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Development of prototype battery management system for PV system

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ABSTRACT

An energy and battery management systems (EMS/BMS) have a great importance in PV-battery system to increase the system efficiency and battery life. In this study, a prototype battery management system (BMS) has been designed and implemented for grid-connected residential-PV system with lithium-ion battery (LIB). Besides the main function of the all BMS which is to keep the LIBs within the safe-operation condition, by measuring/monitoring and controlling the battery parameters during the charge/discharge cycles, this designed BMS manages also the energy flow between PV system, battery, grid and load. In the designed BMS, there is a measuring unit (to measure current, voltage and temperatures), a control unit (to control the energy flows in the system), balancing circuit (capable of balancing in each of the four modules with 7LIB connected in series), the battery circuit (to fix the batteries well and measure the charge/discharge currents on the battery module).

The proposed prototype system includes the designed BMS, 400Wp PV modules, 18650 type lithium-ion batteries (LIB) block with a capacity of 353 Wh, the programmable 300 W electronic DC load for modelling the various load profiles by reducing the real home energy consumption by 1/15, 300 W power supply for supplying the energy from the grid and 24 V light bulbs for the sale of excess energy to the grid. For retired and working household power consumption profiles, various scenarios were created for 24-h power consumption on different days on weekdays/weekends to test the proposed prototype system. These scenarios were uploaded on the electronic load, the operation of the designed battery and energy management system was tested with these experiments by using proposed prototype set-up. The battery management system ensured that the batteries operate in safe working conditions. Due to the energy management function of BMS, when the PV-batteries system is not sufficient, the energy will be taken from the grid; when the PVs charged batteries fully, the excess energy will be sold to the grid. Therefore, the designed prototype system, providing a flexible manner with various load profiles, will be useful tool in the investigation of the optimum conditions for a grid connected PV-battery system designed.

1. Introduction

Lithium-ion batteries are widely used in electric vehicles/hybrid electric vehicles and also energy storage systems due to their advantages, such as higher energy and power density, lower self-discharge rate [1]. Benefit from the rapid development of the electric vehicles, the lithium-ion battery is the fastest evolving of all existing chemical and physical energy storage solutions [2]. However, LIBs are easily affected by both environmental and working conditions, and its lifecycle is significantly reduced as a result of misuses. Serious safety problems arise when such battery isn't used in the appropriate working frame, especially in hot and cold conditions [3]. The indigent tracking and controlling of LIB systems can end up with quick and irreversible deteriorations, significant performance reductions, and even worse catastrophic accidents [4]. In recent years, fire accidents caused by batteries of electric vehicles have increased the requirements for management technologies [5].

When working with LIBs, a management system that will enable the batteries to work effectively and efficiently is of great importance. Management system that ensures safe and durable operation of the battery under appropriate operating conditions by using temperature, current, voltage and load information. In the

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literature, such management system is called battery management system (BMS). The battery management system; monitors and controls the charging/discharging process, ensuring optimum use of the energy in the battery and preventing damage to the battery [6–8]. Battery management system (BMS) is crucial to the industrialization and marketization of LIBs and advancing improved and smart BMSs for LIBs has become a current research topic [9].

When the recent studies of LIBs are examined in the literature, studies on BMS have increased even more [10–20]. Studies on the effects of temperature, voltage, charging/discharging current and aging on battery performance have been conducted in order to increase the performance of lithium-ion batteries [13–17]. Exclusively, the effects of over-charging/discharging, over-current and high/low temperature conditions effects on batteries have been investigated [15–17]. On the other hand, most of the studies on BMS are for electric vehicle (EV) and hybrid electric vehicles (HEV) recently [18–24]. Chen et al. reviewed on EVs fast charger designs and also discussed the thermal management issues about the these charging methodology [18]. Kabir et al. [19] examined the battery management system for unmanned vehicles, emphasizing that if the battery management system becomes widespread in these types of vehicles, the logistics sector will make significant progress. In the joint study of Infenion company with Essen University [20] the BMS, which has active balancing, designed for electric vehicles, was tested on 12 serially connected LIBs. As a result of this study, it has been claimed that the useable capacity of each battery increases, and therefore the driving range of the EVs can increase by using the developed BMS. Delphi firm tried to find the most suitable balancing method for the BMS [21]. Z. B. Omariba et al., inspected the different balancing methodologies for LIBs, and appraised their relationship with battery performance [22]. CENS Energy-Tech Co. Ltd and Harbin University of Science and Technology on instantaneous capacity calculation methods for lithium-ion batteries [23]. R. Sreedhar et al., suggested the design and simulation of common BMS for EV applications with four different batteries namely Nickel-Metal-Hydride, Ni–Ca, Li-ion and Lead-Acid. This proposed BMS, can continuously monitor the battery parameters with high accuracy, especially in SoC measurement [24].

