M
89	M	H	H	N	M	M	M
90	M	H	H	VN	M	H	H
91	H	L	L	VP	M	H	H
92	H	L	L	P	M	H	M
93	H	L	L	Z	M	H	L
94	H	L	L	N	M	H	M
95	H	L	L	VN	M	H	H
96	H	L	M	VP	M	M	L
97	H	L	M	P	M	M	L
98	H	L	M	Z	M	M	L
99	H	L	M	N	M	M	H
100	H	L	M	VN	M	H	H
101	H	L	H	VP	M	L	L
102	H	L	H	P	M	L	L
103	H	L	H	Z	M	M	M
104	H	L	H	N	M	H	H
105	H	L	H	VN	M	H	H
106	H	M	L	VP	H	M	H
107	H	M	L	P	H	M	H
108	H	M	L	Z	H	M	M
109	H	M	L	N	H	H	L
110	H	M	L	VN	H	H	L
111	H	M	M	VP	H	M	M
112	H	M	M	P	H	M	L
113	H	M	M	Z	H	M	L
114	H	M	M	N	H	M	L
115	H	M	M	VN	H	H	L
116	H	M	H	VP	H	L	M
117	H	M	H	P	H	L	L
118	H	M	H	Z	H	M	L
119	H	M	H	N	H	H	L
120	H	M	H	VN	H	H	H
121	H	H	L	VP	H	M	H
122	H	H	L	P	H	M	H
123	H	H	L	Z	H	M	M
124	H	H	L	N	H	H	L
125	H	H	L	VN	H	H	L
126	H	H	M	VP	H	M	H
127	H	H	M	P	H	M	M
128	H	H	M	Z	H	M	L
129	H	H	M	N	H	H	L
130	H	H	M	VN	H	H	L
131	H	H	H	VP	H	L	H
132	H	H	H	P	H	L	M
133	H	H	H	Z	H	M	L
134	H	H	H	N	H	H	L
135	H	H	H	VN	H	H	L

2.4. Defuzzification

The technique of converting fuzzy variables to crisp variables is Defuzzification; this process has been performed for crisp values as the output of the fuzzy inference system is not a crisp value. There are several defuzzification techniques available. In this study, the centroid method was used for defuzzification, that is, for reliability, economy, and improper operation. Formula to defuzzify the output -

$$Centroid\ \bar{X} = \frac{\sum_i^n x\mu(x)}{\sum_i^n \mu(x)}$$

where $\bar{X}$ = crisp output

$\mu(x)$=aggregated membership function

x=output variable

2.5 Fuzzy Inference System

Fuzzy Inference consists of a rule viewer which shows the complete fuzzy inference system in a single view. Fuzzy expert system, rule viewer shows that they are 135 rules with four input parameters and three output parameters.

