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Mix-Mode Energy Management Strategy and Battery Sizing for Economic Operation of Grid-Tied Microgrid

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Abstract

This paper presents a novel 'mix-mode' energy management strategy (MM-EMS) and its appropriate battery sizing method for operating the microgrid at the lowest possible operating cost. The MM-EMS is developed by combining three proposed operating strategies, namely "continuous run mode", "power sharing mode" and "ON/OFF mode" for a 24h time period. The objective functions for the proposed strategies are solved using linear programming (LP) and mixed integer linear programming (MILP) optimization methods. A sizing method using the particle swarm optimization (PSO) technique to determine the optimal energy capacity of battery energy storage (BES) in kWh is also presented. Since the size of the BES influences the microgrid's operating cost, the energy management strategy (EMS) and BES capacity are simultaneously optimized. The proposed MM-EMS and battery sizing method were first validated. Then, the variation of optimal battery capacity for different battery state of charge (SOC) levels is analyzed. The variation of microgrid's associated costs for different battery's

initial state of charge (SOC) levels is analyzed as well. Finally, a recommendation on the choice of initial SOC level during the start of the day for the economic operation of microgrid is also suggested.

Keywords

Energy management, battery storage, battery sizing, microgrids and particle swarm optimization (PSO).

1. Introduction

The conventional power system distribution network is currently undergoing a major change due to the addition of microgrids. The benefits of using microgrids include the fact that it is capable of supplying loads with negligible losses, reduce fossil fuel consumption, and postpone investment in a distribution system. Connecting intermittent sources such as solar photovoltaic (PV) generators and wind turbines in the grid-connected microgrid introduces challenges in various technical aspects, such as power quality, protection, generation dispatch control, and reliability. Challenges caused by these intermittent sources render the battery energy storage (BES) an indispensable source [1]. When a grid connected microgrid consists of two or more dispatchable source, it is necessary for the grid operator to run it economically. If battery energy storage (BES) is one of the dispatchable sources, it is essential that an appropriate size of BES is installed for the optimal microgrid operation.

A power management and battery sizing algorithm is proposed for a grid connected microgrid, consisting of PV, diesel generator, and BES in [2]. However, the battery size is not optimum, because the algorithm does not consider economic operation of microgrid. A smart energy management system based on matrix real-coded genetic algorithm is proposed in [3] for economic operation of grid connected microgrid. The optimal operation of grid connected

microgrid is presented in [4,5], where the microgrid's economic dispatch problem is solved by minimizing the microgrid's operational cost using mesh adaptive direct search (MADS) algorithm. Mixed integer linear programming (MILP) is used to solve the economic dispatch of microgrid sources in [6]. An optimal energy management is presented in [7], where the objective is to minimize the generation cost of the grid connected microgrid. The economic dispatch problem is solved using mixed integer quadratic programming (MIQP). Similarly, the sizing of battery energy storage is carried out in [8], where the economic dispatch problem is solved using linear programming (LP). Apart from solving the energy management problem using numerical methods, metaheuristic methods are used to solve energy management problem found in [9-12]. The energy management problem from the aforementioned references is based on one particular strategy. Moreover, in few papers, the optimal sizing of battery storage is not taken into account.

Energy storage devices play a crucial role in the economic operation of microgrid. Battery storage can take advantage of time of use tariffs, where it can be an effective option when the power purchasing price from the utility grid is high. Therefore, the accurate sizing of battery source is essential to ensure a microgrid's economic operation. The sizing of BES involves determining the optimal energy capacity in kWh with the aim of reducing microgrid's daily operating cost. An optimal sizing of battery storage for microgrid is presented in [13]. The optimal sizing of battery energy storage using improved bat algorithm is presented in [14]. Genetic algorithm based method for sizing battery storage is proposed in [15]. The energy management system in this paper is based on fuzzy expert system. In [16], matrix real-coded genetic algorithm (MRCGA) is used to determine the optimal energy capacity of BES. In a recently published article [17], the battery size is evaluated in order to minimize the microgrid's operation cost. The sizing problem was solved using Grey Wolf Optimizer (GWO). The energy

management problem solved in aforementioned references is based on a single operating strategy. The battery sizing methods presented in these references is focused on one particular energy management strategy, which may not incur the lowest operating cost.

The prominent focus of most work in literature pertaining to this subject was on solving economic dispatch for microgrid sources using a single operating strategy. It is possible that the microgrid might operate at lower operating cost in the case of a newly designed operating strategy. There are only a few works in literature that accounted for the sizing of battery storage, which is an important aspect of economic operation of a microgrid. In addition the papers in the literature discuss battery sizing methods that considers the economic operation of microgrid for one particular strategy. Therefore, in this paper an energy management strategy to operate the grid connected microgrid at the lowest possible operating cost is discussed. A method to estimate optimal BES size in kWh will also be presented. This work involves the development of an energy management using mix-mode operating strategy to operate the microgrid at the lowest possible operating cost. The proposed mix-mode operating strategy is developed by combining three proposed operating strategies, namely "continuous run mode", "power sharing mode" and "ON/OFF mode" for a 24h time period. The objective functions for these operating strategies were minimized using linear programming (LP) and mixed integer linear programming (MILP) methods. The mix-mode operating strategy is based on combining the aforementioned strategies keeping the operating cost in mind. The non-linearity of the PV output power and load demand, daily grid electricity price profile, the price of the natural gas, as well as battery state of charge (SOC) limits were all taken into account in the development of this model. In this paper, the BES's energy capacity for the microgrid under the proposed mix-mode operating strategy is solved using the PSO optimization technique. Due to the fact that the operating cost produced

using mix-mode strategy depends on the characteristics of battery storage, both the EMS and BES capacity needs to be simultaneously optimized. The discussion section will detail the, validation of the proposed MM-EMS and battery sizing method. Then, the variation of the optimal battery capacity for different battery state of charge (SOC) level is analyzed. Also, an analysis on variation of microgrid's operating cost (OC), battery's total cost per day (TCPD), and the combined cost of OC and TCPD will be carried out for different values of initial SOC levels. Finally, a recommendation is also suggested on choice of battery's initial SOC level during start of the day.

2. Proposed 'Mix-Mode' Energy Management Strategy (MM-EMS)

Operating the microgrid in more than one operating strategy is referred to as the mix-mode operating strategy. Three operating strategies, namely the continuous run mode, power sharing mode, and ON/OFF mode are proposed and explained in the following subsections.

2.1 Proposed operating strategies

The optimal generation dispatch for energy sources is calculated on an hourly basis to satisfy the load requirements considering hybrid system limits and constraints. The proposed operating strategies are explained in the subsequent sections.

2.1.1 Strategy 1: Continuous run mode

In this operating mode, the power drawn from the utility grid is always zero. The fuel cell operates continuously during a 24h time period. The output power from the fuel cell depends on the load demand and output powers from the PV and battery storage. During this strategy, initially the output power from PV and battery is used to supply the load demand. If demand is not met, the fuel cell is optimally dispatched to satisfy the load demand. There are chances where the output power from the PV exceeds the load demand, and in this case, the battery is charged,

and the fuel cell is forcibly switched OFF. The objective function for this mode is to reduce the daily operating cost, which can be expressed as:

$$obj1 = Minimize\left[C_{gi} \sum_{i=1}^{N} \frac{P_{FCi}}{\eta_i} + \beta\left(P_{BATi}\right) \right] \quad (1)$$

where,

C_{gi} is natural gas price to supply the fuel cell in dollars per kilowatt-hour

P_{FCi} is fuel cell power at time interval 'i'

β is taken as 1×10^{-6} to obtain the dispatch solution of P_{BATi}

P_{BATi} battery power at time interval 'i';

If P_{BATi} is positive battery discharges mode, if P_{BATi} is negative battery charging mode

η_i is cell efficiency of SOFC at time interval 'i' which is given as,

$$\eta_i = \frac{\left(\frac{V_{stack(i)}}{N}\right)}{E^o} \quad (2)$$

E^o is standard electrochemical potential which is 1.482 volt/cell

V_{stack} is fuel cell output stack voltage at instant 'i'

N is number of cell in fuel cell stack

At any given time instant 'i', the sum of the power generated from the distributed sources should be equal to the load, which can be expressed as:

$$P_{PVi} + P_{BATi} + P_{FCi} = P_{Li} \quad i = 1,2,...24 \quad (3)$$

The power produced from PV is uncontrollable. The fuel cell and battery is modeled as a variable controllable source, which should be operated within the prescribed limits for a 24h time period. The constraints for the controllable source are given as:

$$P_{FC\min} \le P_{FCi} \le P_{FC\max} \quad i = 1,2,...24 \tag{4}$$

The constraints related to battery energy level and allowable charge/discharge power considered for this work will be explained in Section 3.

2.1.2 Strategy 2: Power sharing mode

In this power sharing mode, the utility grid, battery source, and fuel cell are all optimally scheduled to supply power to the load demand. The battery source is charged when the output power from the PV exceeds that of the load demand. The objective function for the power sharing mode is to reduce the daily operating cost, which can be expressed as:

$$obj2 = Minimize\left[C_{gi} \sum_{i=1}^{N} \frac{P_{FCi}}{\eta_i} + C_{ei}\left(P_{Li} - P_{neti}\right) + \beta\left(P_{BATi}\right) \right] \tag{5}$$

where,

C_{ei} tariff of electricity purchased in dollar per kilowatt-hour

P_{Li} is the load demand at interval 'i'

$P_{net\,i}$ is the net power produced at interval 'i'

At any instant of time 't', the summation of total generated power from PV, fuel cell, battery source and utility grid should be equal to the total load demand.

$$P_{PVi} + P_{BATi} + P_{FCi} + P_{Gi} = P_{Li} \quad i = 1,2,...24 \tag{6}$$

Since the microgrid operates at the distribution level, the excess power from the microgrid is utilized to charge the battery. This is necessary to avoid the power from being injected to grid, which will activate the reverse power flow relay installed at the point of common coupling (PCC). The power imported from the grid at time instant 'i' can be used to charge the battery or

157 supply the load. Therefore, considering the power drawn from the grid as a constraint which can
158 be expressed as,

159 $$P_{Gi} \geq 0 \quad i = 1,2,...24 \tag{7}$$

160 Moreover, the boundary constraints for fuel cell given in eq.(4) are taken into account for this
161 strategy. The limitations related to battery energy level and allowable charge/discharge power
162 considered for this work will be explained in Section 3.

