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A robust and sustainable microgrid to resist energy disruption during a pandemic

Abhishek Kumar[1*ƚ], Bikash Sah[2ƚ], Yan Deng[1], Xiangning He[1], Praveen Kumar[2], R.C. Bansal[3], R. M. Naidoo[4]
[1*]College of Electrical Engineering, Zhejiang University, China
[2]Department of Electronics and Electrical Engineering, IIT Guwahati, India
[3]Department of Electrical Engineering, University of Sharjah, Sharjah, United Arab Emirates
[4]Department of Electrical, Electronics and Computer Engineering, University of Pretoria, South Africa
[*]Corresponding Author Email: abhi@zju.edu.cn [ƚ]*Authors contributed equally to this work.*

ABSTRACT
The growth of load or depreciation resulting from load shifting and peak shifting are two major phenomena observed when an epidemic or pandemic strike. Robust and reliable power and energy management system becomes the need of the hour to meet the load variation. Hence, in this work, a power and energy management system for an isolated microgrid using fuzzy based controller considering a real-time load growth scenario is illustrated. The microgrid consists of renewable energy technologies (RETs) utilizing the locally available resources (solar and wind) and lead-acid battery as storage and diesel generator as backup. The selection and sizing of the microgrid's various elements are carried based on the load determined and predicted before the pandemic. An intelligent fuzzy-based controller (IFBC) is designed to manage the power flow between the microgrid elements efficiently. IFBC can deal with the system's uncertainties through an IF-THEN rule-based approach, reducing mathematical modeling requirements. Further, it is robust to the load variations and operates without boundary conditions. The modeled IFBC has three input variables and two outputs. The input variables of the IFBC are total available power from RETs, total existing load demand, and the difference between power from generation and connected load. Fuzzy logic controller (FLC) output is power, fed to the load and battery energy storage system (BESS) for compensating the gap between power demand and supply and meeting the demand to keep the batteries at minimum SOC of 20%. The analysis presented in this work is based on the actual load data collected from a remote village in India before and during the pandemic, demonstrating the proposed controller's effectiveness.

Keywords: microgrid, renewable energy, COVID 19 impact, pandemic.

1. INTRODUCTION
Energy security and sustainable energy planning and management give a strong impetus to the development of a nation. The unprecedented impact of an epidemic or pandemic like the one experienced due to COVID-19 demands robust and reliable energy planning. The rise or fall of demand for energy in a region is incalculable. The instance becomes critical when energy management is to be planned for isolated distributed generation (DG) systems such as microgrids. Microgrids (MG) is the most promising solutions considered for distributed generation and integrating renewable energy sources. Microgrids are planned energy and power systems designed and deployed based on a region's requirements, population growth, load forecasting, and available distributed generation sources. The planning of the energy and power systems involves selecting a robust controller or management system to meet the sudden change in the region's load demand. In the EU approach, an MG is defined as "a low voltage distribution network comprising of various DG, storage devices and controllable loads that can operate interconnected or isolated from the main distribution grids" [1]. Microgrids are considered clusters of distributed energy sources, loads, and controls, organized to deliver the optimum energy service [2]. MG is the best to check the permutation of various locally available energy resources for optimal utilization. MG can be configured as either a remote or isolated electric system or a grid-connected system [3]. This work will focus on energy management in an isolated MG.

Various works have been reported in the literature for an isolated MG's energy and power management. [4] proposed a model for scheduling of energy resources along with management of loads that incorporate charging of plug-in electric vehicles (PEV), distributed

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renewable energy generations (DREG), and operation of battery energy storage system (BESS) for an isolated MG. Equivalent CO_2 emission models of distributed generation units are proposed on their emission features and fuel required basis. These two proposed models were then combined with the MG unit commitment (UC) model [5]. Similar models with a multi-objective approach are developed to study the operational impact of MG on emissions and costs while considering the deviation in the forecast of renewable and demand through a model predictive control approach [5-8]. Several MG energy management system (EMS) models with predictive control are proposed for optimal dispatch of the storage system (ESS and pumper hydro storages), generators, with peak demand management for loads (controllable and residential) when the UC constraints and power flow being considered simultaneously [9-12]. Another novel and highly detailed mathematical model of the energy management problem for isolated microgrids is presented [13]. Various control algorithms for power management based on reactive power control for an isolated hybrid system based on renewables are illustrated in detail [14]. A control architecture with the mathematical formulation of a stochastic predictive EMS for isolated MG is done in [15].