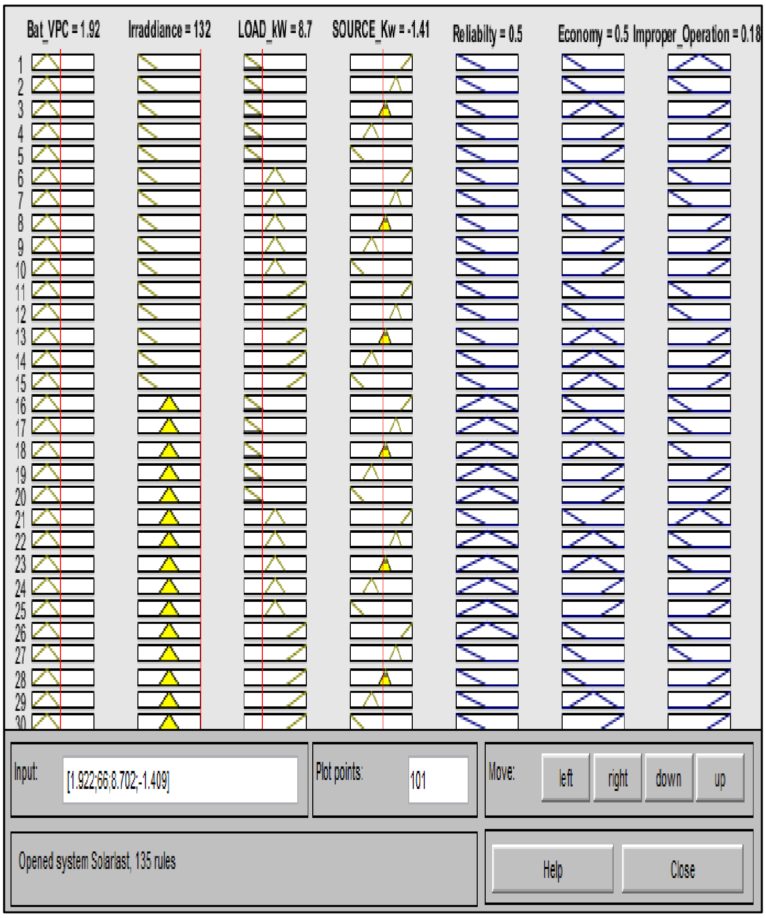

Fig 8. Rule Viewer

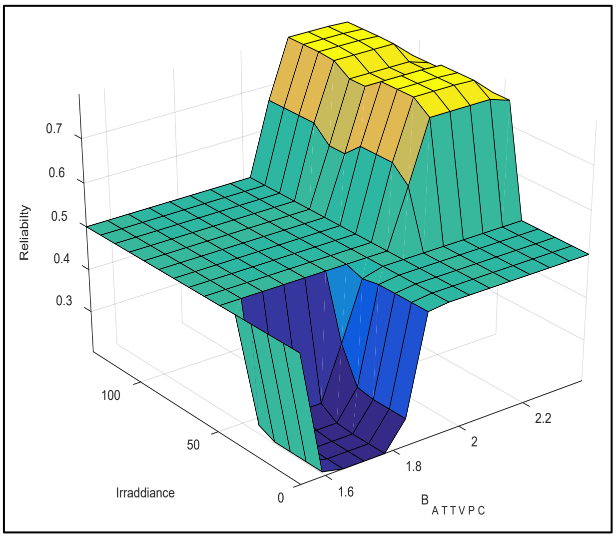

Fig 9. Surface Viewer of Expert System

3. Results and Discussion

Using this proposed Fuzzy Expert system, we can easily determine the current state of the SPV plant in terms of reliability, economy, and possibility of ongoing improper operation and can take corrective measures as per necessity. The described fuzzy expert system was designed and implemented using MATLAB Software. Testing of the fuzzy expert system was performed against test cases designed using historic data collected at Dayalbagh Educational Institute, Agra, and the results were verified using the actual prevailing conditions of the time. The fuzzy expert system was first tested in offline mode and then deployed for online mode operation. In offline mode, the results of various test cases have been analyzed by experts for the operation of the power plant over the last decade, and rules have been modified in case of discrepancy.

3.1 Result Analysis

Various test cases were designed to check the effectiveness of the fuzzy expert system, n1(variable name) was used to provide inputs value i.e. battvpc, solar_irrad, load_kW, and Source_kW to the fuzzy expert system.

Test_Case1 –

battvpc	solar_irrad	load_kW	Src_kW
2.173	119.1	1.6	-27.7

In this case, the value of “batt_vpc” is high, “irradiance” is high, “load_kW” is low and the value of “Source_kW” is very negative i.e. electricity is being exported to the grid.
Output- “Possibility of “improper operations” is low”, so no suggested problem.
Active Rule- This case conforms to rule 125.
Reason- battery is almost fully charged, solar irradiance is high and load is low, so electricity is exported to the grid.