163 **2.1.3 Strategy 3: ON/OFF mode**

164 In this strategy, the objective is to obtain an optimal ON/OFF schedule for the fuel cell, utility
165 grid, and battery source, thereby minimizing the microgrid's operating cost. Here, the output
166 power from both the PV and battery source supplies the load demand. Any deficit in the power
167 required by the load is delivered by optimally dispatching fuel cell and the utility grid. In this
168 operating strategy, when the fuel cell is switched ON, it is forced to run at its rated output power.
169 For the rest of the time, the fuel cell is switched OFF. Since the fuel cell is switched ON/OFF, a
170 binary switching variable is introduced to enhance control over the fuel cell. The objective
171 function for this ON/OFF mode is given as:

172 $$obj3 = Minimize\left[S(i)\left(C_{gi} \sum_{i=1}^{N} \frac{P_{FCi}}{\eta_i} \right) + C_{ei}\left(P_{Li} - P_{neti}\right) + \beta\left(P_{BATi}\right) \right] \tag{8}$$

173 Where *S(i)* is a switching function, which takes the value of *0* or *1*. When *S(i)* is *1*, the fuel cell is
174 operated at its rated capacity. When *S(i)* is *0*, the fuel cell is switched OFF. Therefore, during the
175 time of the fuel cell operation, its output is constant.

176 At any given time instant '*i*', the sum of power generated from the distributed sources and utility
177 grid should be equal to the load, which can be expressed as:

$$P_{PVi} + P_{BATi} + (P_{FCi})S(i) + P_{Gi} = P_{Li} \quad i = 1,2,...24 \tag{9}$$

Since the fuel cell is forced to run at its rated capacity, the operating range of fuel cell is either zero or at its rated capacity. The boundary constraint for utility grid power eq.(7) is also considered. The limitations related to battery energy level and allowable charge/discharge power considered for this work will be explained Section 3.

2.2 Development of mix-mode operating strategy

This section explains the development of "*mix-mode*" operating strategy. The primary objective of mix-mode operating strategy is to dispatch power from the distributed sources to the varying load with lower daily operating cost. The idea of mix-mode strategy is presented in Fig. 1. Initially the forecasted PV output power and load demand for the time instant '*i*' is considered. For the given time instant with the PV power, load demand, prices of electricity and natural gas as inputs, the economic dispatch problem is solved for the three proposed strategies. *Obj1*, *Obj2*, and *Obj3* are the obtained objective functions for strategy 1, strategy 2 and strategy 3, respectively, for the given time instant '*i*'. The lowest value of the three objective functions should deliver the lowest operating cost. Therefore, the optimal dispatch values corresponding to the lowest objective function is selected and provided as a reference to the distributed generators present in the microgrid. The aforementioned steps are repeated for every time instant '*i*' and this microgrid is operated for 24h time period.

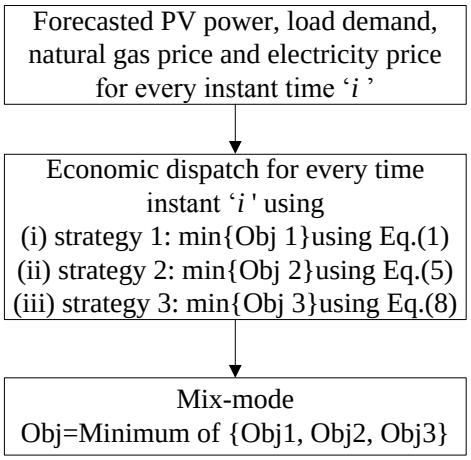


Fig.1. Mix-mode operating strategy

3. Optimal sizing of battery source for MM-EMS: Problem formulation

On top of the proposed energy management strategy, optimal sizing of BES for MM-EMS is also formulated. To obtain the optimal battery sizing, the initial capital cost (CC) of BES should be considered. Total cost per day for BES ($TCPD_{BAT}$) is the function of initial capital cost of BES. The optimal BES sizing is obtained by minimizing the total cost function, which is a summation of the daily operating cost of microgrid and BES's $TCPD_{BAT}$. The daily operating cost of the microgrid (*Obj*) is obtained from the previous section by operating the microgrid in the mix-mode operating strategy. Therefore, the total cost function formulated for this problem can be given as:

$$MinF(X) = \sum_{i=1}^{24} Obj(i) + TCPD_{BAT} \tag{10}$$

Here, the $TCPD_{BAT}$ for a particular battery energy rating will be same for all the three strategies. The expression for $TCPD_{BAT}$ is given as,

$$TCPD_{BAT} = \frac{1}{365}\left(\frac{r.(1+r)^{Lt}}{(1+r)^{Lt}-1}.CC\right) \tag{11}$$

$$CC = C_P.\overline{P} + C_E.\overline{E} \tag{12}$$

where CC is the capital cost of the battery source, and C_P and C_E are specific costs associated with the battery source's power and energy capacities, respectively. r is interest rate for financing the battery source, Lt is the battery source's lifetime and $\overline{E}$ and $\overline{P}$ are rated energy and power capacities of the BES.

The proposed sizing problem is solved subjected to constraint given below,

(a) Battery constraints:

The charge in the BES must be bounded between,

$$E_{BAT}^{\min} \le E_{BAT} \le E_{BAT}^{\max} \tag{13}$$

where E_{BAT} is the energy stored in the battery at the end of instant 'i' in kWh.

$E_{BAT}^{\min}$, $E_{BAT}^{\max}$ are minimum and maximum charges to be maintained for battery storage

Discharging mode:

Constraint limited to release of energy from battery source is given as,

$$E_{BAT,i} = \max\left\{\left(E_{BAT,i-1} - \Delta t.P_{BAT,i} / \eta_{discharge}\right), E_{BAT}^{\min}\right\} \tag{14}$$

Charging mode:

Constraint limited to energy stored in the battery source is given as,

$$E_{BAT,i} = \min\left\{\left(E_{BAT,i-1} - \Delta t.P_{BAT.i}.\eta_{charge}\right), E_{BAT}^{\max}\right\} \tag{15}$$

In addition to the limitation in charging/discharging levels, the maximum and minimum discharging/charging power is also given as,

$$P^{c}{}_{BAT,i} \le P_{BAT,i} \le P^{d}{}_{BAT,i} \quad i = 1,2,...N \tag{16}$$

where,

$$P^{c}{}_{BAT,i} = \max\left\{P_{BAT,\min}, \left(E_{BAT,i-1} - E_{BAT}^{\max}\right)/\eta_{charge}.\Delta i\right\} \quad i = 1,2,...N \tag{17}$$

$$P^{d}{}_{BAT,i} = \min\left\{P_{BAT,\max}, \left(E_{BAT,i-1} - E_{BAT}^{\min}\right)\eta_{discharge} / \Delta i\right\} \quad i = 1,2,...N \tag{18}$$

Δi is the commitment period which is 1h in this paper

The proposed battery sizing problem should fulfill the aforementioned constraints in Eq.(13)-(18) for solving the energy management strategy proposed in Section 2.

(b) Dispatchable distributed generator constraints

The PV source is uncontrollable, and its output depends on solar radiation. The operating output of other dispatchable sources should be limited within the minimum and maximum limits. The operating limits of the fuel cell and utility grid for the proposed strategies are provided in corresponding Sections 2.1.1, 2.1.2, 2.1.3.

4. Proposed sizing method

In the ordinary form, solving the optimal BES sizing for the proposed mix-mode operating strategy is a complex optimization problem. Therefore, the particle swarm optimization (PSO) technique, which is a population based optimization technique, is used to solve the battery sizing problem. The economic dispatch problems proposed in the three strategies are solved using linear programming (LP) and mixed-integer linear programming (MILP) optimization techniques. The objective functions for the strategy 1 and strategy 2 for continuous run and power sharing modes have been modeled as a linear function of microgrid's distributed sources output power. Therefore, for strategy 1 and strategy 2, the optimization problem is solved using the linear programming (LP) solver "*linprog*" in MATLAB, which can be expressed as:

$$\min_{x} f^{T} obj \text{ subjected to } \left\{ \begin{array}{c} A.x \le b \\ Aeq.x = beq \\ lb \le x \le ub \end{array} \right\} \tag{19}$$

where: *f, x, b, beq, lb* and *ub* are vectors; *A* and *Aeq* are matrices.

The objective function for strategy 3 has been modeled as a mixed integer linear function of the microgrid's distributed sources output power, where the switching function for the fuel cell generator in Eq.(8) is an integer. Therefore, the objective function is modeled as a mixed integer linear programming (MILP). This MILP problem can be solved using MILP solver "*intlinprog*" in MATLAB. The "*intlinprog*" finds minimum of a problem by considering the constraints specified by,

$$\min_{x} f^{T} obj \text{ subjected to } \left\{ \begin{array}{c} x(\text{int } con) \\ A.x \le b \\ A_{eq}.x = b_{eq} \\ l_b \le x \le u_b \end{array} \right\} \tag{20}$$

where: *f, x, intcon, b, beq, lb* and *ub* are vectors; *A* and *Aeq* are matrices.

The BES's energy capacity for the microgrid under the proposed mix-mode operating strategy is solved using PSO. Simultaneously, the economic dispatches for three strategies are performed using linear programming and mixed-integer linear programming optimization techniques. In support of this, the flowchart of the proposed battery sizing method is presented in Fig.2.

