Smart Hybrid AC-DC Microgrid Test-bed for Power System Studies & Restructuring Laboratory - Part II

M. R. Barazesh, M.A. Zangiabadi, Alireza Rezaei,
S. Mojtaba Hosseini, Hossein Javidi D.B.
Power System Studies & Restructuring Lab
PSRES Lab,
Mashhad, Iran

Maria Rashki
Science based Company of Sunflower Industrial research
SIRCo
Mashhad, Iran

***Abstract*—Laboratory-scale microgrid of Power System Studies and Restructuring Lab. (PSRES Lab.) could be operated in both grid-connected and islanded modes. The objective of the operation problem in grid-connected mode is to maximize profit as well as reducing battery life depreciation. This problem is simulated in GAMS to evaluate its effectiveness. Simulation results highlighted the effect of preserving battery lifetime on optimal operation schedule, where energy exchange between microgrid and the grid is significantly limited.**

Keywords—Operation and Control; Microgrid test-bed; island mode; grid-connected.

I. INTRODUCTION

Microgrids are small scale systems located near the end user which can be operated in both islanded and connected modes to the main grid. Microgrid implementation provides fundamental advantages for both utility and end user. In some cases, where there is no access to the main grid, the microgrid is the only supply source of electricity and is operated in islanded mode. In cases where the access to the main grid is possible, microgrids provide benefits such as reliability improvements due to protection of consumers against power outages, improving local energy delivery, making the grid more resilient, helping to reduce the emissions of CO2 and counter climate change due to integrating renewable energy resources and so on.

Microgrid operation is inherently a difficult and complex optimization problem due to stochastic behavior of microgrid components such as renewable resources and loads. The Energy Management System (EMS) of the microgrid should be able to maintain power balance as well as satisfying other requirements such as flexibility, reliability and operation cost reduction. Typically, most EMS systems are centralized which use hierarchical control strategy. In [1] the energy management problem is solved using bi-level optimization. The upper level presents the optimization to submit optimal bids to the market and the optimal scheduling is handled in the lower level problem. In [2], operation of central controller of the microgrid were presented considering different market policies. The design of a centralized control strategy for stand-alone microgrids are discussed in [3]. Also, some test protocols have been proposed to analyze the performance of the system. The status of hierarchical control strategies applied to microgrids are reviewed in [4].

A. Operation modes of the microgrid

Microgrids with access to the main grid, are operated through two following operating conditions.

Normal Interconnected Mode: the microgrid is connected to the main grid either being supplied by the grid or injecting energy to it.

Grid-fault Mode: the microgrid operates autonomously when the upper grid become unavailable due to faults.

The fundamental roles of the microgrid control structure are as follows [5]:

- Voltage and frequency regulation in both operation modes
- Proper load sharing and DG coordination
- Resynchronization of the microgrid with the main grid
- Power flow control between the microgrid and the macro grid
- Optimizing operating cost of the microgrid
- Handling transients and restoration when switching between modes

In islanded mode, microgrid dynamics will be strongly dependent on the connected sources and also on the power regulation control of the converter interfaces [6]. Different methods of islanding detection have been proposed by many researchers [7], [8]. A control strategy for islanded mode of microgrid operation over voltage, frequency and protection is defined in [9] and [10].

The hierarchical control strategy (Fig.1) of microgrids consists of three levels:

- Primary control which includes:
    - Voltage stability provision
    - Frequency stability preserving

  - Plug and play capability of DGs
  - Circulating current avoidance among DGs
- Secondary control which considers:
  - Compensating the voltage deviation caused by primary control
  - Compensating the frequency deviation caused by primary control
- Tertiary Control which focuses on:
  - Optimal operation in both operating modes
  - Power flow control in grid-tied mode

We initially present considerations about the microgrid structure such as placement of components and switches, enabling it to operate in both above mentioned modes. Then The operation model formulation and simulation results are presented.

II. PSRES LAB. MICROGRID OPERATION MODES

The Smart AC-DC PSRES Lab micro-grid shown in Fig.2, is operated in both grid-connected and isolated operation modes.