The use of batteries with renewable energy resources has gained speed in order to ensure that these resources can be connected to the grid properly and meet the needs of the consumer. Especially in the grid-connected PV-battery systems, an appropriate energy management system and an efficient battery management system for batteries are required to meet the energy needs of households, which have a large share in the energy consumption pie [25]. Concerning the PV systems, energy storage with battery accounts for a large proportion of the cost in systems. Increasing electricity prices and the expected decrease in battery prices suggest that energy storage could be a profitable option in the near future. A recent study has revealed that lithium-ion batteries will provide the best economies compared with lead-acid batteries and flow batteries if battery ageing is considered [26]. The method of use of the battery varies according to the usage pattern and operating conditions of the system. For example, the battery block designed for an EV cannot be used for PV systems, as their operating and environmental conditions are different from each other. BMS designed for a battery/battery block is specific to that system [27].

In the literature, it is seen that the studies on BMS/EMS design for PV-systems are generally modelling and simulation studies [28–33]. There are a few experimental studies for PV-batteries system [34–37]. Huang et al. aimed to design a battery charging control system for stand-alone solar PV-battery system. In their study, with PV module (85 Wp), lead-acid battery (12 V/38 Ah), and an 18 W LED as the load for lighting at night, improved control system was tested. While the solar irradiation is abruptly changed from 337 to 843 W/m^2, the system could suppress battery voltage overshoot within 0.1 V. In this way, overcharging of the batteries is prevented and heavy-duty operation of the batteries is ensured [34]. Haq et al., suggested a BMS with features such as data acquisition, safety protection, determination and prediction the state of charge (SOC), and the ability to control the charging and discharging for lithium ferro phosphate (LFP) type batteries. But in this study, LFP batteries were charged with a DC power source and discharged with a dummy load on a level with very low current like 0.05C [35]. Bogno et al., carried out a detailed analysis based on experimental result with off-grid PV battery system for the health and for the quality of charge of batteries. The experimental work was performed with a battery (24 V-55 Ah) charged by a 175Wp PV module, through a Maximum-Power-Point-Tracking/Three-Stage-Charging-Cycle (MPPT/TSCC) charge controller. In their study, lead-acid type batteries, which are much more resistant than lithium-ion batteries, were used and BMS was developed for only charging this type of batteries. They offer that, their proposed method provides safety, longevity, and performance of lead-acid batteries and this solution can keep lead-acid batteries up to be a preferred storage solution for off-grid PV systems [36]. Torres-Moreno et al., proposed a novel strategy which is a rule-based controller managing the power flows between the grid and the batteries of both the PV system and the electric vehicle. load demanded by a laboratory during standard working days. Through experimental data and simulations, this strategy was tested under different scenarios. The selected testbed consisted of the laboratory of a research centre, which could be easily scalable to the entire building. Results showed the benefits of using an electric vehicle as an active agent in energy balance, leading to a reduction of the energetic costs of a micro-grid [37].

In our study, an energy and battery management system, has been designed and implemented for the prototype battery-PV system as if grid-connected that can meet the real home consumption reduced by 1/15 ratio, in Ankara climate condition. For the real home consumption; the actual consumption of all electrical devices has been measured carefully and 24-h load profiles have been created as 15-min strings. Then these real profiles have been reduced at a specified rate (1/15) per day to obtain the load profiles for programmable electronic load (Chroma 63004-150-60). Designed battery management system has been tested with various scenarios having different energy consumption profiles for different days on the proposed prototype PV system. This proposed prototype experimental set-up consists of programmable DC electronic load to create various load profiles, PV panels connected in series/parallel, battery block consisting of 18650 type lithium-ion batteries, DC power supply providing supply from the grid and dummy load that enables the sale of excess energy to the grid [38].

