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A FUZZY BASED PARAMETRIC MONITORING AND CONTROL ALGORITHM FOR DISTINCTIVE LOADS TO ENHANCE THE STABILITY IN RURAL ISLANDED MICROGRIDS

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Abstract. *Effective monitoring and control of isolated rural microgrid in the developing world is challenging. The modern communication and monitoring is difficult to handle in such communities due to a complicated approach to the area, lack of modern facilities and unavailability of skilled manpower. Implementation of a microgrid in such areas using intermittent renewable sources and limited storage is challenging. Uncontrolled load consumption leads to the system-wide outages due to prolonged storage utilization in peak hours and is referred here as battery storage stress hours (BSSH). This research is focused to study and analyze the behavior of parametric load monitoring and control algorithm that could control the distinctive load of the microgrid during BSSH. In the proposed algorithm, the residential loads are distinctively controlled while utilizing the three locally available parameters that are the state of the charge of storage, solar irradiations and ambient temperature. In other words, the natural parameter variations have been uniquely utilized as a monitoring tool for load control. The fuzzy controller takes a decision for the activation or deactivation of any load based on the three parameters variation ranges. It is observed from the simulation and experimental results that while only utilizing locally available parameters the effective load control is possible.*

Key words: *Microgrid, stability and control, Algorithms, renewable energy, fuzzy logic, load*

1. INTRODUCTION

There has been exponential growth in the power system installations, transmission systems enhancement, rehabilitation and up-gradation for reliable power supply. This development in power systems not only strived to fulfill the energy demand of the users but also provided a platform for the researchers to explore and address the issues of modern power systems. Besides all the research and actual enhancements, some of the rural areas in developing countries remains neglected and above billion people in the world shall remain

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without electricity by 2030 [1]. These unconnected rural areas are far from the developed cities where the habitats cannot afford expensive modes of power generation like diesel generators to fulfill their power needs. Nevertheless, recent research shows that microgrids; a low voltage power systems are the potential candidate to resolve the issue. A microgrid is a low voltage transmission system having its own generation, control and storage to supply power to the remote locations where main stream network is unreachable [2]. Microgrids control the voltage and power within its system using a centralized controller equipped with the energy management algorithms [10-15], load control [18] and demand response [10], [18]. These control schemes are one of the integral parts of the islanded microgrid that provides stable power to the end users while ensuring efficient power dispatch, optimized storage utilization and real-time load control. Several control algorithms have been introduced for power balanced demand and supply match. Such control schemes utilize monitoring [16], robust communication protocols [18], [25], internet for forecasts [18], [27] for feedback monitoring and balanced control between the loads, generation and storage. Burgio et al. [4] proposed the central load controlling algorithm using behavior tree model approach to control the house-hold load.

The central controller acts as a compact box to take optimized decisions based on different parameters. However, strong communication is used to get parameter information and forecasting, etc. Su sheng et al. [5] developed a dynamic programming model for economically utilizing the 3 power sources that are solar PV, battery storage and diesel generators. Burmester et al. [6] presented a centralized load controlling mechanism with the objective to economically purchase power from the grid. The mechanism is based on a thermostat controller where loads are shifted to the solar PV source while ensuring maximum power being produced by the Solar PV. The central controller utilizes the maximum power point tracking scheme for instantaneous load shifting to the cheaper source of energy hence reducing the power purchase from the main grid network. Thanh Lich et al. [7] presented a decentralized droop control scheme to monitor the voltage and current deviation for the power balance between the load and distributed generation sources. Similarly, Mashood Nasir et al. [8] provided a decentralized I-V droop control technique that takes the information of the solar DC bus and state of the charge (SOC) of the storage for the coordinated power-sharing among the contributing grids. Annette et al. [9] presented a bi-level power sharing between the multiple microgrids using bi-level converters. However, the emphasis on load control has not been shared in details. Mohammad Ali Fotouhi et al. [10] presented a smart home energy management algorithm to schedule the controllable loads programmed on smart meters. Bartosz Soltowski et al. [11] presented smart residential load management that utilizes pre-defined consumption profiles of particular households that acts as reference energy to be supplied or received from that house. The results are encouraging but the authors have used simulations to test the system. R. K. Chauhan et al. [12] developed a load sharing control technique between the battery storage, distributed generation source. The system was tested on distributed as well as lumped load. The DC microgrid storage follows its own ideal charging/discharging characteristic for power sharing, however, the reliable source of public utility has been considered in the operation. Ashray Manur [13] proposed a novel energy management system for residential microgrids while intelligently controlling the power dispatch from the battery to the load using multi layers communication, cloud computing and internet of things. Garells et al. [14] presented a novel idea of generating power as well as sharing it to the neighbor houses in case of excess generation using networked communication and wireless communication infrastructure. In such cases, the consumer also becomes a prosumer. Each household has its own generation source and it also acts as a load at the same time when less power is available. J. Gouveia et al. [15] presented an energy management algorithm to control the load during its autonomous operation. The objective is to maximize the autonomous operation. The load management algorithm relies on the forecasting result. The main objective of the research is to maximize the autonomous operational hours of the microgrid when the grid power is not available.