Test_Case2 –

battvpc	solar_irrad	load_kW	Src_kW
1.529	3	1.2	1.9

In this case, the value of “batt_vpc” is low, “irradiance” is low almost nil, “load_kW” is low and the value of “Source_kW” is zero (it should be positive).
Output- “Possibility of “improper operations” is medium”, The suggested problem by the expert system is “Grid Outage/ battery charging disabled.
Active Case-This case conforms to rule 3.
Reason- when the battery is not charged and solar irradiance is low then more electricity should be drawn from the grid i.e. its value should be positive (> +4kW)

Test_Case3 –

battvpc	solar_irrad	load_kW	Src_kW
1.8	119.1	9	20

In this case value of “batt_vpc” is low, “irradiance” is high, “load_kW” is low and the value of “Source_kW” is very positive (it should be zero or negative).
Output-“possibility of “improper operations” is high”, so the suggested problem is “Excessive Battery Charging through Grid-check software setting”.
Active Rule-This case conforms to rule 31.
Reason- when solar irradiance is high, the load is low and the battery was not fully charged, so electricity should be exported to the grid but it is imported.

Test_Case 4 –

battvpc	solar_irrad	load_kW	Src_kW
1.6	118	10	12

In this case value of “batt_vpc” is low, “irradiance” is high, “load_kW” is medium and the value of “Source_kW” is positive (it should be negative).
Output-“Possibility of “improper operations” is medium, so the suggested problem is- “Dusty Panels/MPPT/ Shadows/ Faulty Connectors”.
Active Rule-This case conforms to rule 37.
Reason- Solar irradiance is high and load is low, then the value of the source should be negative i.e. electricity should be exporting but it is importing.

Test_Case5 –

battvpc	solar_irrad	load_kW	Src_kW
1.825	42.5	12.25	-16.25

In this case value of “batt_vpc” is low, “irradiance” is low, “load_kW” is medium and the value of “Source_kW” is very negative (export of electricity is not possible unless battvpc is high).
Output – “Possibility of “improper operations” are high, so the suggested problem is- “Problem with grid export settings”
Active Rule -This case conforms to rule 10.
Reason- Battery is not fully charged and solar irradiance is low, electricity should be imported from the grid i.e. value of the source should be positive (+)

Test_Case6 –

battvpc	solar_irrad	load_kW	Src_kW
1.529	119.1	0	5

In this case, the value of “batt_vpc” is low, “irradiance” is high, “load_kW” is low and the value of “Source_kW” is positive (it should be negative).
Output- “Possibility of “improper operations” is medium,

so the suggested problem is- "Dusty Panels/MPPT/ Shadows/ Faulty Connectors".
Active Rule- This case conforms to rule 32.
Reason- when solar irradiance is high, electricity should be exported to the grid but it is imported i.e. the value of source_kW should be negative.

```
Command Window
New to MATLAB? See resources for Getting Started.
>> Test_Case1

n1 =

    2.1730  119.1000    1.6000  -27.7000

HIGH RELIABILITY
HIGH ECONOMY
LOW IMPROPER OPERATIONS
>> Test_Case2

n1 =

    1.5290    3.0000    1.2000    1.9000

MEDIUM RELIABILITY
MEDIUM ECONOMY
MEDIUM IMPROPER OPERATIONS
SUGGESTED PROBLEM: Grid Outage/Battery charging through Grid is disabled
>> Test_Case3

n1 =

    1.8000  119.1000    9.0000   20.0000

MEDIUM RELIABILITY
MEDIUM ECONOMY
HIGH IMPROPER OPERATIONS
SUGGESTED PROBLEM: Excessive Battery Charging through Grid- Software Setting
```

```
Command Window
New to MATLAB? See resources for Getting Started.
>> Test_Case4

n1 =

    1.6000  118.0000   10.0000   12.0000

MEDIUM RELIABILITY
LOW ECONOMY
POSSIBILITY of IMPROPER OPERATIONS:-MEDIUM IMPROPER OPERATIONS
SUGGESTED PROBLEM: Dusty Panels/ Faulty Connectors/Shadows/MPPT Problem
>> Test_Case5

n1 =

    1.8250   42.5000   12.2500  -16.2500

LOW RELIABILITY
HIGH ECONOMY
POSSIBILITY of IMPROPER OPERATIONS:-HIGH IMPROPER OPERATIONS
SUGGESTED PROBLEM: Problem with Grid Export Settings
>> Test_Case6

n1 =

    1.5290  119.1000         0    5.0000

MEDIUM RELIABILITY
MEDIUM ECONOMY
POSSIBILITY of IMPROPER OPERATIONS:-MEDIUM IMPROPER OPERATIONS
SUGGESTED PROBLEM: Dusty Panels/ Faulty Connectors/Shadows/MPPT Problem
```