Considering and comparing the experimental studies in the literature with our study, in the literature; actual household consumption with 24-h real data evaluation is not considered as load. Various load profiles and also numerous charging/discharging scenarios are not evaluated. There is no study with grid buying and selling expectation together and also detailed experimental study obtained in various climate conditions. So, our study has novelty as prototype BMS/EMS that provide flexibility to investigate the optimum design of various PV module and battery combinations for different load profiles and to obtain optimum conditions for grid-connected battery-PV system design and energy flow by using 24-h real-time data.

2. Methodology

Block diagram of BMS and prototype test system are given in Fig. 1. As seen in this figure, whole system consisted of;

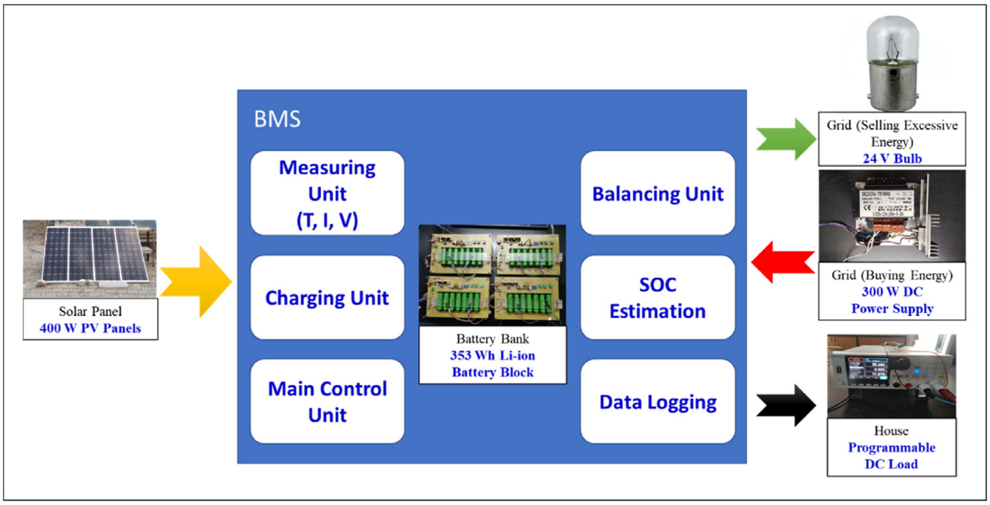

Fig. 1. Block diagram of BMS and prototype test system.

- 400Wp PV modules,
- battery pack (connected as 7 series 4 parallel block) with 353 Wh (25,2 V, 14 Ah) capacity,
- 300 W power supply and dummy load to get power from the grid and to sale the excess energy to the grid respectively,
- a programmable electronic DC load to simulate the load profile of household consumption by the ratio of 1/15 of the real consumption,
- designed BMS includes measuring unit (to measure and monitor the total voltage, the current and indoor/outdoor temperature), main control unit (to control all energy flow between PV system, batteries, household loads and grid), charging unit (DC/DC converter used as a battery charging circuit), balancing circuit (to measure voltage of each LIB in battery block, charging/discharging current and temperature of battery module and also to keep the batteries in safety conditions).

In line with studies [39,40], it can be assumed that daily average electricity consumption amount of a family house with 3 people in Ankara that uses natural gas energy for heating (does not use electrical appliances for it) will be between 7 and 8 kWh. It is presumed that the average daily power consumption of the house, used in the design, is 7000 Wh [38]. Since whole system has been designed as a prototype in this study, the diminished value of 1/15 of the actual average consumption is taken as ~470 Wh. The day/night time consumption distinction is considered when deciding the size of the PV modules and the battery block.

PV modules are placed in Hacettepe University Beytepe Campus and for this region, using the PVGIS (Photovoltaic Geographical Information System) interface [41], when the slope angle is 37° and the azimuth angle is 0°, the monthly solar radiation amounts are determined in this study [38]. The size of the PV system was decided according to the month of January when the irradiation level was worst with 70.33 kWh/m^2 as being 400 Wp.

In the assessment made for the daily energy consumption of the household given in Ref. [38], it is seen that there is a distribution of; 40% during daylight hours, 60% during the night hours. According to this; approximately 280 Wh of the average energy consumption during the day is spent at night and the remaining 187 Wh is consumed during the day. By taking the DoD ratio 80%, the battery block, is expected to be at least 350 Wh to meet the average energy consumption during the night. LG MJ1 brand 18650 LIB was used in this study and in order to provide energy at the specified 350 Wh capacity, 28 of these LIBs must be used. The battery block consists of 4 battery modules connected in parallel, and each battery module has 7 serial connected 18650- LIBs.