The single-line diagram of the PSRES Lab micro-grid in the grid-connected mode is illustrated in (Fig.3). In this mode, the switches S1 and S2 are closed and the inverter is disconnected from the AC bus by opening the S3 switch. In this operation mode, only the grid feeds the AC bus and is responsible for the power balance and voltage stability. The SMPS links the DC bus to the power grid and is responsible for the control of DC bus voltage and maintaining the balance of production and consumption. The power balance in the DC bus is met by controlling the current injected to the batteries and the DC Load through a signal sent by the micro-grid control unit to the SMPS. The operation strategy of the DC bus in this mode is to utilize maximum PV power production in meeting the DC load and battery needs and the grid supports solar lack of production. Because the power grid can supply the lack of production of the PV panels, the demand dispatch unit allows maximum power demand to be supplied. This means the smart lighting system can set the LEDs to maximum illumination and all the smart outlets can supply the AC loads of the AC bus. In the grid connected mode, all the electricity demand can be supplied either from electricity grid or microgrid. The illumination of the laboratory in the presence of designed LED lamps is examined by means of DIALux software. It should be noted that, all the LED lamps are designed and built by the members of SIRCo and PSRES Lab. Each lamp consists of 6 LED branches, three series branches of two parallel LEDs, consuming 26W with the total luminous flux of 3200 lumens.

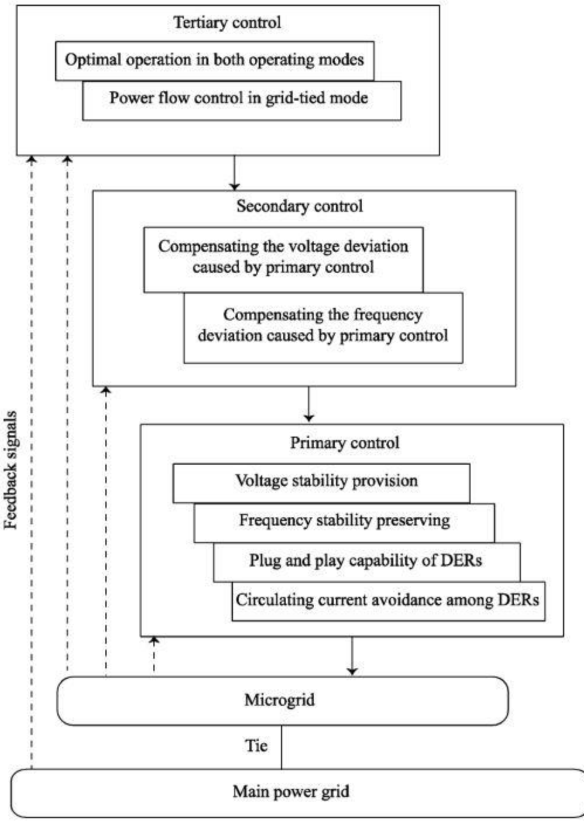

Fig.1: hierarchical control levels of a microgrid [4].

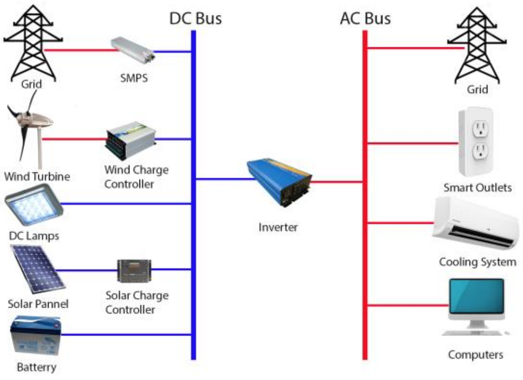

Fig.2: Microgrid structure

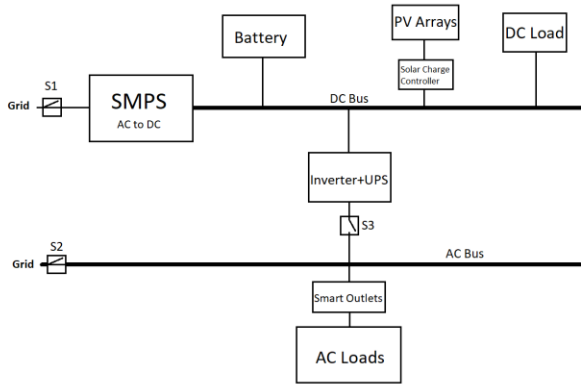

Fig. 3: Grid-connected mode of operation in PSRES Lab. Smart AC-DC microgrid system

The illuminance isolines of the laboratory which is calculated in DIALux is shown in Fig.4. Based on the illumination standard by the national illumination committee of Iran [11] and [12], the proper amount for lab usage is 500lux which is easily provided by using designed lamps.