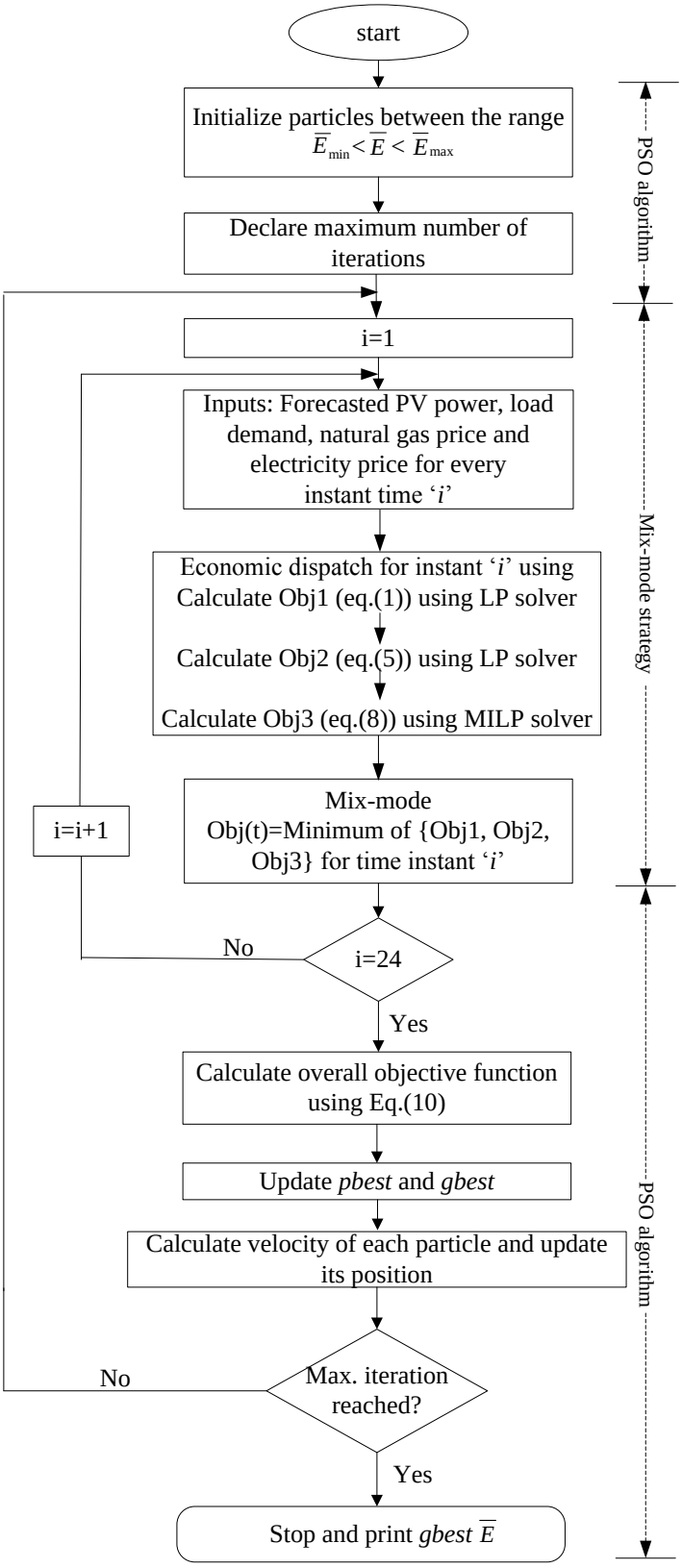


Fig. 2. Flowchart of the proposed sizing method for mix-mode energy management strategy

The proposed methodology is based on 24h microgrid operation. To perform the sizing of battery source, 24h data for the following variables are required: forecasted PV output power, load demand, natural gas price and utility grid electricity price. As the first step in the proposed method, the particles between the range is declared to be,

$$\overline{E}_{\min} < \overline{E} < \overline{E}_{\max} \tag{21}$$

The value of $\overline{E}_{\min}$ and $\overline{E}_{\max}$ is set according to the microgrid's characteristics. In this paper, the value of $\overline{E}_{\min}$ and $\overline{E}_{\max}$ is set as 100 kWh and 3,000 kWh, respectively. It means that the search space for PSO is between the range of [100 kWh, 3,000 kWh]. The power capacity of the battery $\overline{P}$ is fixed to 100 kW in this paper. Initially, particles between the search ranges are generated randomly. Then, for each particle, the economic dispatch is solved for every time instant '*t*' for the three proposed operating strategies. The operational constraint for the battery source, fuel cell, and utility grid is considered while solving the economic dispatch problem. From the three solved objective function for time instant '*t*', the lowest objective function is selected and explained in Section 2.2. This procedure is repeated for the 24h time period. Then the objective function (*Obj*) for a 24h time period solved using mix-mode strategy is summed with the $TCPD_{BAT}$ to obtain the overall cost function. This procedure is repeated for all of the particles. Once the objective functions for all the particles are evaluated, the particles personal best (*pbest*) and global best (*gbest*) is updated. Then, the velocity of each particle is updated, and based on the velocity, the new position of the particles is obtained. Thus, the whole process is repeated until the maximum number of iterations is reached. When the number of iteration reaches its maximum, the system prints the optimal value of BES capacity $\overline{E}$ in kWh.

5. Case studies and results discussion

To assess the validity of the proposed mix-mode energy management strategy and the proposed battery sizing method, a low voltage grid connected microgrid shown in Fig. 3 is considered. The grid connected microgrid consists of 200 kW solar PV, two identical 100 kW solid oxide fuel cell, and a battery bank operated parallel with the load. The minimum and maximum operating range of the single fuel cell unit is fixed as 10 kW and 100 kW, respectively. Operating outside the operating range will reduce the fuel cell's life [18]. The technical specification considered for modeling solid oxide fuel cell is taken from [19]. Utility grid electricity pricing and natural gas pricing is shown in Fig.4 and is obtained from [20]. The forecasted PV output power and load demand for 24h time horizon is considered for this work. The microgrid uses lead-acid battery, while the specific costs associated with the BES's power capacity (C_P) and energy capacity (C_E) are set as \$234/kW and \$167/kWh, respectively [15]. The battery lifetime and interest rate for financing the battery source are set as 3 yrs and 6%, respectively. The charging and discharge efficiency are same and are set to 95%. $P_{BAT,min}$ and $P_{BAT,max}$ of the battery is set as -100 kW and 100 kW, respectively. The minimum and maximum level of SOC for the battery should be maintained within 20% and 100%, respectively. To reflect this in the optimization, $E_{BAT}^{\min}$ and $E_{BAT}^{\max}$ are minimum and maximum level of charge that should be maintained, which is set as 20% of $\overline{E}$ and 100% of $\overline{E}$, respectively.

As a first step the superiority of the proposed mix-mode operating strategy in reducing the overall microgrid's operating cost for a particular battery capacity is presented. Then, the proposed battery sizing method is validated by comparing it to the trade-off method. The variation of the optimal battery sizes for different battery's initial SOC levels is presented. With this, an analysis on variation in microgrid's operating cost is also carried out.

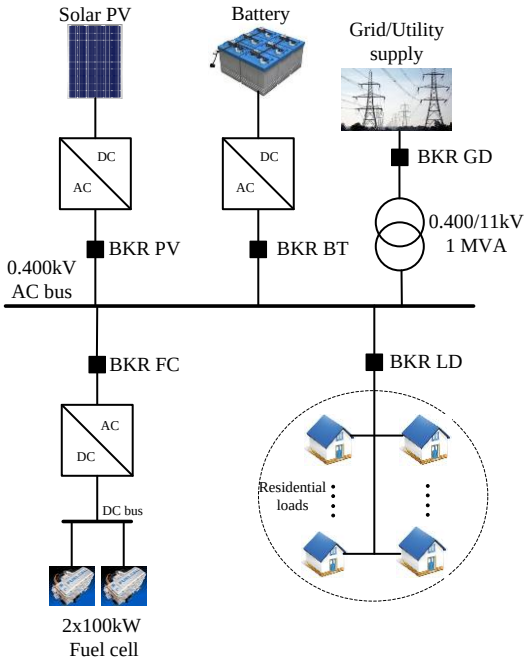


Fig.3 Microgrid test system

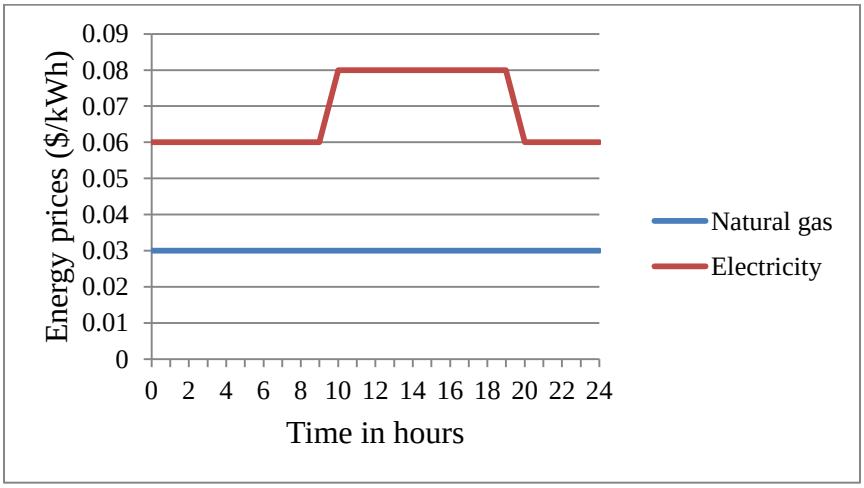


Fig.4. Utility energy prices in ($/kWh)

5.1 Comparison of the proposed mix-mode operating strategy with other operating strategies

In this section, the superiority of the proposed mix-mode energy management strategy is validated for the microgrid model presented in Fig. 3. In this study, since the battery source is considered, the optimal size of the battery is determined using the proposed sizing method. The initial SOC level of the battery during the start of the day is kept at 90%. The battery size is optimized within the range [100 kWh, 3,000 kWh], considering all the battery and distributed sources constraint. The optimal battery capacity for this case is found to be 2,497.6 kWh. The results of the optimal dispatch values for the distributed sources in the microgrid for mix-mode strategy are presented in Fig. 5. Fig. 6 show the battery state of charge (SOC) level maintained within its limit.