A supervisory controller based on the state machine approach for an isolated hybrid AC/DC MG is proposed to satisfy load power demand in both the AC and DC MG while maintaining the SoC of battery banks with fuzzy control [16]. An energy management algorithm that properly shares power and controls the voltage is proposed in [17]. The system modeled is a real-time hybrid DC MG comprising of pulse load, supercapacitor bank, steady-state load, and a 3-ϕ source. A decentralized multi-agent system is employed for power management of a hybrid (diesel and storage battery) MG in grid-connected and islanded modes in [18]. The authors have presented the importance of using many objectives, including round trip efficiency and battery system operational cost, to make better power management decisions for hybrid or MG systems that incorporate storage. A novel double-layer coordinated control approach for MG energy management is proposed in [19]. A comprehensive power flow control strategy is designed utilizing renewable energy and energy storage for a DC MG with a purpose to reduce the burden of the conventional grid due to peak demand [20]. A central energy management system for MG is presented for both grid-connected and isolated modes. The energy management is proposed as a UC problem concerning the distribution network and corresponding constraints leading to a mixed-integer non-linear programming formulation [21]. [22] proposed integration technique to incorporate battery energy storage with MGs. An energy management system for both grid and off-grid hybrid systems comprising of wind, photovoltaic, and the battery is proposed in [23]. IoT based EMS is proposed in [24]. A fuzzy and analytical hierarchical process evaluation model is proposed for monitoring industrial energy conservation.

None of the work has considered the sizing of MG as an integral problem of energy management of the mentioned work above. Determining an optimal combination of locally available energy resources to model MG based on key performance indicator is missing. The objective of the work is to design an energy management system with the following objectives:

1. Power supply or availability should be able to cater to the need of the load side and maintain the SoC of ESS.
2. The Minimum State of Charge (SoC) of ESS should be maintained at 20%.
3. The energy management system should be able to deal with uncertainties in the variation of load.

The following assumptions are made:

1. No converter losses during power conversion.
2. All converters are considered as ideal, and the system is designed considering ideal sources.
3. Idealized average mathematical models are being utilized.
4. Real Power (kW) is only taken into account.

The author takes a down top approach for developing the MG and an EMS.

2. PROPOSED ALGORITHM

This paper focuses on designing a power management controller for an isolated MG by optimally utilizing all renewable energy technologies (RETs) using the proposed IFBC. MG based on RETs is characterized by large power variations due to dependency on weather conditions. Most controllers tend to fail to manage the power flow to meet the load demand in such cases. Epidemic or pandemic adds further variations in the load demand of a region. An intelligent system is a necessity to meet such variation. FLC can deal with the system's uncertainties through a simple IF-THEN rule-based approach, thereby eliminating the need for a mathematical model of the system that is beneficial for a complex system for which a complete mathematical model representation may not be possible.

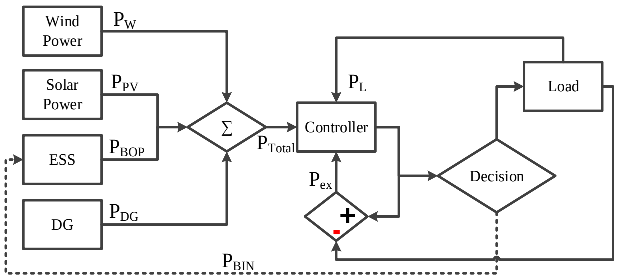

Figure 1: The control architecture based on the proposed algorithm

However, the fuzzy logic-based system complexity increases rapidly with a greater number of inputs and outputs. This system is modeled as an FLC with three inputs and one output, as shown in Fig. 1. The input variables of the FLC are total available power from generation, total load, and difference of total power and load. The output of FLC is power, which is fed to the load and Energy Storage System (ESS) for compensating the gap between power demand and supply and meeting the demand of keeping batteries in ESS at minimum SoC of 20%. The working algorithm of the system is based on the following assumptions:

1. Current Load Demand= P_L
2. PV Power Output = P_{PV}
3. Wind Power Output = P_W
4. Diesel Generator Power Output = P_{DG}
5. Battery Discharge Power Output = P_{BOP}
6. Battery Charge Power Input = P_{BIN}
7. Total Power Generated from RETs, $P_{RET} = P_{PV} + P_W$
8. The initial state of charge of the battery is 100 %, and the minimum should be 20 %.

The rules of FLC are mentioned in Table I. The proposed algorithm is verified based on the design of a microgrid which is explained in the next section.