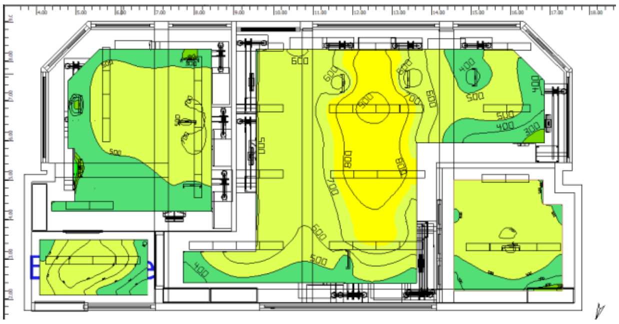

Fig.4: Illuminance isolines of the laboratory

TABLE I. OUTPUT OF THE DIALUX SOFTWARE

Test Positions	Avg.(Lux)	Min/Avg.	Min/Max
1	672	0.63	0.52
2	588	0.42	0.27
3	743	0.38	0.26
4	667	0.4	0.31

Three remarkable indices that specify the illuminance of the laboratory, are shown in Table I. These indices prove that the illumination of the laboratory satisfies the national and international standards and is proper for the laboratory.

In islanded mode of operation, the micro grid opens the S1 and S2 switches as shown in (Fig.5). The UPS module automatically triggers the inverter to turn on and closes the S3 switch to supply the Ac power demand. Since the demand in AC bus is more than the energy stored in the batteries and PV production, the demand dispatch unit forces the smart outlets to curtail some of the unnecessary loads like air conditioning system, refrigerator, tea maker, coffee maker, printers and scanners. In this mode, the demand dispatch unit also signals the smart lighting to dim or turn off the LEDs and reduces their power consumption to half of its maximum value. The UPS function of the power inverter also warns the monitoring system that the micro grid is in islanded mode. This function notifies the lab members to wrap up their important works on their computers and save their data in case of possible micro grid blackout during the night hours. Applying this demand response scheme insures safe operation of the micro grid.

As expressed above, only a fraction of demand can be supplied in islanded mode. In this project, less than half of the LED lamps are considered to be turned on as the emergency lighting, regarding the capacity of supply. Emergency lamps (the lamps that are kept on in islanded mode) are chosen by simulating multiple scenarios in DIALux. There are 15 LED lamps in the main hall of the laboratory, 7 of which can remain on. Among all the possible scenarios, three scenarios provide better illumination comparing to others. The position of turned on lamps in these scenarios and corresponding illumination factors are expressed in the Fig.6 and Table II.

In future expansion of the PSRES lab micro grid, more renewable energy production like wind power turbines will be added, thus the microgrid would be able to feed energy into the main grid and perhaps gain revenue. Furthermore, the available