1.1 Problem statement

Islanded residential microgrids operation during the night hours needs a comprehensive energy management algorithm that takes care of overall energy balance due to limited storage and intermittent distributed generation as a prime power source. Mostly, residential loads are under operation during the night hours and less storage availability leads to the system wide outages. Real-time monitoring is the heart of the energy management system responsible for effective energy management, load management, feedback control and demand and supply match. Different communication layers, protocol, wireless communication, serves as a feedback controlling tool to isolated microgrids systems [16], [17], [25]. On the other hand, internet, weather forecast, market trends have been used for the generation, load forecasting and for economic operation [25]. However, the area under study has a major setback of easy access to all the discussed facilities and modern monitoring and communication tools [25]. If these are made available up to some extent to these areas, then its operation, maintenance and effective utilization is questionable due to less educated areas and unskilled manpower.

1.2 Proposed residential load management scheme

A remote area in Punjab Pakistan has been taken as a case study. The interviews from the residents were taken to find out the related loads, total number of houses and the expected total number of loads in one house as shown in Table 1. Climate conditions of the area, educational level and availability of the technical and communication facilities were also checked. The research paper is focused to develop real-time monitoring and control of residential loads simply utilizing the available intrinsic parameters of the microgrid integrated components that are storage, solar power generation and temperature. The objective is to practically test the performance of the microgrid in terms of its operation during the BSSH hours. The feedback monitoring is based on the states of the intrinsic parameters like solar irradiations, light intensity, temperature and state of the charge of storage. A fuzzy logic controller that takes the parametric states as input in real time and based on the designed rules sets operation of different distinctive loads within the single household. The fuzzy controller is distributed controller installed at every home. Fig. 1 shows the block diagram of the distributed controller. The salient features of the proposed algorithm are:

1. Distributed controller approach; in case of the controller of any home not working will not affect the overall grid
2. Real-time monitoring based only on the intrinsic parameters that reduce the communication and networks and works only on installed sensors
3. Energy conservation and energy efficiency
4. The distributed controller is flexible in operation; the ranges of the fuzzy input membership functions can be settled based on the resident's ease. For example, the activation and deactivation values for the fan loads can be settled as per the comfort and weather conditions of the area.

Table 1 Expected size of the microgrid under study based on an interview

Load	Power (Watts)	in Single House	Total number of house	Total consumption (kW)
Fan	150	2	30	9.0
Lights	10	3	30	0.9
Water Pump	1000	1	30	30.0
Washing Machine	150	1	30	4.4