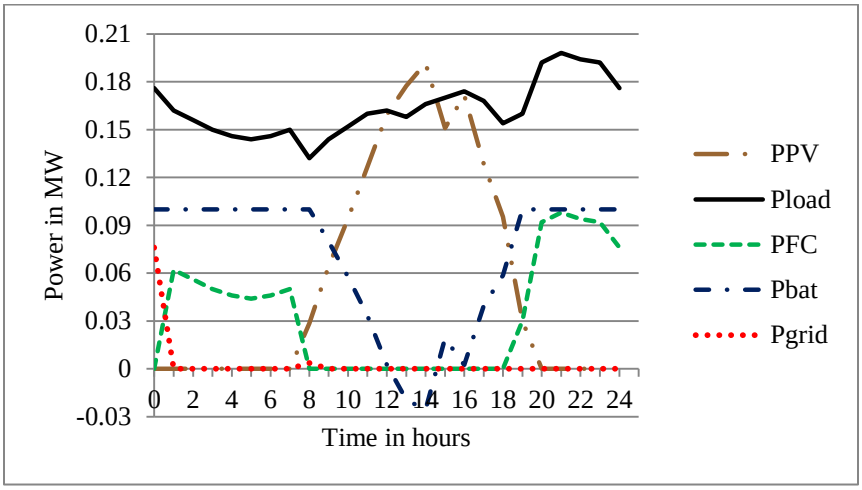


Fig.5. Optimal output of distributed source in microgrid for mix-mode strategy

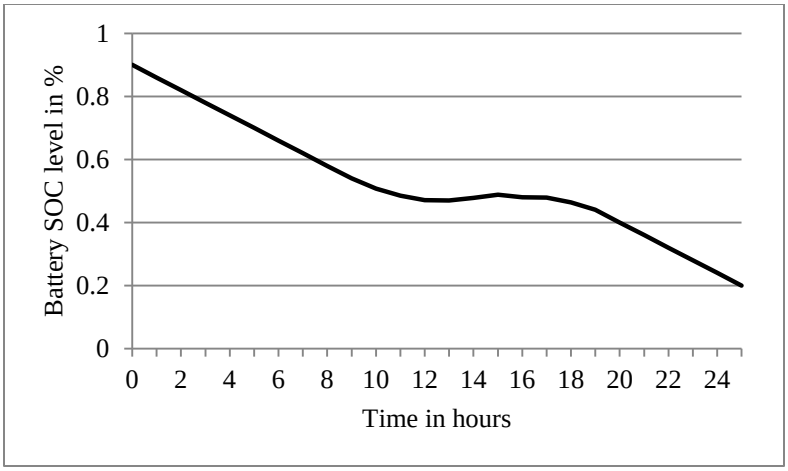


Fig.6. Battery SOC level for mix-mode operating strategy

A comparison on the daily operating cost for the proposed mix-mode strategy with other strategies is tabulated in Table 1.

Table 1 Comparison of daily operating cost

	Strategy 1: Continuous run mode	Strategy 2: Power sharing mode	Strategy 3: ON/OFF mode	Mix-mode
Operating cost in $	1,880.8	1,003.5	1,073.6	978.8768
FC operating hours	24	14	4	13
Grid operating hours	0	1	11	2

The results from Table 1 shows that operating the microgrid in continuous run mode is more expensive. The fuel cell is also forced to run for the 24h time period. The operating cost of microgrid is found to be less when the microgrid is operated under the power sharing mode when compared to the ON/OFF mode. However, the fuel cell is operated for 14h, which exceeded the ON/OFF mode where the fuel cell is forced to run at its rated capacity for only 4h. The

advantage of operating the microgrid in the ON/OFF mode is that, when the fuel cell is forced to run at the ON/OFF mode, the excess power can be used to charge the battery source. Moreover, the run time of fuel cell is less during the ON/OFF mode, which will increase its calendar life. The overall operating cost of the microgrid for the proposed mix-mode operating strategy is less than other operating strategies. This proves that operating a microgrid in different operating strategies for 24h time period will incur the lowest operating cost.

5.2 Validation of the proposed battery sizing method

In this section, the validation of the proposed battery sizing method is carried out. The proposed battery sizing method is validated with the "trade-off" method. Trade-off method can be used to find the approximate battery storage capacity in kWh. For this purpose, the operating cost (OC) of the microgrid, battery's TCPD, and sum of OC and TCPD cost is plotted for different values of the battery's energy capacity. Since the minimum and maximum range of the battery energy capacity for this work is [100 kWh , 3,000 kWh], the OC, $TCPD_{BAT}$, and ($OC+TCPD_{BAT}$) are plotted in Fig.7 for different energy capacities between these ranges on regular intervals. Fig. 7 is plotted by taking into account the initial charge of the battery being equal to 100% of the battery capacity, which is the initial SOC level of the battery during the start of the day taken as 100% in this case.

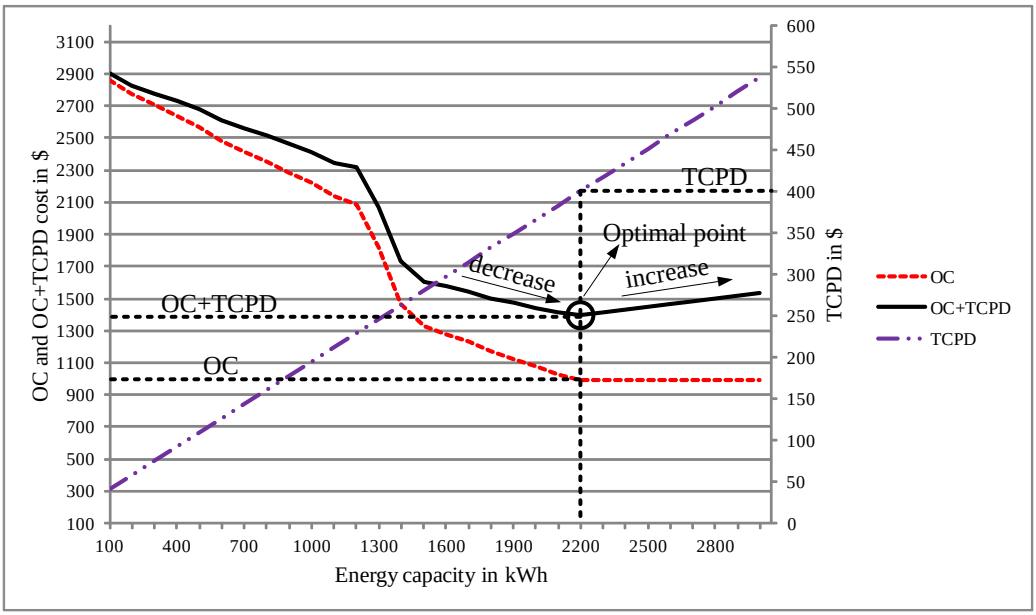


Fig.7 Optimal value of energy capacity in kWh using trade-off method

The operating cost (OC) of the microgrid is very high for lower battery capacities. As the battery capacity increases, the OC of the microgrid decreases. This is due to the availability of sufficient battery source for an economical microgrid operation. On the other hand, as the battery capacity increases, the battery's TCPD cost also increases. This is because the TCPD of the battery is directly associated with battery's installation cost. Therefore, with an increase in the battery capacity starting from 100 kWh, the sum of operating cost (OC) and battery's TCPD, which is the combined cost of *OC* and *TCPD*, tend to decrease. With the increase in battery capacity at one point, the OC of the microgrid attains a minimum value, from where it does not decrease and remains constant for further increment in battery capacity. In this instant, the readers can notice a sudden change from a decreasing to an increasing trend in the combined cost of *OC* and *TCPD* costs. The point where a sudden change in the trend happens to be the optimal point, where the combined cost OC+TCPD is quite less. The point where the combined cost of OC and TCPD is less is encircled in Fig. 7, for which the corresponding battery capacity is found to be 2,200 kWh. Here, the optimal battery capacity is obtained by a trade-off between microgrid's OC and

383 battery's TCPD costs. The approximate operating cost (OC) of the microgrid for the optimal
384 value is plotted, and it is found to be $ 1,000, while the TCPD cost associated with the battery is
385 approximately $ 400. Therefore, the total combined cost of OC and TCPD from the Fig. 7 is
386 closer to $ 1,400 per day. That is the point encircled in Fig.7, where it is closer to $ 1,400 per
387 day. It can be noted from Fig. 7 that further increase in battery capacity beyond the 2,200 kWh
388 increases the combined cost of OC and TCPD, which is due to the increase in battery's TCPD
389 cost. On the other hand, it can be noticed that the OC of the microgrid remains constant for
390 further increase in battery capacity beyond 2,200 kWh. Choosing any value below 2,200 kWh
391 will increase the microgrid's operating cost.
392 In this paper, we propose an accurate method to determine optimal battery size using the PSO
393 optimization technique necessary for economic operation of microgrid. The microgrid is
394 operated in a mix-mode operating strategy. In this case, the battery size and operating cost of the
395 microgrid are simultaneously optimized. The battery capacity is optimized by considering the
396 initial SOC level during start of the day as 100%. The optimal value of battery capacity
397 optimized using PSO is found to be 2,185.4 kWh. Table 2 provides a comparison between the
398 optimal value of battery capacity obtained using the trade-off method and the proposed sizing
399 method. In the table, the OC, TCPD and OC+TCPD costs obtained from the proposed sizing
400 method is compared with the trade-off method. The capacity of the battery and costs tabulated
401 for the proposed sizing method is very close to the values obtained using the trade-off method.
402 From the table, it is clear that the proposed battery sizing method is accurate enough to calculate
403 the battery capacity in kWh for the economic operation of the microgrid.
404

Table 2 Comparison of optimal value obtained using trade-off method and proposed sizing method

	Trade-off method	Proposed sizing method
Optimal battery capacity (kWh)	2,200	2,185.4
OC ($)	1,000	978.8768
TCPD ($)	400	398.0547
OC+TCPD ($)	1,400	1,376.9315

5.3 Analysis of variation in optimal energy capacity of battery source for initial SOC levels 100%, 90% and 80% during start of the day

The main advantage of adding battery source in the microgrid is to maintain stability, improve power quality, and facilitate the integration of renewable sources [21-24]. In this case, the optimal battery capacity required for the economic microgrid operation is evaluated by considering the initial SOC of the lead acid battery to be 100%, 90%, and 80% during the start of the day. Therefore, the optimal battery capacity $\overline{E}$ for each of the initial SOC level is optimized within the range [100 kWh , 3,000 kWh] using the proposed battery sizing method.