Fig 10. Some test cases and their outputs

The computational time of the fuzzy expert system for each set of values is 0.7188 seconds.

```
>> tEnd=cputime-tStart

tEnd =

    0.7188
```

3.2 Discussions

The expert system was tested with over 35 test cases (table 3), the results obtained from the fuzzy expert system show that the results as almost as per expert team expectations, which proves the validity of framed rules. The computation time of the fuzzy expert system is 0.7188 seconds is quite convincing. The computation time of 0.71 seconds is achieved on the i3 processor but it can be improved on i5 or i7 processors. The proposed fuzzy expert system is unique in its type as it not only informs about the health of the solar plant but also suggests problem concerns with the particular case, in case of improper operations. The expert system's performance degrades, in case of poor internet connectivity while operating in real-time conditions.

4. Conclusion

This paper describes the methodology for designing a Fuzzy Expert System to determine the current state of the Solar Photo Voltaic plant. Fuzzy logic is best suited for this study because no accurate mathematical model is available or can be designed for this type of stochastic system (solar radiance and load are dynamic). The Fuzzy expert system determines the state in terms of reliability, economy, and improper operations. The results show that the objective of designing an expert system was achieved as the framed rules work according to the expectations of our expert team. With only four input parameters, the state of the Photo Voltaic plant was determined. These four parameters have a strong correlation with other parameters, which allows us to leave others under redundancy. In addition to the state of the Solar Photo Voltaic plant, the possibility and type of improper operations are also provided and corrective measures are suggested to assist the operator in maintaining a reliable, economic, and smooth operation of the plant. The proposed method is sensitive to parameter variations, and even a small change in the parameter values is considered and becomes the basis for determining the state of solar photovoltaic plants.

Table 3. Showing various Fuzzy Rules for Expert System

	Input Variables				Active Rule	Output Variable			Suggested Problem
	Battery _VPC	Irradiance*	Load_kW	Source_kW		Reliability	Economy	Improper Operation	
1	2.1730 high	119.1000 high	1.6000 low	-27.7000 V negative	125	0.8250 (high)	0.8606 (high)	0.13941 (Low)	-------
2.	1.6460 low	0 low	11.3000 medium	-1.5000 zero	8	0.2125 low	0.1695 low	0.8305 high	Grid Outage
3.	1.9540 medium	0 low	0.3000 low	0.1000 zero	48	0.5000 medium	0.5000 medium	0.5000 medium	Grid Outage
4.	1.8000 low	119.1000 high	9.0000 low	20.0000 Very positive	31	0.5000 medium	0.5000 medium	0.8104 high	Excessive Battery charging
5.	1.8000 low	45.0000 medium	22.0000 high	0 zero	28	0.2416 low	0.1928 low	0.8072 high	Grid Outage
6.	1.8000 low	40.0000 low	9.0000 low	20.0000 very positive	1	0.2377 low	0.1896 low	0.5000 medium	Excessive Battery charging
7.	1.6000 low	118.0000 high	10.0000 medium	12.0000 positive	37	0.5000 medium	0.1932 low	0.5185 medium	Dusty Panels
8.	1.8250 low	42.5000 low	12.2500 medium	-16.2500 very negative	5	0.2430 low	0.8063 high	0.8063 high	Problem with Grid Export Settings
9.	2.1450 high	76.4000 medium	10.1000 medium	-10.1000 negative	114	0.7599 high	0.8086 high	0.1914 low	--------
10	2.1740 high	43.1000 low	0.4000 low	-9.5000 negative	94	0.5000 medium	0.8050 high	0.5000 medium	Problem with Grid Export Settings
11.	2.1770 high	61.0000 high	4.5000 low	0 zero	123	0.8104 high	0.5000 medium	0.5000 medium	Grid Outage
*** solar radiation is scaled by factor 1/10**									

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