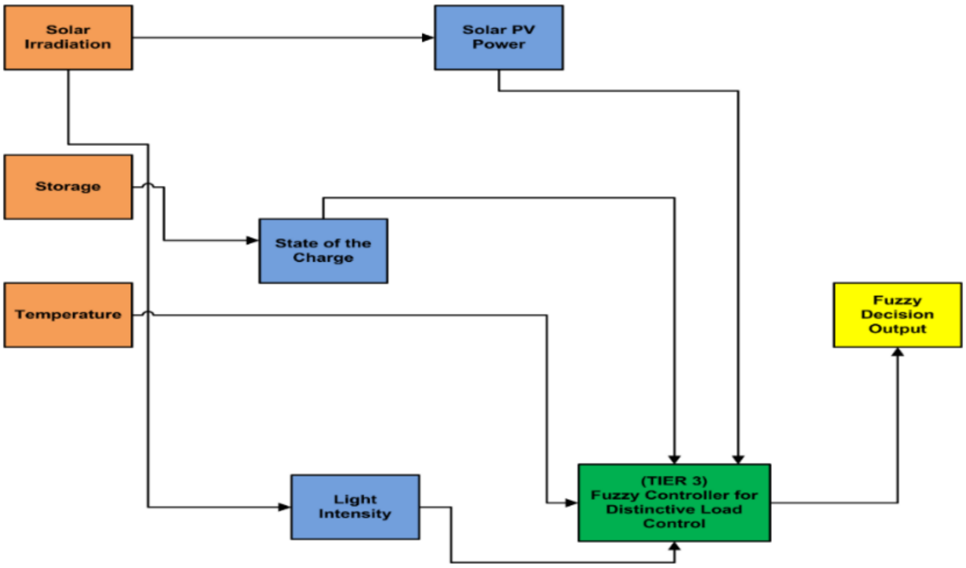


Fig. 1 Proposed microgrid algorithm block diagram

The fuzzy logic controller is responsible for the operational duration of any of the house hold load based on the developed fuzzy rules and set parametric ranges. The fuzzy controller makes real-time decisions based on the condition of the microgrid. In case of better parametric conditions, the operation of the distinctive loads increases, on the other hand in case of less SoC and solar irradiations availability, the operation of the loads reduces, for instance, while monitoring the operation of the fan, the ambient temperature, SoC of the storage and solar irradiations are monitored and based on the real-time values the duration of the fan operation is decided. IF SoC is low and LESS solar irradiations are available the operation of the fans will be reduced. The same applies for the case of other loads. Table 2 shows the loads and associated membership functions for fuzzy ranges and rule base. In this way, the distinctive controller makes it possible to rely only on the available parameters of the grid to make intelligent decisions. The complete flow diagram of the distinctive load controller is shown in Fig. 2.

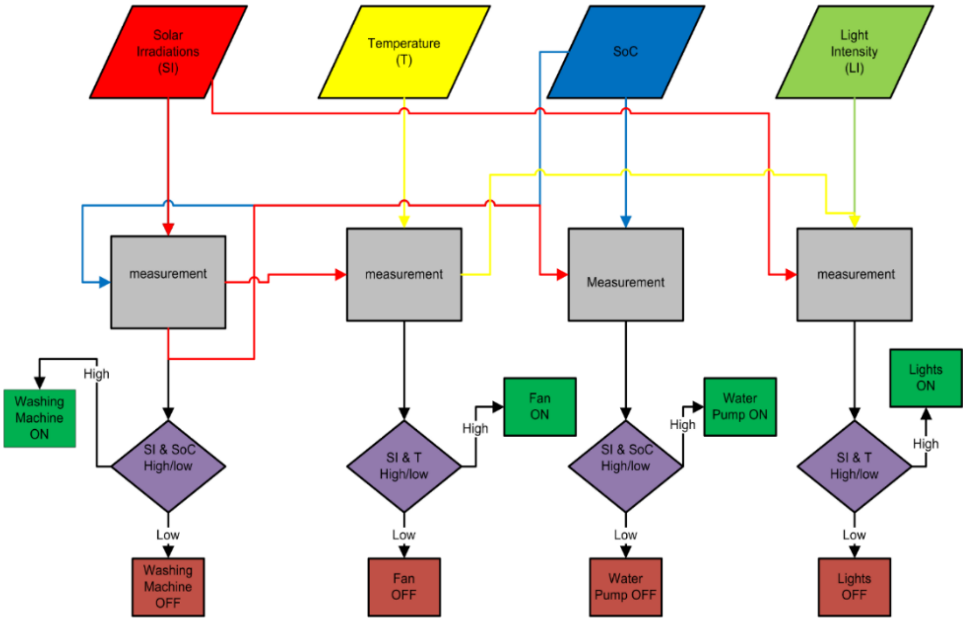


Fig. 2 Distinctive load controller flow diagram

Table 2 Membership function assigned to each load for fuzzy rule base

Load	Input membership functions		
	SoC	Ambient temperatures	Solar irradiations
Fans		✔	✔
Lights		✔	✔
Motor pump	✔		✔
Extra Load	✔		✔

2. Mathematical Model

The mathematical for fuzzy decision parameters such as SoC estimation, conversion of solar irradiation to light intensity, conversion of solar irradiations into solar PV, residential loads and consumption of residential loads are given in this section.

2.1. Residential load

Washing machines P_{wm}, motors P_{motor} that work as pumps for irrigation purpose and also for household use, lights P_L and fans P_F Equation 1 shows the load of total residential loads

$$L_R(t) = (\sum_1^n P_{wm} + \sum_1^n P_{motor} + \sum_1^n P_L + \sum_1^n P_F) \tag{1}$$

2.2. Residential load consumption model

Consumption model for electricity device for monthly consumption is given in equation 2 and 3 [24]. The equation in 2 is used to calculate the monthly power consumption where the duration of the power consumption is taken in seconds. The density of the usage is calculated using equation 2. Equation one can be used to calculate all the residential loads being utilized in the islanded microgrid.

$$\mathrm{P_{Monthly}} = \sum_{\mathrm{id}=1}^{12} . \left(\frac{\mathrm{P_{measured}}}{3600}\ \mathrm{Duration(ID)}\right) \times \left(\mathrm{Density(ID)}\right) \tag{2}$$

$$\mathrm{Density(ID)} = \mathrm{f(x)} = \begin{cases} \text{daily; Density(ID)} = \text{Usage count } \times 30 \\ \text{weekly; Density (ID)} = \text{Usage count} \times 4 \\ \text{monthly; density (ID)} = \text{Usage Count} \end{cases} \tag{3}$$