The optimal values of the BES are found to be 2,185.4 kWh, 2,497.6 kWh and 2,913.9 kWh when the battery initial SOC levels are 100%, 90% and 80% respectively during the start of the day. This is validated using the trade-off method by plotting various costs against different battery capacity ranging between [100 kWh , 3,000 kWh].

The results for the optimal energy capacity using the trade-off method when the microgrid is operated under mix-mode strategy, considering the battery source with initial SOC levels as 100%, 90% and 80% during the start of the day are presented in Fig.8. The optimal values are attained for the lowest value of combined cost of OC and TCPD is found to be 2,200 kWh, 2,500 kWh and 2,900 kWh for initial SOC cases of 100%, 90%, and 80% respectively.

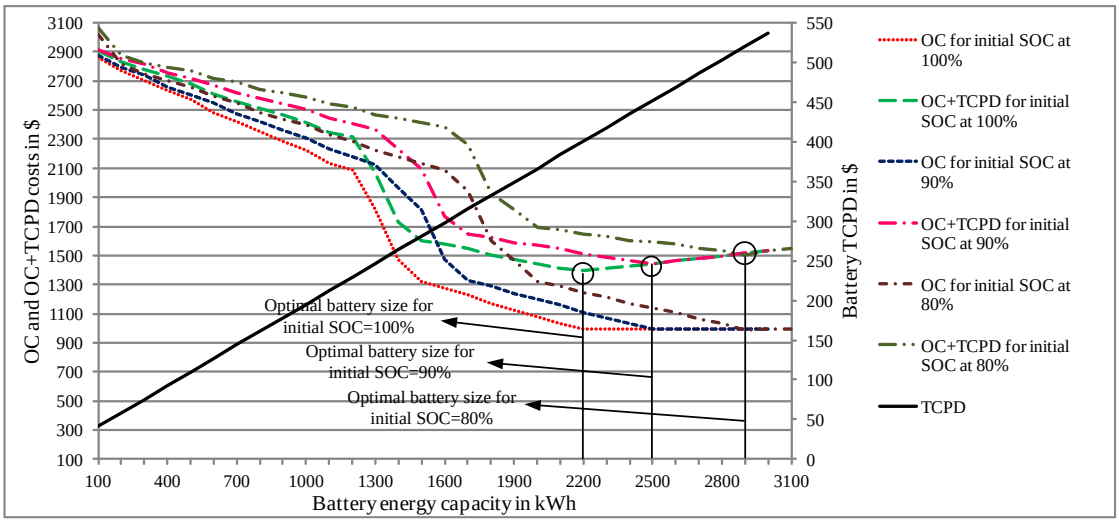


Fig. 8. Optimal value of energy capacity in kWh using trade-off method for initial battery SOC at 100%, 90% and 80%

From Fig.8, it can be noted that the microgrid's operating cost (OC) and the combined cost of OC and TCPD is not same when the battery source initial SOC levels during start of the day are 100%, 90% and 80%. The OC and combined cost of OC and TCPD is very much decreased when the battery initial SOC level during the start of the day is 100%. In other words, if the battery's initial SOC level is very large, the operating cost of the microgrid is reduced to its lowest value. Fig.8 shows that the operating cost of the microgrid settles to a constant value of the battery's optimal capacity value. For example, in the case of the battery initial SOC level 100%, the operating cost settles at an approximate value of $ 1,000 at 2,200 kWh. Similarly, for cases of initial SOC levels at 90% and 80%, the operating cost settles down to a constant value of $ 1,000 at optimal values of 2,500 kWh and 2,900 kWh, respectively. A clear comparison between the optimal values obtained for different battery initial SOC levels for the trade-off method and the proposed sizing method is presented in Table 3.

Table 3. Comparison of optimal value obtained using trade-off method and proposed sizing method for battery initial SOC levels 100%, 90% and 80%

	Trade-off method			Proposed sizing method		
Initial SOC at	100%	90%	80%	100%	90%	80%
Optimal battery capacity (kWh)	2,200	2,500	2,900	2,185.4	2,497.6	2,913.9
OC in $	1,000	1,000	1,000	978.8768	978.8768	978.8768
TCPD in $	400	450	520	398.0547	451.4934	522.7506
OC+TCPD in $	1,400	1,450	1,520	1,376.9315	1,430.3702	1,501.6274

Table 3 show that with decreasing levels of the battery's initial SOC level during the start of the day, the battery's optimal capacity increases. Therefore, in order to reduce the microgrid's operating cost to its lowest value with less battery initial cost, it is suggested that the optimal battery capacity with higher initial SOC be used during the start of the day. This will reduce the microgrid's operating cost with less battery initial cost.

5.4 Analysis of variation of microgrid's operating cost for different initial SOC levels during start of the day

This section will analyze the variation in the microgrid's operating cost for different initial SOC levels during the start of the day. Prior to the analysis, it is necessary that the microgrid's operating cost in the absence of battery energy storage, be evaluated. Hence, this section is divided into two sub-sections, (i) microgrid operation without battery source, and (ii) microgrid operation with battery source having initial SOC levels at 100%, 70%, and 50% during the start of the day.

5.4.1 Microgrid operation without battery energy storage

This section discusses the operation of grid connected microgrid without battery source. All the distributed sources present in the microgrid, including utility grid, should satisfy the forecasted load demand for the 24h time period. In this case, there may be instances where the output power

from the PV may exceed the load demand. Since the battery source is unavailable for charging the excess power, a load resistor is modeled to ground the excess power. By load demand and maximum available power from the distributed sources, the results for the microgrid operation for mix-mode are presented in Fig. 9.

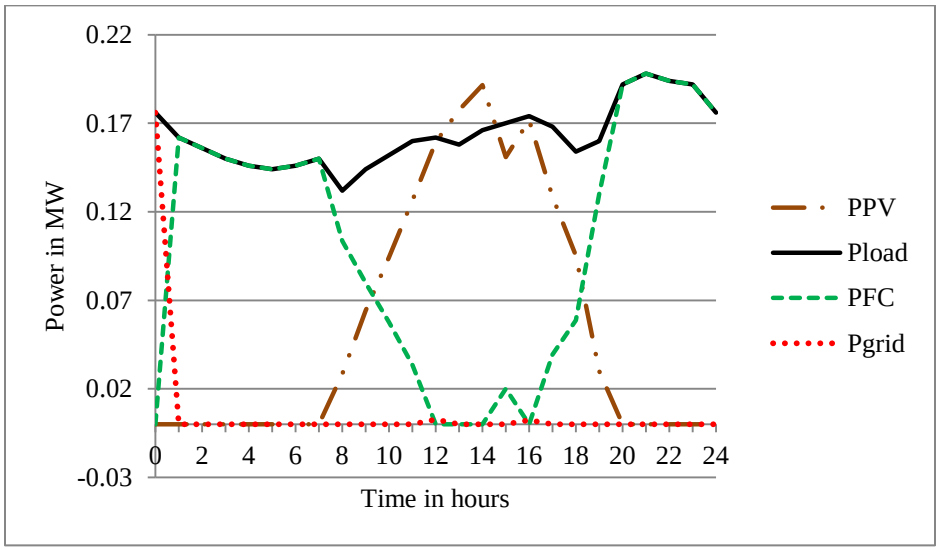


Fig.9 Optimal operation of microgrid without battery source

The total operating cost of the microgrid in this case is $ 3,332/day. Since there is no battery source available to deliver ancillary service, the maximum available power from the fuel cell and utility grid is drawn by the load. This forces the fuel cell to extend its operating hours by 20h. Overall, since no battery is employed, the microgrid rely on power from the fuel cell and the utility grid. Furthermore, the fuel cell operating hours exceeds that of the utility grid operating hours. This is because the power drawn from the fuel cell is cheaper than power purchased from the utility grid. There are instances where utility grid is scheduled instead of the fuel cell. During the entire 24h operating time, the utility grid is optimally scheduled for 3h.