3. CASE STUDY

In this work, an energy management system is proposed for a remote village named “Leporiang” in the Papumpare District, North Eastern Region of India. The possibilities of the microgrid is studied in previously published works [25]–[27]. Previous works reported technically mature, commercially available and government regulated energy sources to generate the possible alternatives. A total of twelve alternatives were proposed in our previous work [26,27]. The first six configurations are considered in a Compact Centralized Off-Grid Generation and another six as Compact Centralized Grid-connected systems. Solar, wind, diesel generator was considered as energy sources along with battery as storage.

Table I: Rules for the controller

P_{total}	P_{ex}	P_L	Power	P_{total}	P_{ex}	P_L	Power
L	L	L	NH	M	M	L	NH
L	L	M	NM	M	M	M	NM
L	L	H	NL	M	M	H	NL
L	M	L	NH	H	L	L	PH
L	M	M	NM	H	L	M	PM
L	M	H	NL	H	L	H	PL
L	H	L	NH	H	M	L	PH
L	H	M	NM	H	M	M	PM
L	H	H	NL	H	M	H	PL
M	L	L	PL	H	H	L	PH
M	L	M	PL	H	H	M	PM
M	L	H	PL	H	H	H	PL

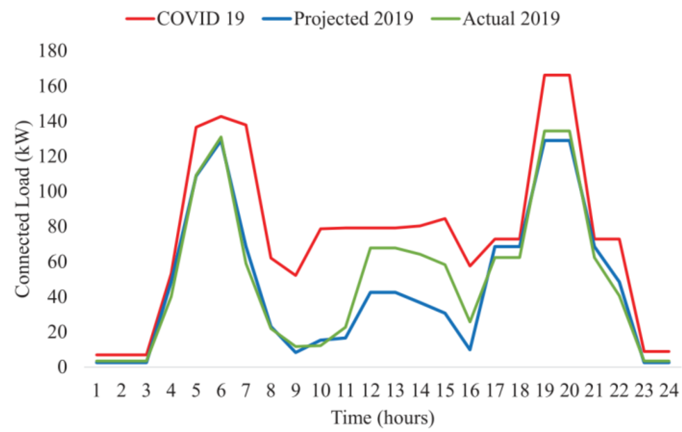

Figure 2: Load profiles used to evaluate the operation of the proposed controller

3.1 Methodology

Door to door survey based on questionnaires is done to collect load data and different energy alternatives. Operational research is used to determine the best energy alternative. Research work in [20] has reviewed various techniques of multi-criteria decision making, a branch of operational research that are being used in the area of renewable energy. The analytical hierarchy process (AHP) is used to determine the most appropriate energy alternative with technical, social, economic, and environmental as criteria. Solar, PV, wind and diesel generator (DG) is determined as the best combination of energy generation configuration. The determination of the most appropriate configuration of the microgrid is followed by determining the sizing of the energy-generating system to cater to the load of the selected locality. The sizing of the system is based on [26]. Three different types of load profiles are considered in work viz. the actual load data collected in June 2019, the projected load data for June 2019 in [26, 27] and the load data is determined after the strike of a pandemic due to the spread of COVID 19. These three different times are selected so that the operation of the controller can be checked at three different unexpected load profiles. From the load profile shown in Fig. 2, it is observed that the projected load for 2019 is the least followed by the actual load of 2019. The difference in the two loads is credited to the developmental works done by the governing bodies at different levels, including an increase in the number of offices, hospitals and schools, and homes. A sudden change in the load profile with load shifting is observed with the strike of COVID-19. Due to unprecedented strict lockdown imposed by the government of India as a non-pharmaceutical infection, the labor forces, employees working at companies, and related human resources were forced to shift to their native places and perform the task as a part of work from the initiative. Since the population shifted from offices to homes; office, schools and commercial loads were declined while the residential load increased. Hence load shifting is observed in the region as shown in Fig. 2.

The controllers proposed in [7] and [26] were designed for loads projected with growth in normal times. The strike of pandemic led to an abrupt change in the load profile, and the present situation demarcates the previous growth of the load profile as compared to the one due to COVID-19. Hence, the controllers previously designed with the projections of the next ten years will possibly fail to sustain the change in load demand. A new robust controller that operates without any constraint is required. This work proposes a Fuzzy based controller which can be designed for a wide range of operation. Further, the precision in operation can be increased by tuning and increasing the number of membership functions used in the rule base [28].

3.2 Results

The operation of the energy management systems (old and the proposed) for the three different load profiles given in Fig. 2 is explained in this section. Figures 3 and 4 are the plots based on the old controller, while Fig. 5 is based on the proposed controller. Fig. 3 shows the power generation utilization profile for meeting the case of projected load demand. The variations in the state of charge (SoC) are also shown in Fig. 3.