2.2.1. State of the charge

The state of the charge is used to calculate the SoC of the centralized storage. The SoC of the centralized storage can be calculated as done in [20] and given in equation (4-7).

$$SOC(t) = SOC(t-1).(1-\sigma) + P_{pv}(t) - \left(\frac{P_{dem(t)}}{\eta_{inv}}\right)\eta_B \tag{4}$$

Battery dispatch at a particular instant of time $P_B(t)$, can be written as given in Equation can 2

$$SOC(t) = SOC(t-1).(1-\sigma) + P_B(t) \times \eta_B \tag{5}$$

SoC at discharging can be measured as

$$SOC(t) = SOC(t-1)(1-\sigma) + (P_{L(TOT)}(t) - \frac{P_{pv}(t)}{\eta_{inv}})\ \times \eta_B \tag{6}$$

Simplifying the 4 will give;

$$SOC(t) = SOC(t-1)(1-\sigma) - P_B(t) \times \eta_B \tag{7}$$

2.2.2. Solar irradiation

The solar irradiations have been used to calculate light intensity and solar photovoltaic (eq.8). Light intensity help in identifying the available light which helps in the operation of lighting loads.

Equation 8 is used by [20] to convert the solar irradiation to solar PV

$$P_{pv}(t) = N_s . N_p . V_\alpha(t) . I_{sc}(t, \emptyset) . FF \tag{8}$$

2.2.3. Mathematical representation of fuzzy logic controller

Equation 5, 6 and 7 are the membership functions for the fuzzy controller. To determine the range of each membership functions for the operation of distinctive loads. Triangular fuzzy membership functions with fuzzy sets are generated as shown in Fig. 3 to 5. [21]. The xi elements are divided into two operational functions that are high or low. The reason is consistent climatic conditions of the areas. The area under study mostly has hot weather with a very small time of winters. There are only two weathers affecting the area that are summer and winters. Due to very hot summer and winter seasons, either the temperature is too hot or too cold so for simplicity, only two ranges low or high has been considered that comfortably covers the operation of the microgrid decision making.

Equation 9 shows the equation for the fuzzy input membership function of the state of the charge.

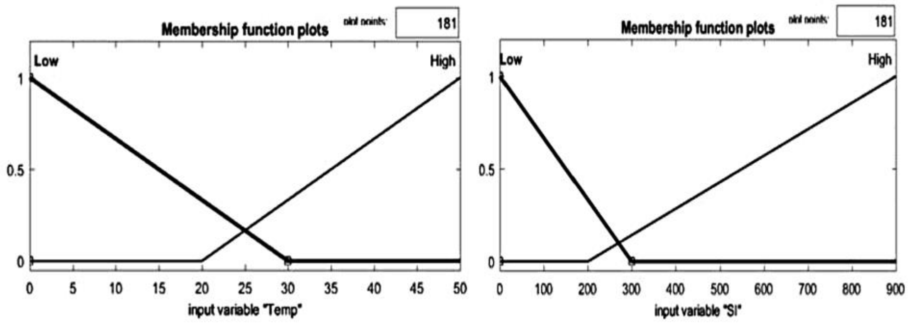
$$SoC = \{\sum_i \mu_{soc}(x_i)/x_i\} \quad (9)$$

Here, μ_{soc} is the state of the charge membership function with x_i element.

Similarly, equation 10 and 11shows a membership function of temperature.

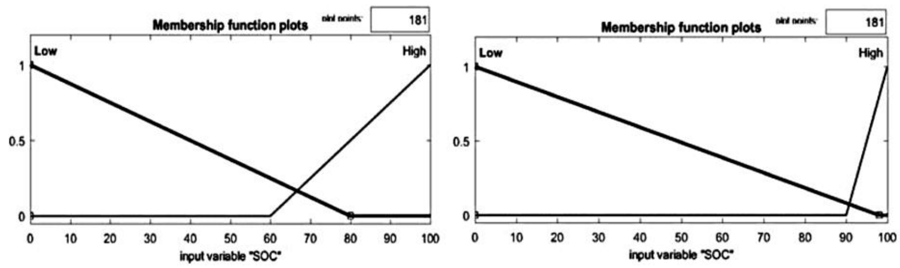
$$Temp = \{\sum_i \mu_{temp}(x_i)/x_i\} \quad (10)$$

$$SI = \{\sum_i \mu_{SI}(x_i)/x_i\} \quad (11)$$



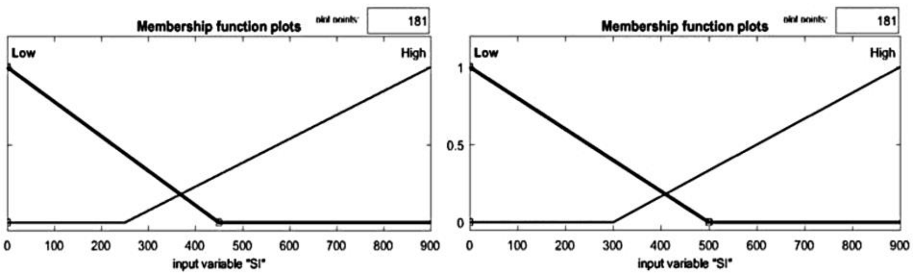
(a) (b)