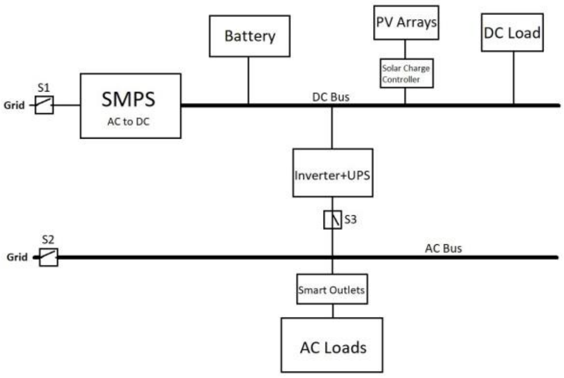

Fig. 5: Islanded mode of operation in PSRES Lab. Smart AC-DC microgrid system

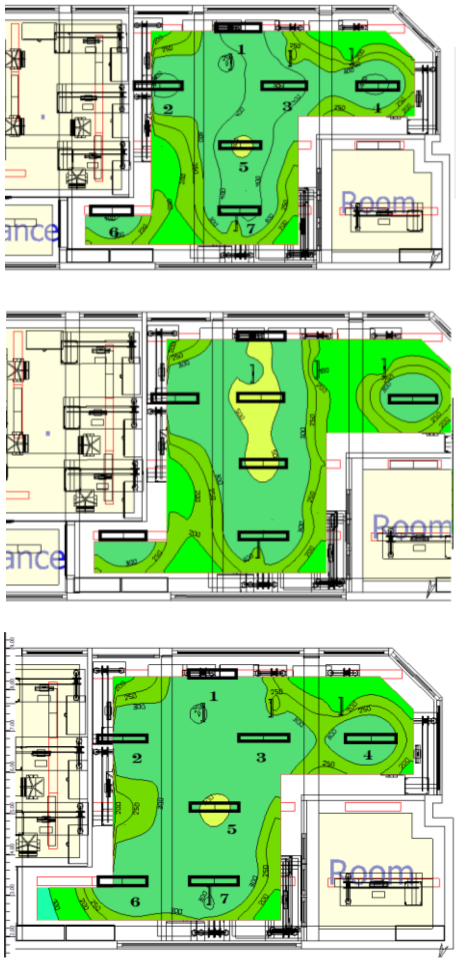

Fig. 6: Position of LEDs in best lighting scenarios, islanded mode

TABLE II. RESULTS OF BEST LIGHTING SCENARIOS IN ISLANDED MODE

priority	Min/Max	Min/Ave	Ave (lux)
1	0.27	0.44	321
2	0.17	0.3	324
3	0.14	0.22	336

storage system can be utilized to store energy from the power grid in off-peak hours to make more income when the spot electricity prices are higher.

III. OPERATION AND CONTROL

In order to maintain the power balance of the microgrid in grid-connected mode, the battery current feedback is fed to the SMPS using PMBus protocol. In other words, the power balance of the microgrid is satisfied using PMBus specifications. The PMBus is an open standard protocol for power management purposes. it is a two-wire communication protocol based on I^{2}C allows the devices to communicate between themselves based on both analog or digital technologies (Fig. 7). As illustrated in Fig. 8, in the management controller unit, the battery power is compared with the reference power and fed to the SPMS. Then, the mismatch between the solar power, load demand and the battery power is fed back to the system to controlling the output power of the SMPS.

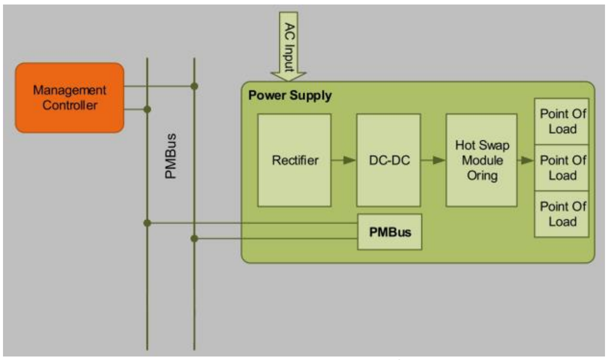

Fig. 7: The implemented control structure for the SMPS, based on PMBus protocol.

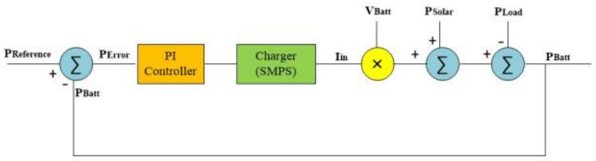

Fig. 8: The implemented management controller structure.

IV. MODEL

Two different operation objectives are considered in this paper.