5.4.2 Microgrid operation with battery source having initial SOC levels at 100%, 70% and 50% during start of the day

The lead-acid battery is added to the microgrid test system for this case study. During the early morning hours, since the battery source is cheap, it will effectively be used to supply the varying load. There is no chance of the battery charging during the early morning hours that is before the sun-rise. Keeping the initial battery cost in mind, the initial SOC of the battery during the start of the day is set to 100%. The results in Fig. 10 portray the optimal dispatch values of the distributed sources in the microgrid when the battery initial SOC level is 100% during the start of the day. The optimal battery capacity for this case is found to be 2,185.4 kWh. During the early morning hours that is before the sun-rise, the power to the load is managed by battery, fuel cell, and the utility grid. During the day, when PV power is present, the battery source is efficiently managed to supply the load or charge when PV power exceeds the load demand. During this period of operation, the power from the fuel cell and utility grid are quite low, or in some cases zero for the majority of the time period. This is due to the availability of cheaper battery power. During the evening hours along the side of battery source the fuel cell is also used to supply the load. The power drawn from the utility grid is zero during this time, because the power purchase cost from the utility grid is very high than the cost of power drawn from battery source and fuel cell. From Fig. 11, it is clear that the battery SOC level is kept within the limits.

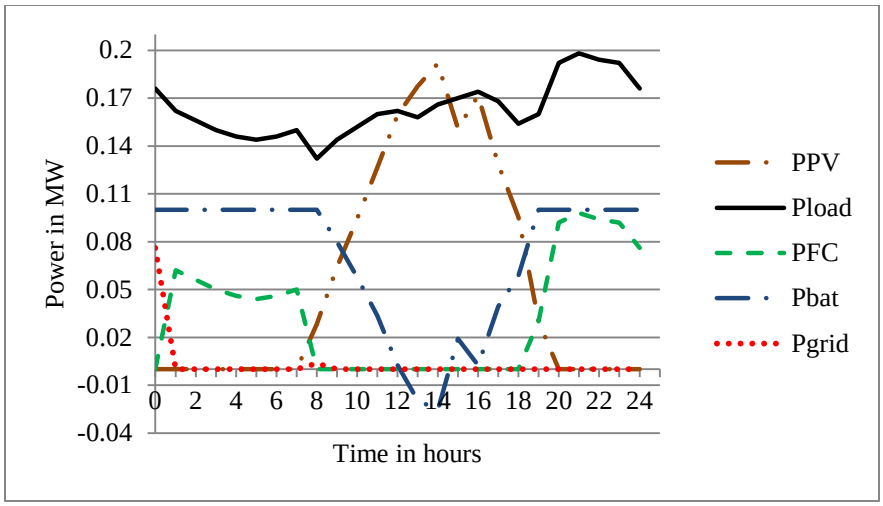


Fig.10 Optimal output of distributed source in microgrid for when battery initial SOC at 100% of 2,185.4 kWh

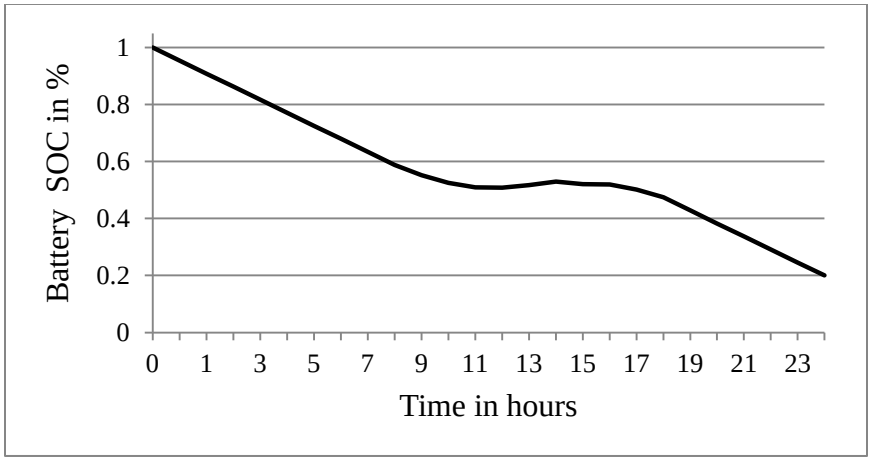


Fig.11. Battery SOC level for mix-mode operating strategy when battery initial SOC at 100% of 2,185.4 kWh

A battery size of 2,185.4 kWh is the optimal capacity when the initial SOC is at 100% during the start of the day. It is our interest to set the initial SOC level to 70% and 50% during the start of the day for the battery size of 2,185.4 kWh and observe the operation of the microgrid and calculate its operating cost. Fig. 12 and Fig.13 shows the optimal dispatch values and battery SOC level when the battery initial SOC level is set to 70% of 2,185.4 kWh during the start of the

day. Similarly, Fig.14 and Fig15 shows the optimal dispatch values and battery SOC level when the battery initial SOC level is set to 50% of 2,185.4 kWh during start of the day.

The discharging action of battery in each time step of the day is restricted to how much it charges in previous hours. It can be noticed from Fig.10, Fig.12 and Fig.14 that when the initial SOC is high during the start of the day the battery operates for longer hours. On the other hand, when the initial SOC level of the battery is set low, the battery operating hours is less due to the scarcity of charge in the battery source. When the initial SOC is 70% in Fig.12, the battery operating hours is found to be less, and the battery is completely switched OFF during the night hours. Similarly, when initial SOC is 50% in Fig.14, the battery is switched OFF during night hours and even for few hours during the day-time. For cases of lower initial SOC levels, particularly during night hours, the second unit of the fuel cell is switched ON to supply power to varying load, since the power drawn from utility grid is more expensive. A brief comparison of the microgrid's operating cost without and with battery source with different initial SOC levels are presented in Table.4. The operating cost of the microgrid without battery source is determined to be $3,332/day. The microgrid operating cost with optimal battery source of 2,185.4 kWh having an initial SOC at 100% at the start of the day is $ 978.8768/day. This means that operating the microgrid with optimal battery sizing reduces the overall operating cost by 70% for a single day. This is due to the availability of the battery source, and therefore, the battery operating hours is increased to 22h. On the other hand, with the same optimal battery size where the initial SOC is set at 70% during the start of the day, it will reduce the overall operating cost by only 55% for a single day. Moreover, this increases the fuel cell operating hours to 14h, and reduces the battery operating hours to 18h. For an initial SOC of 50% during the start of the day case, the operating cost of the microgrid is $ 2,335.3/day, where the savings is only 30% for a single day, which is

even lesser than the higher initial SOC cases. In this case, the fuel cell and utility grid operating hours are increased to 18h and 3h, respectively while the battery run time is reduced to 10h.

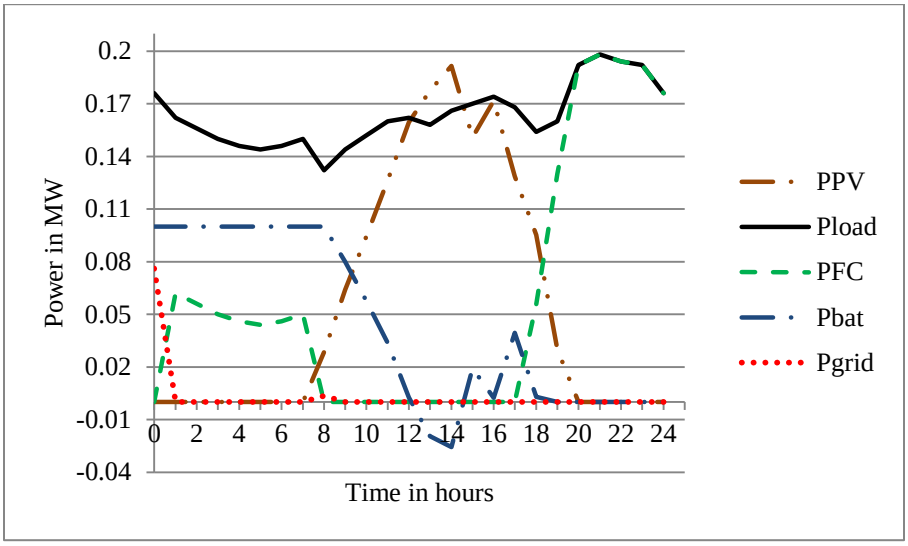


Fig.12 Optimal output of distributed source in microgrid for when battery initial SOC at 70% of 2,185.4 kWh

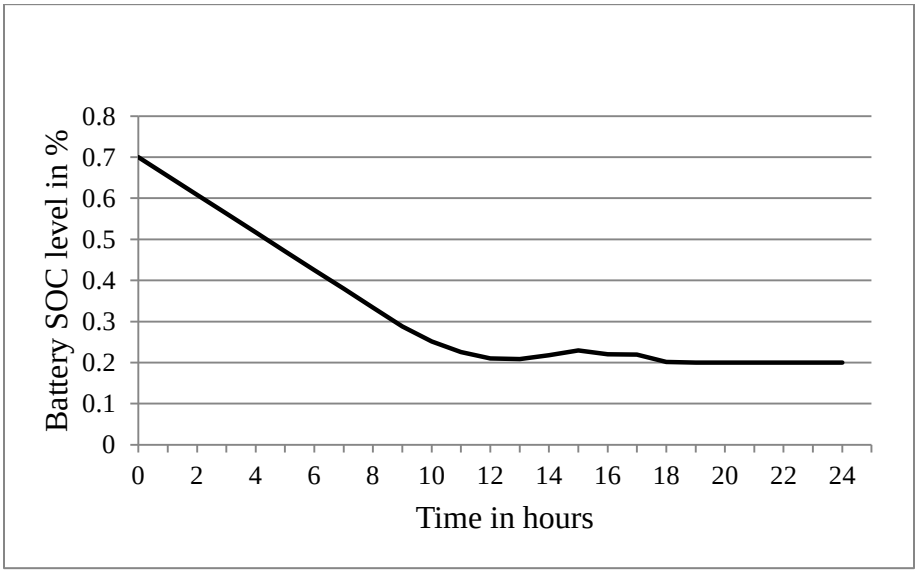


Fig.13. Battery SOC level for mix-mode operating strategy when battery initial SOC at 70% of 2,185.4 kWh