Fig. 3 Input membership function of Solar Irradiations for Fans and Lights



(a) (b)

Fig. 4 (a) shows the input membership function of SoC for solar pump while (b) shows the input membership function SoC for extra load

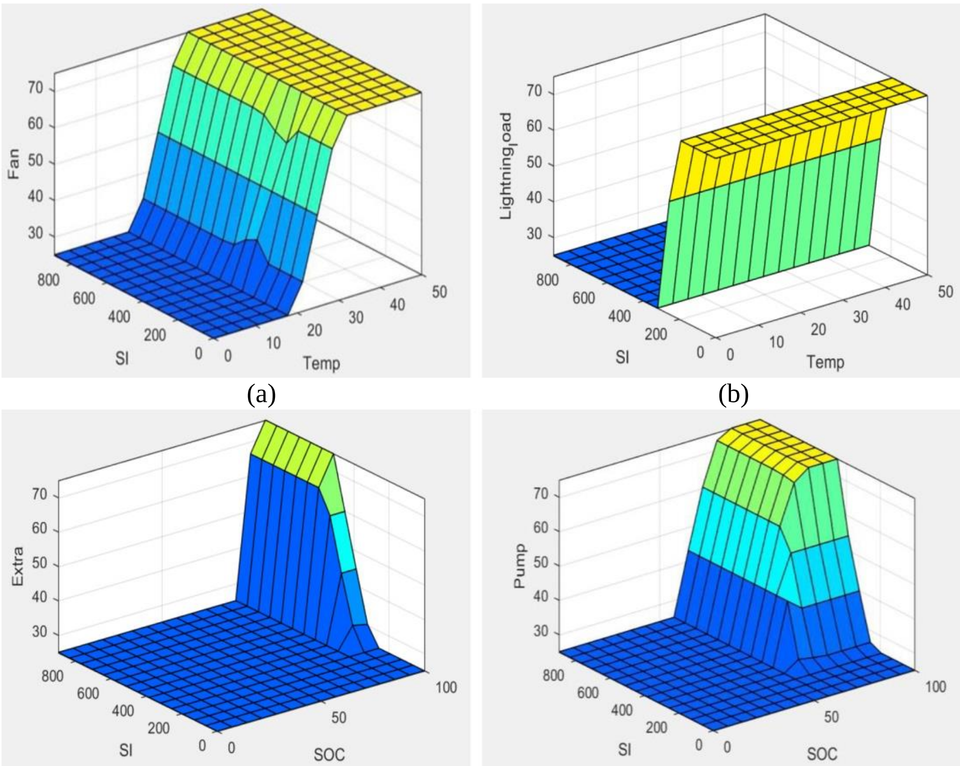


(a) (b)

Fig. 5 (a) shows the input membership function of SI for extra load while (b) shows the input membership function SI for water pump

3. SIMULATION

To analyze the effectiveness of load operation in response to the intrinsic parameters variation, the fuzzy simulation was performed. The simulation was performed in Matlab toolbox using Mamdani FIS system. Fig. 6 (a) shows the operation of fans. Solar irradiation membership function for available solar power and temperature function for the customer comfort has been taken. The operation of the fan depends on the temperatures and available solar irradiations. If the temperature remains high with high solar power available, the fan operates on the other hand in case of low solar power and temperatures the operation of the fans is reduced or turned off. Similarly, Fig. (6) b shows the operation of the lights.



(c) (c)

Fig. 6 Fuzzy surface plots of the loads operation in response to the variation in the membership functions (a) shows the surface plot of fans (b) shows the surface plot of lights (c) shows the surface plot of extra load and (d) shows the surface plot of water pump

The membership functions to control the lighting loads include the SI however; temperatures have the least dominance while controlling the lighting loads. In the same way, Fig. 6 (c) shows the activation and deactivation of the extra load in response to the variations in the solar irradiations and state of the charge of storage. Since, the washing machines and another such type of loads are responsive in the sense that their operation can be shifted to other time hours in case of unfeasible grid conditions. The designed fuzzy rules for washing machine has been set with flexible ranges of membership functions as shown in Fig. 5. These flexible ranges help provide save power and utilize such loads during better SoC and solar power conditions. It can be seen in Fig. 6 (c) that the operation of the washing machine remains inactive during low SoC and solar irradiation conditions and activated only during better SoC and SI conditions. Fig 6 (d) shows the behavior of water pump load in response to the variation in SI and SoC membership function, like extra load operation the fuzzy rule and specified ranges are set in order to provide maximum power to the lighting and fans load during the night time. This helps in saving more battery during the BSSH hours. Fig. 6 (d) shows that water pumps operate during the day time only when maximum power is available. But as the water pump is required for irrigation as well as domestic use, the fuzzy rules and ranges are designed with slightly flexible values as compared to the extra load ranges. This shows the operation activation more than the extra loads.