In order to test the designed BMS for the PV-battery system, 24-h load profiles were created for both weekdays and weekends, realizing 1/15 of the real energy consumption of the house where retired and working people live. Named *Retired_profile* and *Working_profile* easily can be uploaded on the programmable electronic DC load, to understand the differences between human habits of energy consumption.

Concerning the aim of designed system in Fig. 1, it is expected that the battery block and PV system, determined for the reduced home consumption, will be sufficient, but on days when irradiation level is not enough and/or consumption is above average, the PV and battery system will not be sufficient to meet the household power consumption. In this case, the required energy will be taken from the grid, batteries will be charged and energy needs of house will be met through the batteries. An algorithm developed in this study to provide precise energy flow for the main circuit is given in Table 1.

2.1. The designed BMS

For a well-designed BMS, it is expected to have main functions such as keeping the batteries within the safe-operation conditions, monitoring and controlling charging/discharging process, preventing any damage to the batteries and also having alert function, when malfunctions are detected. In this study, a BMS has been implemented by considering all functions mentioned above, additionally to have the function of controlling the energy flow within the whole system.

The detailed block diagram of the designed BMS has been given in Fig. 2, including all sub-components and also considering the all connections to proposed prototype PV-battery system.

As seen in upper part of Fig. 2, designed BMS consist of 4 slave circuits. Each slave circuit has two circuits, balancing and battery circuit. In the balancing circuit, Arduino Uno, which has an ATmega328 P processor as a microcontroller, was chosen. The developed control algorithm is uploaded into this processor which fulfils all functions of the slave circuit. Hereby each slave circuit measures the voltage of each battery, the charge/discharge current; balances each battery with passive balancing method, measures

Table 1
Energy flow of the main circuit.

No.	Condition	Direction of Energy Flow
1	**Batteries empty,** -Sufficient energy is obtained from PV system, -PV system charges the batteries and meets the needs of the household load.	**PV⇨ Batteries ⇨ Load**
2	**Batteries full**, -PV system can generate more energy than the needs of the household load, -PV system meets the needs of the household load, and the excess energy generated is consumed on dummy load as if selling it to the grid.	**PV⇨ Batteries ⇨ Load + Grid (selling)**
3	**Batteries empty,** -Energy cannot be obtained from PV system, -DC power supply feeds the batteries as if taking energy from the grids, - DC power supply (grid) both meets the need of the house load and recharges the batteries.	**Grid (buying) ⇨ Batteries ⇨ Load**
4	-PV system cannot supply batteries, -The batteries are full; they meet the needs of the household load.	**Batteries ⇨ Load**

the temperature in the battery modules, informs the main control circuit about the voltage of each battery and the charge/discharge current values, shows the whole information on the LCD screen, reports the fault in the system with the visual/auditory warning system. As a necessity of the BMS, the voltage of each battery must be measured accurately and precisely to decrease the fluctuations and noise affect all parameters (current, voltage and temperature) have been measured 20 times and then averaged. In this study, even though batteries started with equal voltage values in the initial state, it is seen that some batteries have lower voltage values in the battery group compared to the other batteries during the experiment. The designed passive balancing circuit has been successful in keeping the batteries below the upper critical voltage level. Considering the balance of batteries, main control parameters have been selected as 4.20 V for upper critical voltage, and 100–150 mA for balancing current, according to not only datasheet of used Li-ion batteries and literature, but also outcomes from so many experiments. Especially during high current charging, no battery has exceeded 4.20 V, which is the upper critical voltage. Battery circuit in the slave circuit provides that seven 18650 type lithium batteries are properly and rigidly connected in series. As seen in lower part of Fig. 2, the main control circuit has Arduino Mega as a microcontroller, which contains an ATmega2560 processor. The control algorithm for determining the energy flow, measuring the current flowing through sub-components, determining the voltages, and measuring the ambient and panel temperature has been developed and loaded into this processor. The main control circuit has been designed to manage the whole system by taking the necessary information from the slave circuits and manages the energy flow between the PV system, battery block, households load, and the grid.