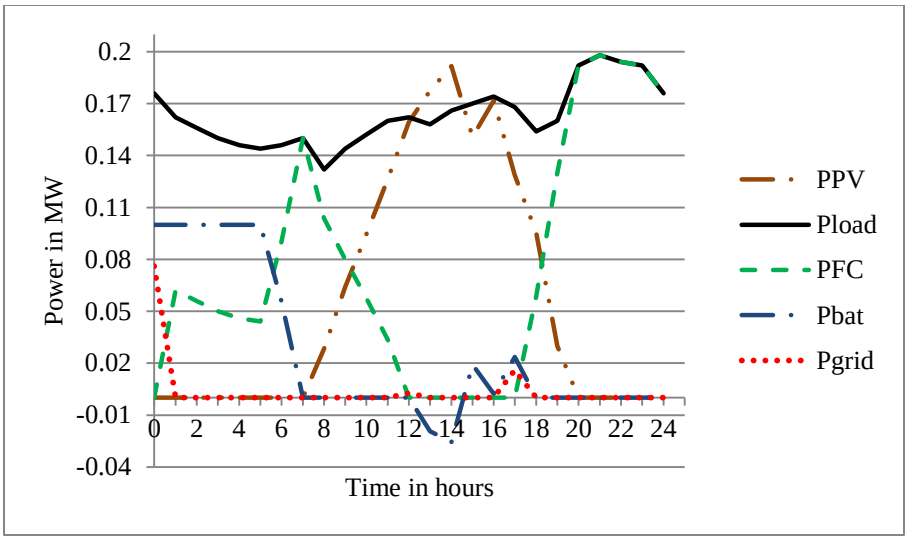


Fig.14 Optimal output of distributed source in microgrid for when battery initial SOC at 50% of 2,185.4 kWh

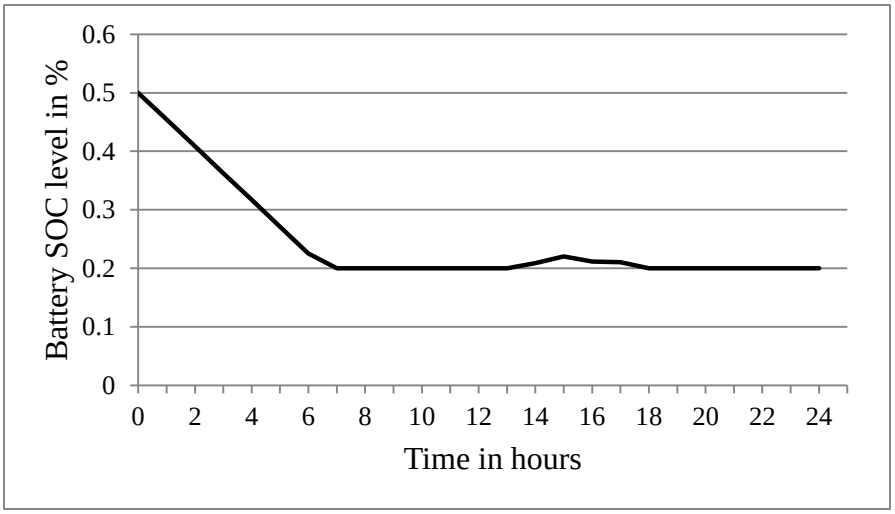


Fig.15. Battery SOC level for mix-mode operating strategy when battery initial SOC at 50% of 2,185.4 kWh

549 Table 4. Comparison of operating cost with and without battery case.

	With battery source			Without battery source
Optimal BES capacity (kWh)	2185.4			-
Battery initial SOC level	100%	70%	50%	-
Operating cost in ($/day)	978.8768	1,491	2,335.3	3,332
Fuel cell operating (hr)	13	14	18	20
Grid operating (hr)	2	2	3	3
Battery operating (hr)	22	18	10	-
Savings in operating cost in %	70%	55%	30%	-

550
551
552 Table 4 shows that if the battery source is optimal with higher initial SOC during the start of the
553 day, there is a significant reduction in microgrid's operating cost. Moreover, the fuel cell
554 operating hours will also be reduced, which will increase its calendar life. During the microgrid
555 mix-mode operation, the utility grid operating hours is lower as the power purchase cost from the
556 utility grid is very high.
557 From the discussions, it can be concluded that,
558 (i) Operating the microgrid under the proposed mix-mode operating strategy can effectively
559 reduce the its operating cost.
560 (ii) Including battery source in the microgrid will reduce the daily operating cost.
561 (iii) Installing optimal battery capacity with higher initial SOC is highly recommended because
562 the optimal battery capacity with higher initial SOC will reduce the daily operating cost with
563 lowest battery's capital cost.
564 (iv) Installing battery capacity with higher initial SOC reduces fuel cell and utility grid operating
565 hours.
566 There is no recommendation found in literature on settings of the initial battery SOC level for
567 microgrid operation. Based on the results depicted in Fig.8 and Table 3 it is highly recommended
568 that the battery capacity with higher initial SOC be used during the start of the day. This will

reduce the microgrid's operating cost with less battery capital cost, which is the battery's TCPD. When there is no possibility of battery charging during the start of the day's operation, it is highly recommended that the initial SOC of the battery be set to 100%. If there are any possible charging events, then the battery initial SOC can be set to 90% - 95%.

5.5 Analysis on variation of microgrid's operating cost considering uncertainty in PV output power

Output power from the solar PV plant is uncertain and relies on solar radiation, which is intermittent in nature. As a result of this, considerable effect in microgrid's operating cost and battery source operation can be found. Therefore, in this section an analysis on variation of microgrid's operating cost and battery source operation is carried out for changes in the PV output power. In this analysis, the energy capacity of the lead-acid battery source, evaluated in Section 5.4.2 for the initial SOC level of 100%, is considered. Hence, the energy capacity of the battery source considered for this analysis is 2,185.4 kWh, and the initial SOC level during the start of the day is set to 100% as recommended in Section 5.4.2.

The optimal battery capacity of 2,185.4 kWh is evaluated for a particular PV output power pattern. This analysis is carried out to study the variation of microgrid's operating cost and battery source operation when the PV output power changes. Two PV output power patterns, (i) PV output power from the solar plant during winter and (ii) PV output power from the solar plant during summer are considered for the study.

Results in Fig.16 shows the optimal dispatch values of the distributed sources in the microgrid for a day in winter, with its corresponding battery SOC level plotted in Fig.17.