4. EXPERIMENTATION

Experimentation at lab scale was conducted on testbed as shown in Fig. 7. The controller embedded with fuzzy logic control was designed on Atmega 2560 [22], [23] using C++ language.The inductive and resistive loads were used that mimic the behavior of resistive and inductive loads that are commonly used in the villages such as washing machines, water pumps, light and fans. The loads are connected with the 60 Ah storage being charged with the solar panel installed. The loads are activated and deactivated based on the commands from the fuzzy controllers. The actuation of loads is done using arrays of relays being installed with the loads.

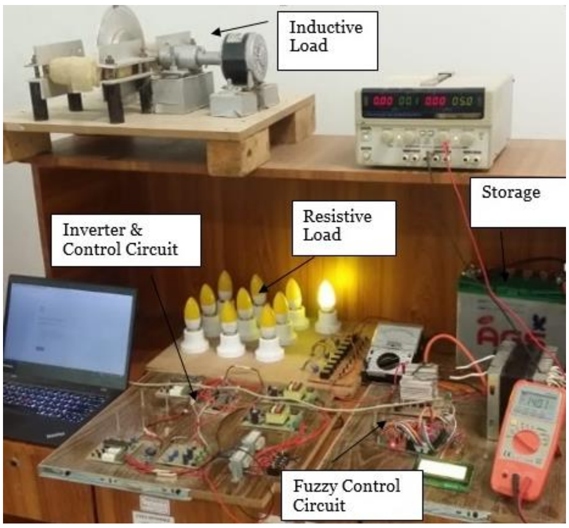


Fig. 7 Microgrid testbed

Table 3 shows the sensors being used during the experimentation.

To validate the robustness of the algorithm the single day and five-day analysis was done. The single-day analysis is done with better solar irradiations while on the other hand, the 5-day analysis comprises of sunny as well as cloudy days.

Table 3 Sensor used in the testbed

Name of Intrinsic parameter	Name of the sensor
Solar irradiation for PV power	Pyranometer
Temperature measurement	DS 18B20 Sensor
State of the charge measurement	ACS 712 Sensor

4.1. Single day analysis

The behavior of different loads was analyzed during real time testing. Fig. 8 shows the operation of the fans during the 24-hour time period. It can be seen that the operation of the fans started at 9:30 after the temperature increases beyond20 °C. The operation of the fans remained on till 23:00. The temperature after 23:00 hours started decreasing. The total operation time of the fans was approximately 50% of the day. In the same way, Fig. 9 shows the operation of the lighting loads. The lights remained off as the solar irradiations were high. The availability of the solar irradiations shows that light intensity is good enough and no need for lights required at the particular instant of time. The lighting load remained inactive from 8:30 AM to 17:30 PM that is 37.5% operation of the complete day. This also ensures the energy conservation measures as lights remained off during the sunny hours and start automatic operation during the night hours. This can significantly reduce energy wastage. Fig 10 (a) showsthe pump operation. It can be seen that the pump remained on for 3 hours starting from12:00 to 15:00 hours when the solar irradiations are at the peak. In the same way, another membership function is Soc of the storage. Fig. 10 (b) shows the operation of a pump with the SoC availability. It can be seen that even the SoC was available the pump operation was restricted the reason was to keep the SoC available for BSSH. The helps not only in reducing the energy wastage but also reduce the stress on BSSH. The pump load was operated for 12.5% of the total day. In the same way, the extra load (Fig. 11) was also operated only when the available solar power was higher during the day time. The extra load also operates for 12.5% of the total day.