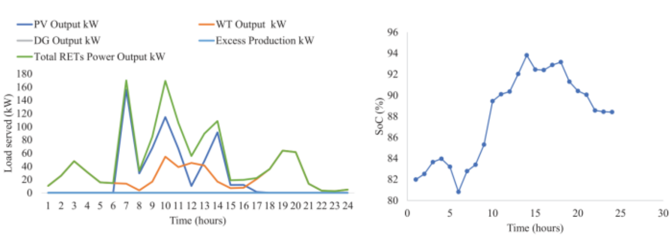

Figure 3: Generation profiles for the case of the forecasted load of 2019 and SoC of the energy storage battery

An increase in the SoC characterizes that the excess power is used for charging the battery while discharging of the battery shows the reduction of SoC.

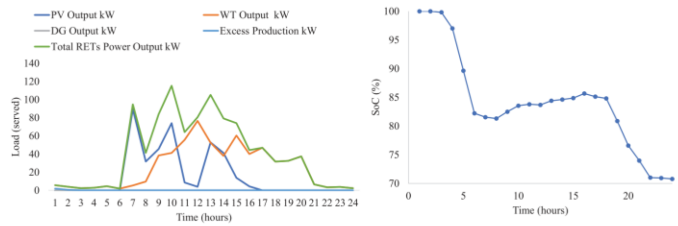

Figure 4: Generation profiles for the case of the actual load of 2019 and SoC of the energy storage battery

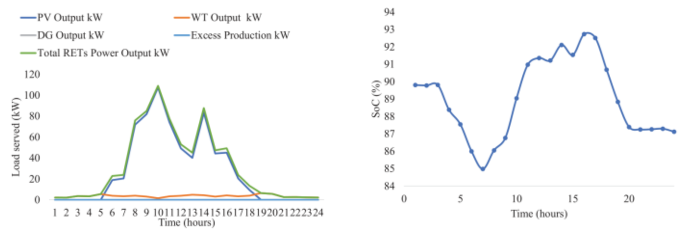

Figure 5: Generation profiles for the case of load during COVID-19 and SoC of the energy storage battery

The PV is utilized the most when available during day time while the wind generation is not being used at the peak to meet the load demand. On the contrary, when the actual data of load was considered in verifying the EMS, it is observed that the use of wind generation is increased with similar utilization of PV generation as compared to the previous scenario of the projected load. The utilization of battery also increased as visible from the plot of SoC. The charging time and the power to charge are insufficient to increase the SoC to a reasonable limit. Hence, it is clear that in the coming days, the battery will be reaching 20% SoC or less. If the SoC reaches 20% or less, the battery will not be utilized until charged. Further, the variations in the load profile due to the strike of COVID 19 makes the operation of the controller more critical. Thus, there is a need for a new controller, which can optimally utilize the available generated power and ensure all the elements contribute to feeding the loads.

The battery used in this work is used to manage energy by saving excess energy during periods of energy surplus and supplying to load during energy deficit. This management is done as per the algorithm proposed in Section II. The EMS consists of an FLC as a controller and a decision box. The inputs to the controller are shown in Fig. 1. The controller decides an amount of power to meet the load demand and maintain the SoC limit of ESS. The decision box decides whether to charge ESS or discharge from ESS. Thus, the output of the controller should be a value considering the energy surplus, deficit, load demand, and SoC of ESS. Fig. 5 shows the utilization of different energy sources to meet the load demand for the COVID-19 load profile shown in Fig. 2. It is to be noted that the load profile is for August 2019 and hence, the solar generation is at peak and the wind is least. Hence, the battery will be utilized at the fullest to meet the load demand. The plots in Fig. 5 show that the proposed controller can meet the load demand optimally. Both PVs and wind are being used at their limits along with the battery. Further, the charging and discharging of the battery are also seen during off-peak and peak load hours respectively. Hence, the proposed controller is better than the previously proposed controller for operations during a pandemic.

4. CONCLUSION

The work proposes an intelligent fuzzy-based controller that is designed to manage the power flow between the microgrid elements efficiently. The microgrid is analyzed for three different load profiles: actual load data, projected load data, and load data determined after the strike of a pandemic due to the spread of COVID 19. Based on the study, a possibility of failure of the existing controller is observed due to unprecedented load variations leading to socio-technical-economic overhaul, while the proposed controller can manage the power flow between loads and maintain the charging and discharging of energy storage. The proposed controller will be further evaluated to study the reliability with multiple case studies where the power balance between the generation and connected load is not obtained.

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