Main circuit consists of 2 sub-sections such as low and high current sections. Low current section is where data flow takes place. In this section, information from slave circuits is collected, the high current side is controlled with collected information and also this information is transmitted to the user. In the high current section, where energy flow is controlled by relays, high currents (maximum 8 A) pass through DC power supply (receiving energy from the grid) or PV modules, batteries are charged, the batteries supply power to the programmable electronic load acting as home consumption, the excess energy is consumed on the DC simple load as if it were transferred to the grid, as seen in Fig. 2.

2.2. Proposed prototype PV- battery system

The real home consumption profiles are considered depending on human habit of energy consumption such as: the consumption profile of the house where the working people live, named *working_ profile* and the consumption profile of the house where the retired people live, in other words, the *retired_ profile*.

The obvious difference between these two profiles is that; while working people aren't at home during the daytime when the PV system can generate the most power, conversely retired people continue to be at home during these hours. This situation is reflected in consumption profiles. Likewise, when working people in the evening come home, consumption increases suddenly. On the

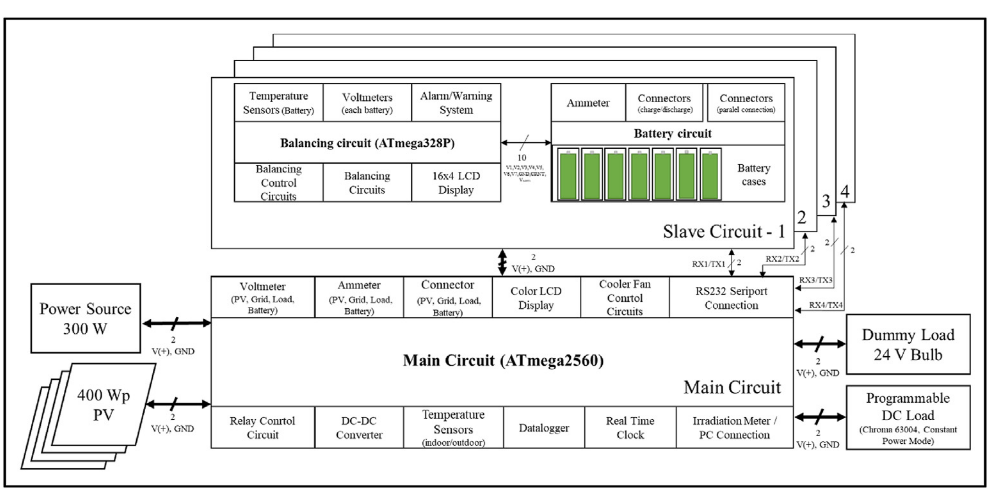

Fig. 2. Block diagram of the designed BMS.

weekend, working people will do the housework that they can't do on weekdays. There is a more uniform distribution among retirees. For retirees, the weekly distribution of energy consumption is more even.

The details of the field experiment with the 7s-4p battery group are given in Table 2. While conducting field experiments, to see the repeatability and credibility, experiments were conducted on different days of the week for various load profiles, which are created by considering the retired and working people consumptions. In addition, the experiments of the system were carried out in October, November and December, which is the most difficult working condition for the PV-battery system, when the radiation is low.

The tests of the designed system were carried out in the Solar House located at Hacettepe University, Beytepe Campus. The experimental test setup is shown in Fig. 3. As seen on the left side of Fig. 3, four 100 W solar panels connected to each other as 2 serial 2 parallel. On the right side; the components of test setup are given such as 300 W power supply, programmable DC electronic load, dummy load and the designed circuits; main circuit, each of the 4 battery circuits and balancing circuits which are interconnected in a sandwich manner.

According to the catalogue values, it is recommended to charge the LG MJ1 LIB with 1.7 A in line with the standard charging methods. In the first experiment, it was determined that charging the battery block with 5 A as distributing 1.25 A to 4 battery modules connected in parallel would be suitable for PV system, power supply and DC-DC converter.

In the initial experiments, the temperature values were monitored throughout the day and the results can be viewed from Ref. [38]. During the experiment, the lowest was recorded as 23.5 °C, when the ambient temperature was the lowest. Then, as the batteries charge, their temperature increases. Temperature of the batteries have increased remarkably due to the high charging current, especially in the constant current phase where the total voltage increases rapidly. The highest temperature during the day was recorded as 30.8 °C in the A battery group. These temperature values are not critical for Li-ion batteries, so there is no need to take any further measure for the temperature controlling.