- Case1: Maximizing Profit
- Case2: Maximizing both profit and battery life

Equation 1 shows the Case1 objective function, which is maximizing total profit only.

$$\max \quad Profit = \sum_t [P_{sell}(t) \times \pi_{sell} - P_{buy}(t) \times \pi_{buy}] \tag{1}$$

Equation 2 shows the formulation for Case1 objective function, which is maximizing total profit in addition to prolonging battery life.

$$\max \quad Profit = \sum_t [P_{sell}(t) \times \pi_{sell} - P_{buy}(t) \times \pi_{buy} - \alpha \left| P_{battery}(t) \right|] \tag{2}$$

Equations (3-9) show problem constraints.

$$s.t. \quad P_{sell}(t) - P_{buy}(t) + P_{battery}(t) = P_{PV}(t) - P_{demand}(t) \tag{3}$$

$$SOC(t) = SOC(t-1) + \frac{P_{battery}(t)}{C_{battery}} \quad \forall t > 1 \tag{4}$$

$$SOC(1) = SOC(24) + \frac{P_{battery}(1)}{C_{battery}} \tag{5}$$

$$\min_{SOC} \leq SOC(t) \leq \max_{SOC} \quad \forall t \tag{6}$$

$$-\alpha \times C_{battery} \leq P_{battery}(t) \leq \alpha \times C_{battery} \quad \forall t \tag{7}$$

$$0 \leq P_{Sell}(t) \leq P_{trans}^{\max} \quad \forall t \tag{8}$$

$$0 \leq P_{buy}(t) \leq P_{trans}^{\max} \quad \forall t \tag{9}$$

In each time period the generation and consumption should be balanced, meaning that when the energy generated by solar panels exceeds the load, the extra energy could be sold to the gird or used to charge the batteries. On the other hand, if the solar power generation does not suffice to meet the load, the remaining demand can be provided either by buying energy from the grid or by discharging the batteries. This strategy is formulated in power balance equation (eq (3)). SoC of the battery pack at the end of each time period is calculated based on the previous SoC and the amount of energy exchanged during that time, as formulated in equations (4) and (5). Equation (5) models the fact that the SoC in the first period depends on the last SoC of the previous day.

The life time of batteries vastly depend on their depth of discharge. In other words, the more the batteries discharge, the more their life time decreases. As a result, in many practical usages, the minimum allowed SoC is limited. In addition, maximum SoC shouldn’t be allowed to exceed one (100%). These limitations are considered in equation (6). Furthermore, the rate of charge and discharge of the batteries is limited and considered as a fraction of its capacity, as formulated in equation (7). Finally, equations (8) and (9) model the capacity limitation of the Point of Common Coupling (PCC).

V. RESULTS

A. Input data

The lighting load profile of PSRES lab. is obtained according to members presence schedule, depicted in fig (9). The lab’s lighting system consists of 26 rectangular LED panels, 10 of which are always ON during active hours. Each LED panel is connected to the 48 Volt DC bus and consumes 0.54 Amperes at maximum illumination, resulting in nominal power of each LED panel to be 25.92 Watts. The annual average PSRES lab solar power production for one day is shown in fig (10). The climate data is obtained from Meteonorm7 software for Mashhad.

The price for selling energy to the grid is considered to be 800 toman/kWh as announced by SATBA. The electricity purchasing price is used equal to the real Iranian distribution TOU tariff for first half of the year, detailed in Table 1.

Fig. 9: Typical lighting load profile of the PSRES Lab

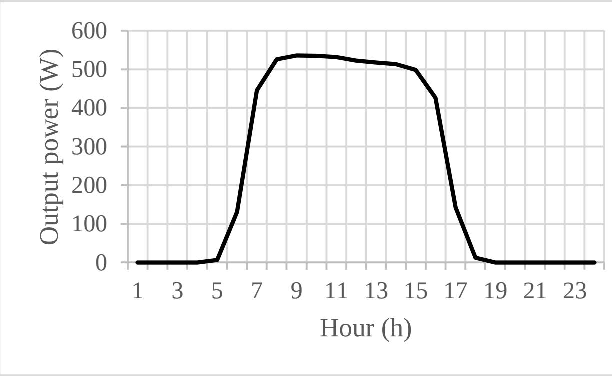

Fig. 10: Solar system hourly generation profile

The annual average PSRES lab solar power production for one day is shown in fig (9). The climate data is obtained from Meteonorm7 software for Mashhad.