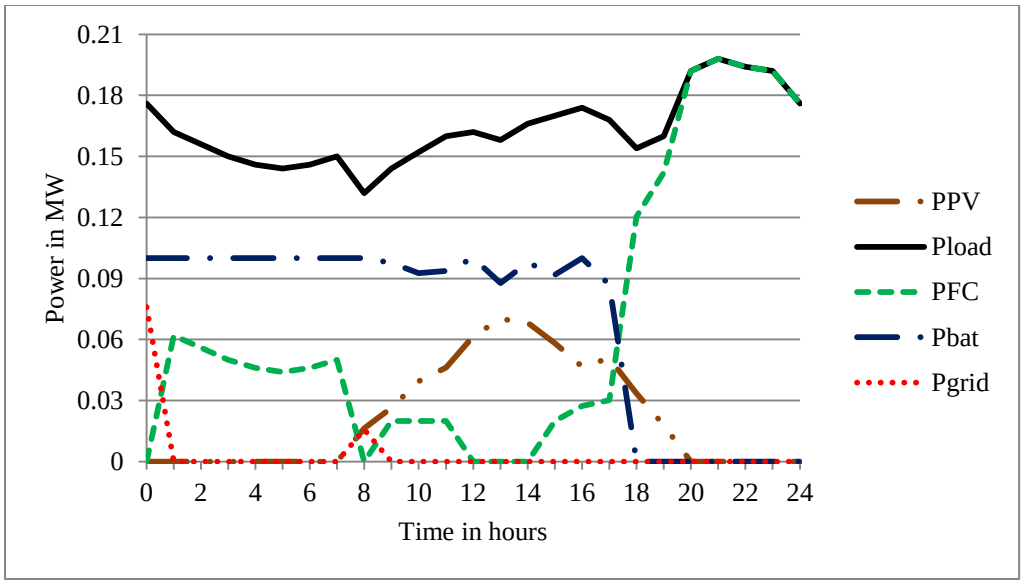


Fig.16 Optimal output of distributed source in microgrid during a day in winter

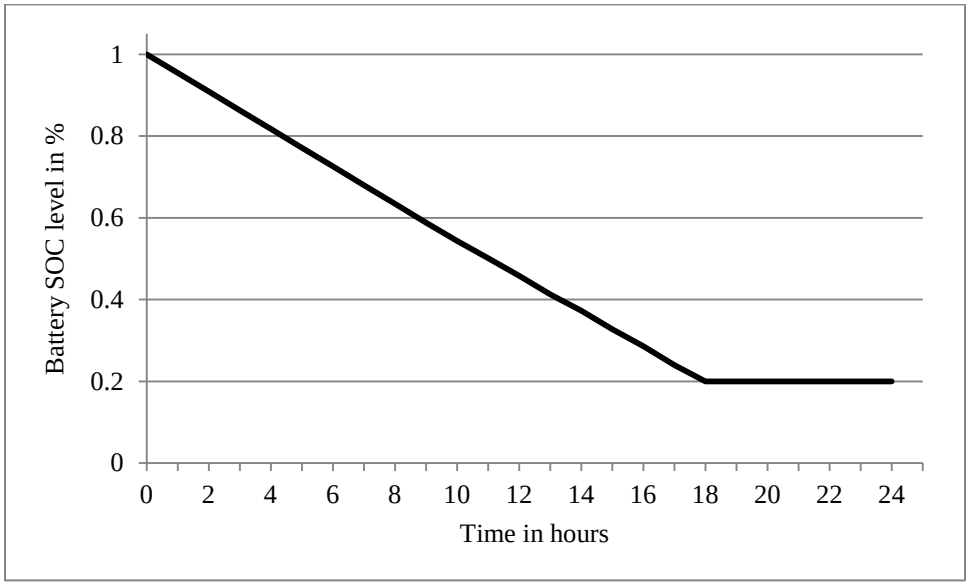
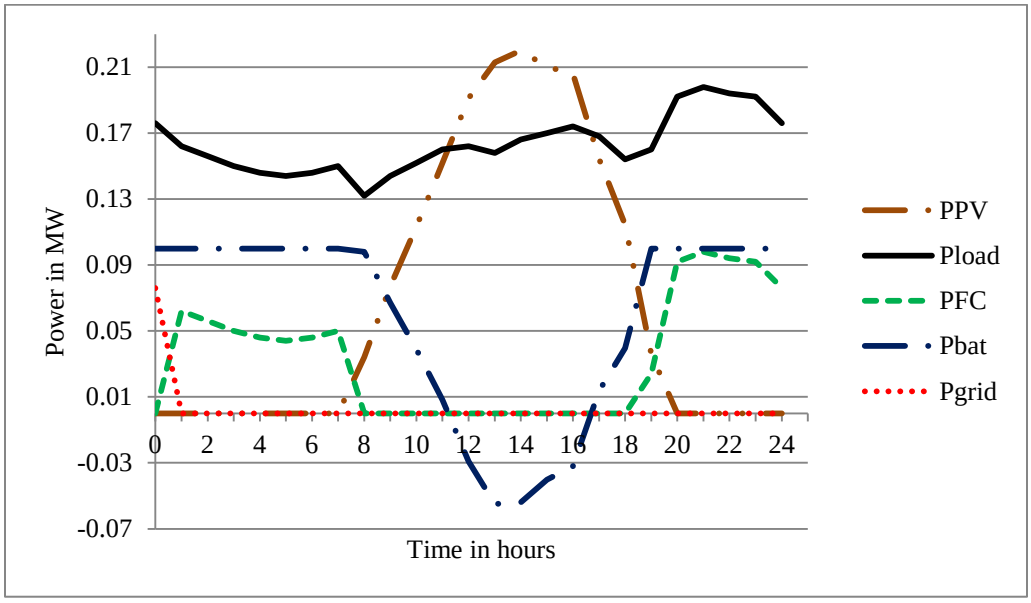


Fig.17 Battery SOC level for a day in winter

During the early morning hour that is before the sun-rise, the power to the load is managed by the battery source, fuel cell, and the utility grid. The utility grid is utilized because the power drawn from the utility grid is cheap in morning hours. During the day hours, the power to the varying load is managed by PV output power, battery, and fuel cell. Since the PV output power is less during the winter, the battery source is forced to discharge in-order to manage the load

599 demand. It is also evident from Fig.16, that the fuel cell dispatches power for few hours during
600 the day to manage power to the load demand. During these hours, the power drawn from the
601 utility grid is kept at zero, considering its cost. Since the power from the battery is cheap, it is
602 utilized most of the time during the day, and since the PV output power is less than the load,
603 there are no battery charging instances. During evening hours, the battery power is unavailable
604 because the SOC level has reached its minimum level due to the fact that the battery source is
605 effectively utilized during the day hours. Therefore, during evening hours, fuel cell is effectively
606 utilized to supply power to varying load demand. As a result of this, both the fuel cell units are
607 switched ON to supply the varying load. The power from the utility grid is kept at zero due to the
608 cost of power produced from the fuel cell is being less compared to the power drawn from the
609 utility grid.
610 Fig.18 and Fig.19 are the optimal dispatch values of microgrid's sources and battery SOC level
611 for a day in summer respectively.



612

613 Fig.18 Optimal output of distributed source in microgrid during a day in summer

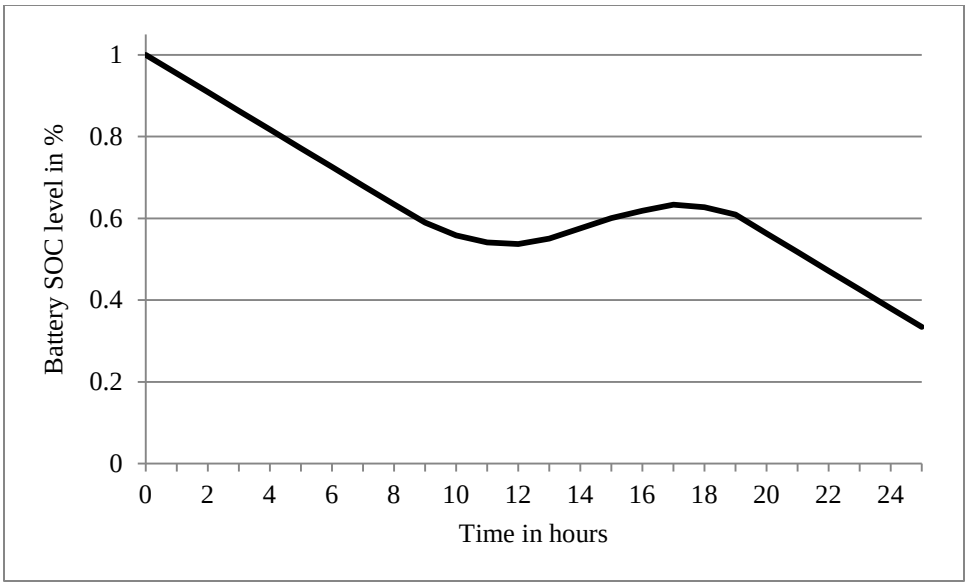


Fig.19 Battery SOC level for a day in summer

During the early morning hours, the load demand is supplied by the power from utility grid, battery source, and fuel cell. The utility grid is utilized because the power drawn from the utility grid is cheap during the morning hours. During the day, when PV power is available, the battery source is effectively managed in order to supply power to the load demand. The power from the PV plant is high during the summer, and there are instances where the PV output power exceeded the load demand. As a result of this, during these instances, the battery source operates in the charging mode. During the day, since the availability of the PV power is high, the power drawn from the utility grid and fuel cell is zero, and as a result of this, the fuel cell operating hours is reduced. During the evening hours, the varying load demand is supplied by the battery source and fuel cell. Since the battery source is charged for few hours during the day, it is effectively utilized to supply power during the evening hours. As a result of this, only one fuel cell unit is utilized to manage the load demand. During the evening hours, the power drawn from the utility grid is zero.

A comparison on microgrid's operating cost and microgrid sources operating hours are presented in Table 5 for a day for both winter and summer seasons.

Table 5. Comparison of microgrid's operating cost and microgrid sources operating hours

Optimal BES capacity (kWh)	2185.4	
Battery initial SOC level	100%	
	Winter	Summer
Operating cost in ($/day)	2,413.630	925.510
Fuel cell operating (hr)	20	13
Grid operating (hr)	2	1
Battery operating (hr)	17	20

It can be noticed that the microgrid's operating cost is very much reduced during the day in the summer compared to winter. This is due to the availability of PV power during the day of summer. During the summer, the availability of PV output power is more and the large amount of load demand during the day hours is taken care of by the power from the PV plant. Simultaneously, there are instances of battery charging during the day time when the PV output power exceeded the load demand. As a result of this, the charged battery power is effectively utilized during the evening hours, which reduces the microgrid's operating cost for the day in summer. Due to this reason the battery operating hours is increased to 20h during the day in summer. Since the battery power is available for longer hours, it eventually contributes to the reduction in utility grid and fuel cell operating hours, and the utility grid and fuel cell operates for 1h and 13h, respectively, during the day in summer.

On the other hand, the output power from the PV plant is lesser during winter, and the battery source is effectively utilized during the day hours to supply power to the varying load demand. Since the power from the PV plant is lesser than the load demand, there are no charging instances for battery source. As a result of this, the battery source is unavailable during the evening hours. Therefore, the battery source's operating hours is reduced to 17h. In order to

supply power to the load during the evening hours, both the units of fuel cell were forced to supply power to the varying load demand. Since the availability of battery source is less in the winter, the fuel cell and utility grid's operating hours increased to 20h and 2h, respectively. As a result of this, the microgrid's operating cost is increased to $ 2,413.63/day during the day of the winter.

6. Conclusion

In this paper, a mix-mode energy management strategy (MM-EMS) for operating the microgrid at the lowest operating cost and optimal battery sizing method for economic microgrid operation is presented. The mix-mode operating strategy is worked out by solving economic dispatch problem for three proposed strategies, namely continuous run mode, power sharing mode, and ON/OFF mode. Linear programming and mixed integer linear programming optimization techniques were used to solve the energy management problem. With this, a method to find optimal battery size for the microgrid operating under mix-mode strategy was also presented. The battery sizing problem was solved using the PSO optimization technique. The battery's capital cost, its energy and power constraints, and distributed generator's operational limits were taken into account while solving this problem.

Compared to other operating strategies, operating the microgrid under mix-mode operating strategy would eventually reduce the microgrid's daily operating cost. Moreover, the proposed battery sizing method was highly accurate in determining the optimal size of battery energy storage for economic operation of the microgrid. The variation of the optimal battery capacity with different sets of initial SOC levels was analyzed, and based on the analysis, it was found that the optimal battery capacity increased as we selected lower initial SOC levels during the start of the day. It was also found that the optimal battery capacity with higher initial SOC level

reduced the microgrid's operating cost effectively with lower battery initial cost. Furthermore, variation to the microgrid's operating cost against different SOC levels was analyzed. It was found that as the initial SOC level during the start of the day was reduced, a significant reduction in savings in the microgrid's operating cost became evident. Based on the results, a recommendation on the choice of initial SOC level during the start of the day for an economical operation of a microgrid was suggested. Finally, an analysis on variation of microgrid's operating cost considering uncertainty in PV output power was carried out. It was found that the availability of PV power from solar photovoltaic plant influenced the microgrid's operating cost and battery source's operation.

Acknowledgements

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