Since the power obtained from the PV system will depend on the irradiance during the day and these power values will be used during the experiment to determine the efficiency of BMS in daily real condition, the experiments were carried out as real time. The experiments started at 06:00 in the morning and were terminated the next day at 06:00 in the morning. During the experiments, the data recorded on the SD card was uploaded to the computer at the end of the experiment and power graphs were drawn with graphics drawing program.

A total of 11 experiments were conducted to test the whole system, five of the experiments were for the working_ profile and 6 of them for the retired_ profile. Various experiments were conducted for both profiles, both on weekdays and on weekends as seen in Table 2.

3. Result and discussion

The results of the experiments performed with the 7s-4p battery group are given in Fig. 4 - Fig. 14 and these results are discussed separately in the following section.

As seen in Fig. 4, Fig. 5, Fig. 6 during *Working_Weekday* experiments; in the morning hours when irradiation level is low, energy consumption has increased as the household wakes up. If the batteries were fully discharged in the morning, the batteries would charge from the grid for a short time until PV system started to generate power; if not, they don't need this process. As working people leave their home after 08.00, energy consumption shows a low profile until 18.00 when they return home. During this time, the PV system is charging the battery block depending on the irradiance. When the batteries are full at noon; the surplus energy obtained from the PV system has started to be consumed on the dummy load as if energy transfer to the grid. Transferring process continued until irradiance intensity decreased. The fact that workers come home after 18.00 shows itself with the increase in energy consumption. After 18:00 in the evening, the consumption profile varies according to the use of electrical household appliances according to day profiles. Batteries meet evening and night consumption for a certain period of time, and when they are discharged totally, the grid is activated.

Weekend experiments (*Working_Saturday* and *Working_Sunday*) for the working people are given in Fig. 7, Fig. 8. As seen, in the morning, unlike the weekdays, households woke up later and therefore power consumption peaks also shifted. It assumed that conscious consumers operate devices with high power consumption (such as vacuum cleaner, washing machine, kettle) when the batteries are full and the irradiance is good. As expected, energy transfer to the grid could not be achieved due to the intense consumption during the daytime. For the energy consumption of the house at night, the batteries were charged twice from the grid and the energy requirement was met from the batteries during the night like weekdays.

Concerning the retired people, before examining the experiments, it was assumed that retired people were at home all day, operated household appliances that consume more energy in the afternoon because they were conscious users like working people, and that their weekly consumption was evenly distributed, regardless of the weekday/weekend difference. Therefore, there is no distinction between weekdays/weekends for retirees. So, when whole experiments examine together as seen Figs. 9–14, unlike working people, retired people woke up later in the mornings and their consumption profiles were shaped accordingly. Since retired

Table 2
The experiments with *working_ profile* and *retired_ profile*.

Experiment	Load Profile	Date	Fig. No.
7s4p_1	Working_Monday	October 13, 2020	Fig. 4
7s4p_2	Working_Tuesday	November 09, 2020	Fig. 5
7s4p_3	Working _Friday	November 13, 2020	Fig. 6
7s4p_4	Working _Saturday	December 04, 2020	Fig. 7
7s4p_5	Working _Sunday	October 26, 2020	Fig. 8
7s4p_6	Retired_Monday	October 17, 2020	Fig. 9
7s4p_7	Retired_Tuesday	November 02, 2020	Fig. 10
7s4p_8	Retired_Friday	November 04, 2020	Fig. 11
7s4p_9	Retirement_Saturday (High Irradiance)	October 23, 2020	Fig. 12
7s4p_10	Retirement_Saturday (Low Irradiance)	December 11, 2020	Fig. 13
7s4p_11	Retired_Sunday	November 27, 2020	Fig. 14