Table III: Electricity Purchasing Price

Tariff	Price (toman/kWh)	hours
Peak load	90	19-23
Mid-load	45	7-79
Low-load	22.5	23-7

The coefficient for battery power in equation (2) is considered to be 100. Battery capacity is 4800 Wh. The minimum and maximum Allowed SoC are 0.5 (50%) and 0.95 (95%) respectively (eq 6). The rate of charge and discharge is considered to be 30% of the battery capacity (eq 7).

B. Simulation Results

The model is simulated for two cases separately and the results are compared.

1) Case1:

As mentioned before, this case represents the profit maximization objective, formulated in equation (1). Fig. 11 illustrates the SoC of the battery packs, in each hour. As expected, the batteries take energy from the grid during low-load hours that the electricity is cheapest. Furthermore, the excess solar generation is stored in the batteries during morning to afternoon, in order to be sold at higher price in the evening.

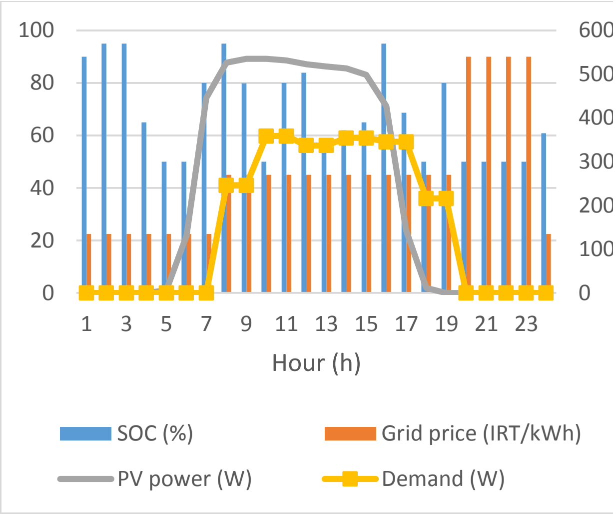

Fig. 11: SoC, Solar PV generation, Price and demand for Case 1

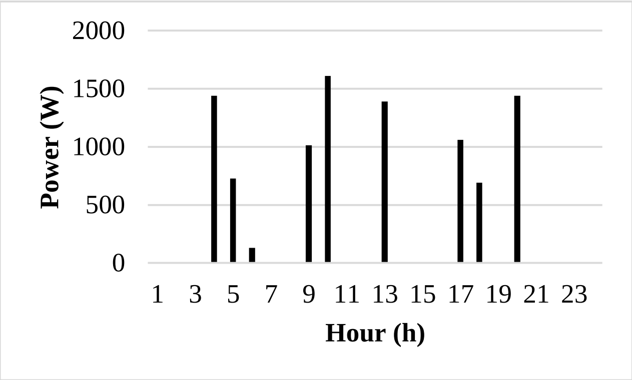

Fig. 12: Electricty sold to the grid in Case 1

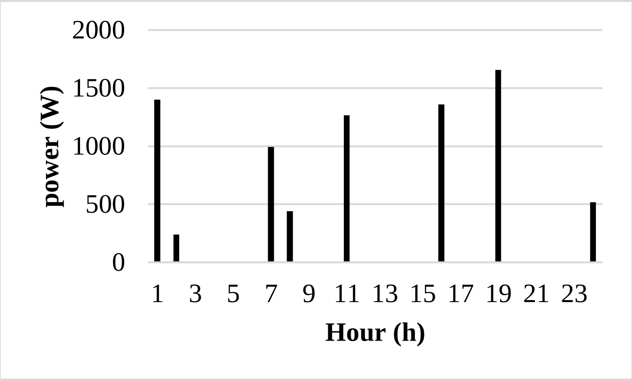

Fig. 13: Electricty purchased form the grid in Case 1

The amounts of electricity sold and purchased to the grid are depicted in Fig. 12 and Fig.13.