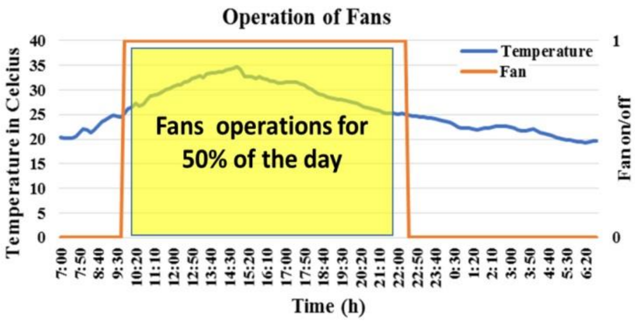


Fig. 8 Fan operation during the 24-hour time

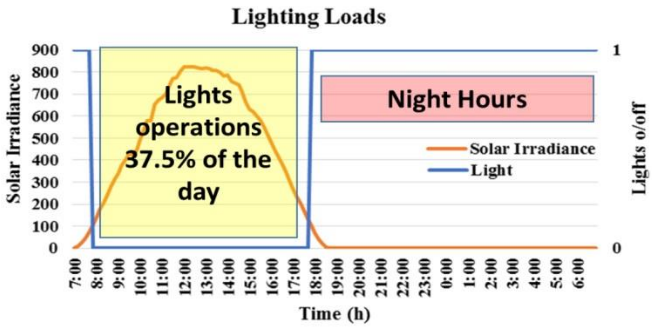
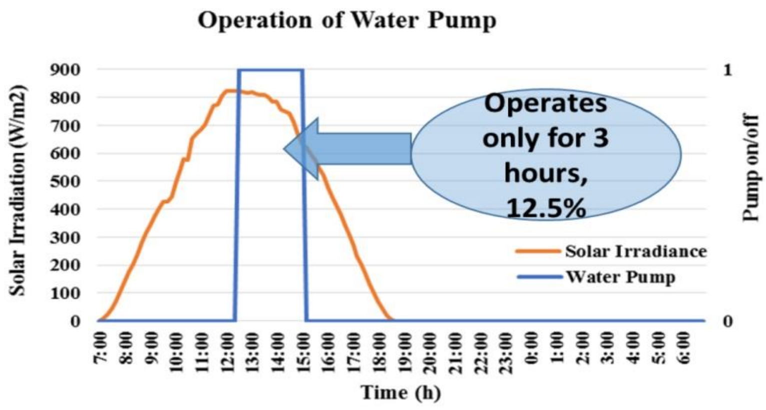
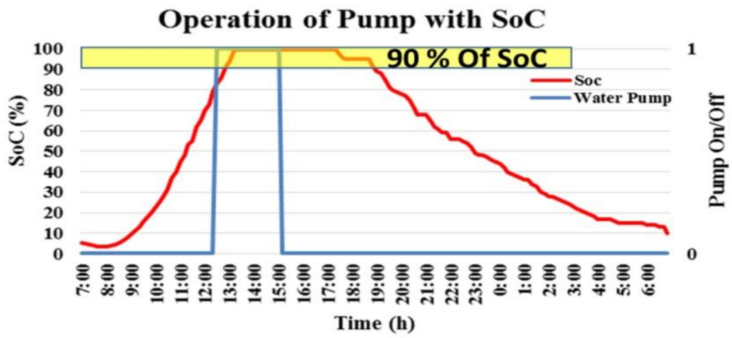


Fig. 9 Lighting operation during the 24 hour time



(a)



(b)

Fig.10 (a) Water pump operation during the 24-hour time (b) Operation of water pump with SoC during the 24 hour time

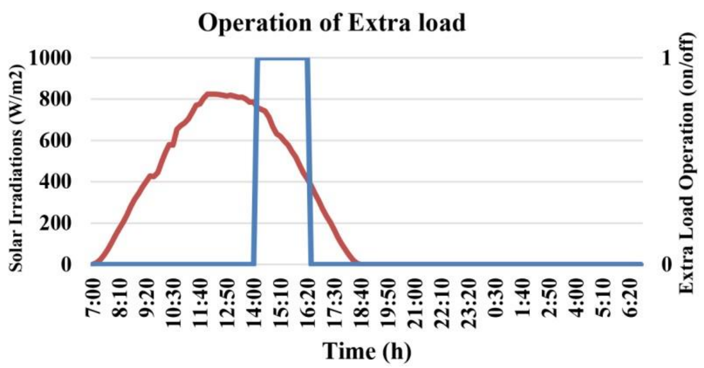


Fig. 11 Extra load operation during the 24 hour time

4.2. Five days analysis

During the five-day analysis, the variation in solar irradiations was observed where day 4 was the most cloudy day with distorting solar irradiation trends as can be seen in Fig. 12

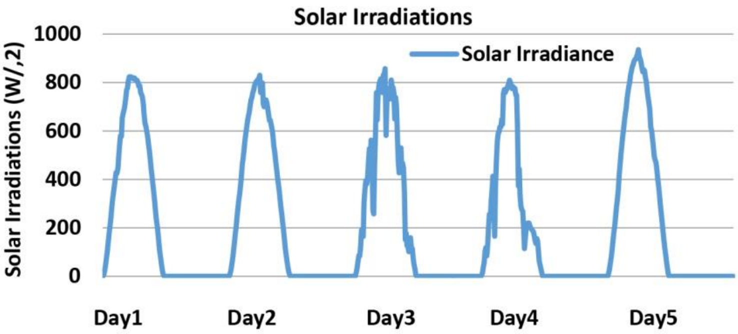


Fig. 12 Solar irradiations during the 5 days time

This also affects the state of the charge parameter. The state of the charge remains less compared to the other days with good solar irradiations availability. The less availability of solar irradiation directly affects the overall operational duration of different loads. As shown in Fig.13 the operations of fans observed less duration compared to the other days (1, 2, 3, and 5). On the other hand,the the situation with the lighting loads is better and there is no big effect on the operation of lighting load as the lighting load is not big and available SoC on day 4 can easily handle the lighting load operation due to proactive big loads deactivation or reduction in the operation. Fig. 14 the shows the operation of lighting load. The water pump operation was also reduced so as to provide better SoC for the night hours this can be seen in Fig. 15.

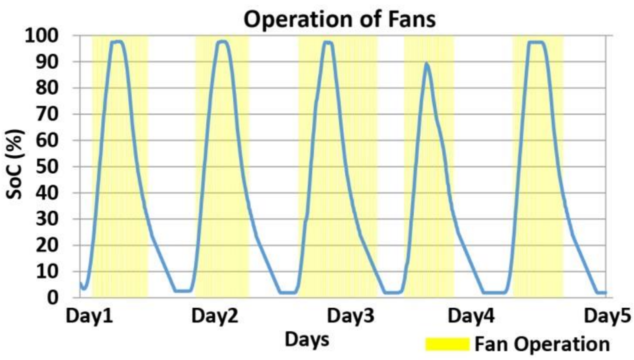


Fig. 13 Fan operation during the 5 days time

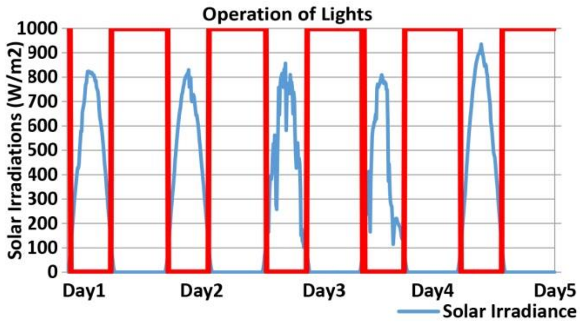


Fig. 14 Lights operation during the 5 days time

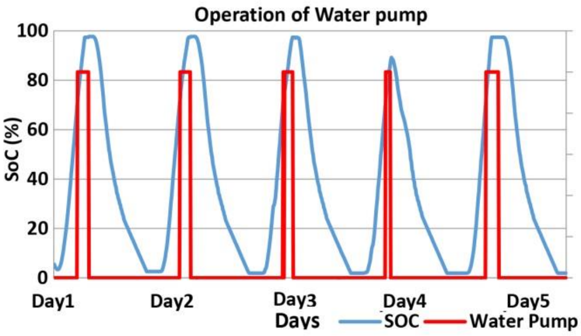


Fig. 15 Water pump operation during the 5 days time

It can be seen in Fig. 16 that extra load didn't operate on day 4 due to less availability of the solar irradiation so as to save the SoC of the storage. It is evident from the 5 days analysis that even on the worst day that was day 4 the SoC remains till the other day starts however the operating hours were reduced. Nevertheless, the operation remained successful due to the proposed load control.

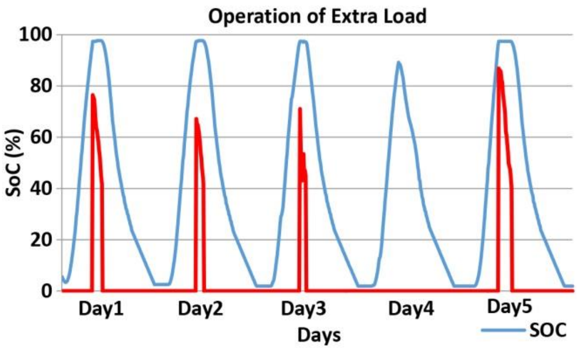


Fig. 16 Extra load operation during the 5 days time

5. CONCLUSION

In this article a novel distinctive load controlling algorithm has been developed, simulated and tested. The objective of this research is to practically analyze and verify the impact of locally measured parameters of the microgrid for controlling the residential loads with less communication and outside information while keeping the residents comfort. The results have shown better resiliency to microgrid during peak hours. There are several extensions to the existing work economic analysis for the strategy can be done in future. The distinctive load control decision parameters can be increase like voltage and system frequency can also be added in the decision parameters to increase the accuracy of the proposed control system. Further, there is a possibility of reduced illumination of a lighting load to further enhance the control on lighting loads.

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