2) Case2:

In this case, the effect of battery life preservation on the optimal operation strategy and total profit is investigated. For this purpose, the total energy exchanged with the battery pack (charging and discharging) is subtracted from the objective function, acting as a penalty. The SoC of the battery packs, in

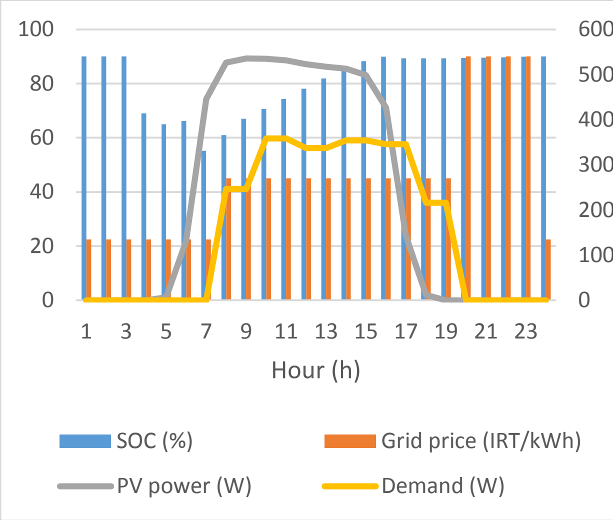

Fig. 14: SoC, Solar PV generation, Price and demand for Case 2

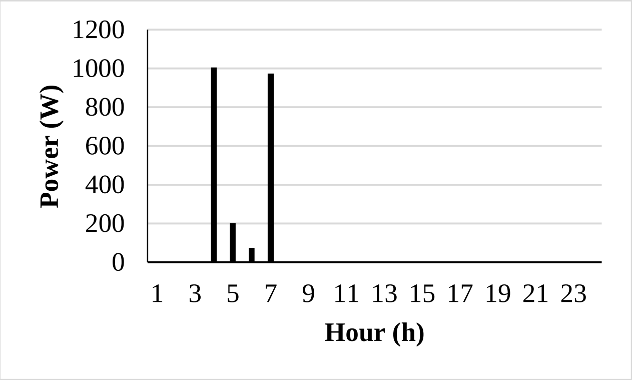

Fig. 15: Electricty sold to the grid in Case 2

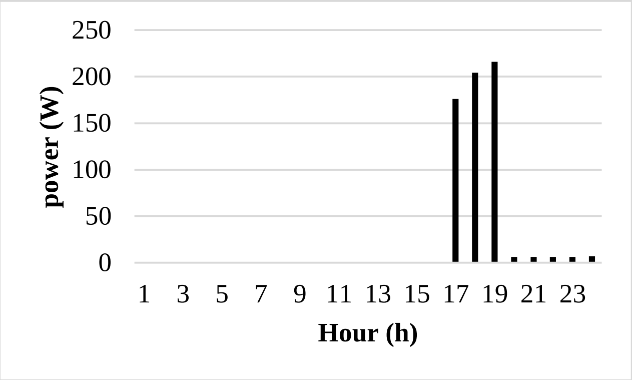

Fig. 16: Electricty purchased form the grid in Case 2

each hour, the amounts of electricity sold and purchased to the grid for second case are presented at Fig.14 to Fig.16.

As expected, considering preservation of battery life as a term in the objective function of the problem, results in preventing high variation of battery SoC, which is highlighted in Fig.14. Moreover, the amounts of sold and purchased energy exchanged between microgrid and main grid, is significantly reduced. In case 2, battery has been charged using PV generation without buying energy from the grid in comparison with case 1. As illustrated in Fig.14, solar PV generation is mostly consumed by battery in spite of selling to the grid.

VI. CONCLUSION

In this paper operation and control strategy of laboratory-scale microgrid of PSRES Lab. was presented. Considerations about the microgrid's structure such as placement of components and switches enabling the microgrid to be operated in both grid-connected and islanded modes were discussed. Furthermore, the operation model formulation and simulation results on two cases were presented. In first case maximization of the profit was placed as the only objective of the optimization problem. To show the impact of battery lifetime consideration on optimal operation schedule, we added a new case. In case 2, reducing battery life depreciation was added to objective function. The results show prevention of high variation of battery SoC and much lower energy exchange to grid.

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