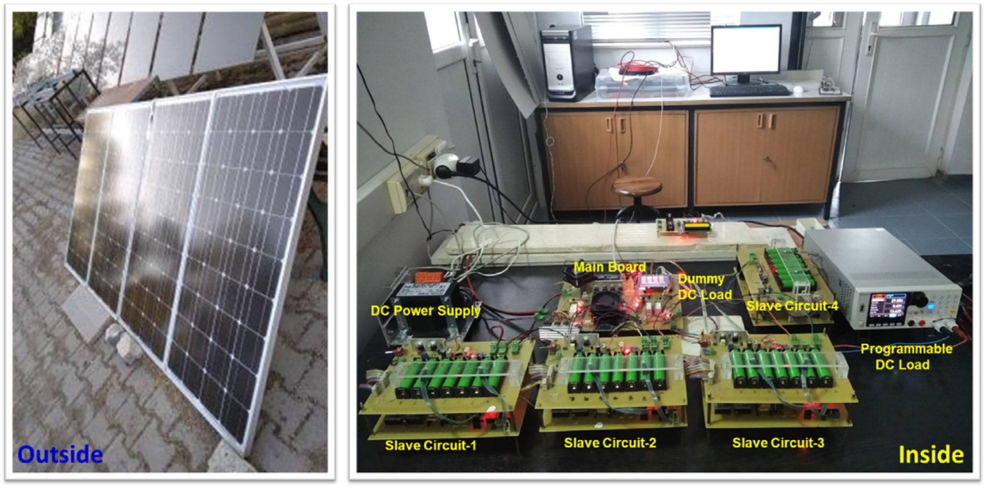

Fig. 3. The experimental test setup.

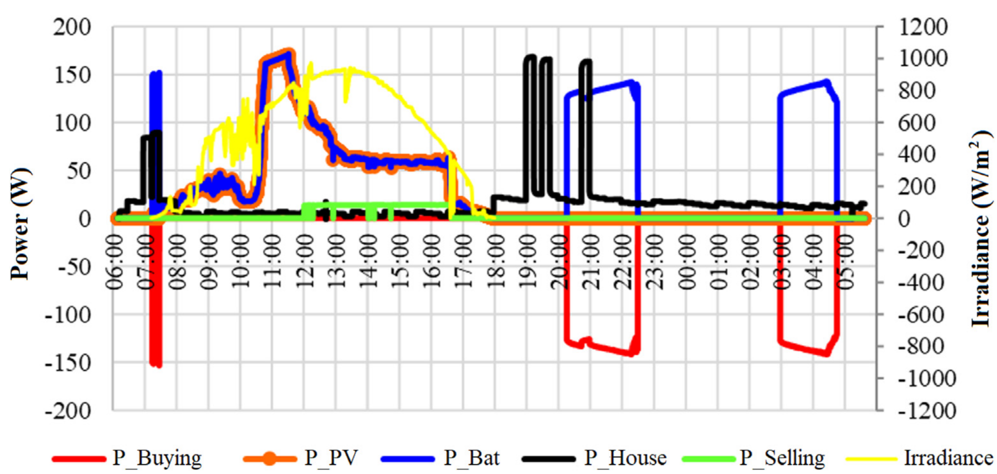

Fig. 4. *Working_Monday* experimental results.

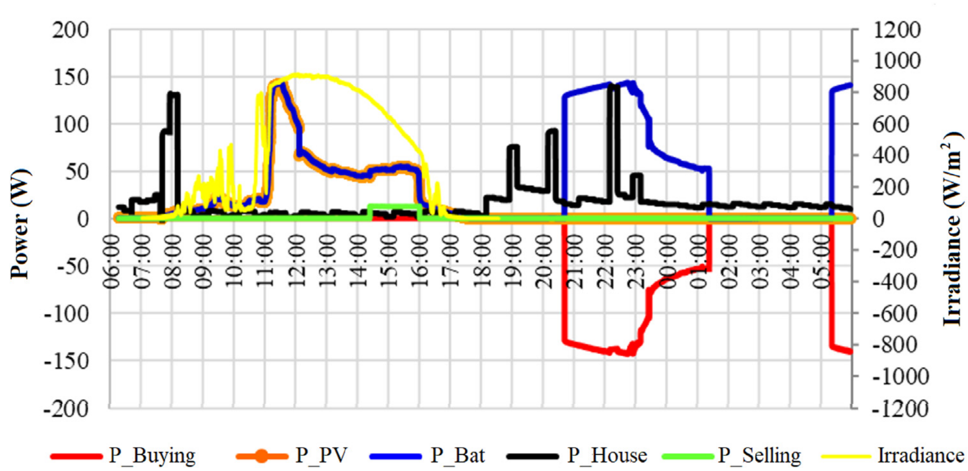

Fig. 5. *Working _Tuesday* experimental results.

people are at home during the day, their energy consumption continues during daytime so batteries can only be utterly charged in the afternoon. When the daytime power consumption is not very high, the batteries are full and the irradiation intensity is still high, the energy transfer process to the grid takes place. For example, on Monday (Fig. 9), the transfer process started at 12.36, it was

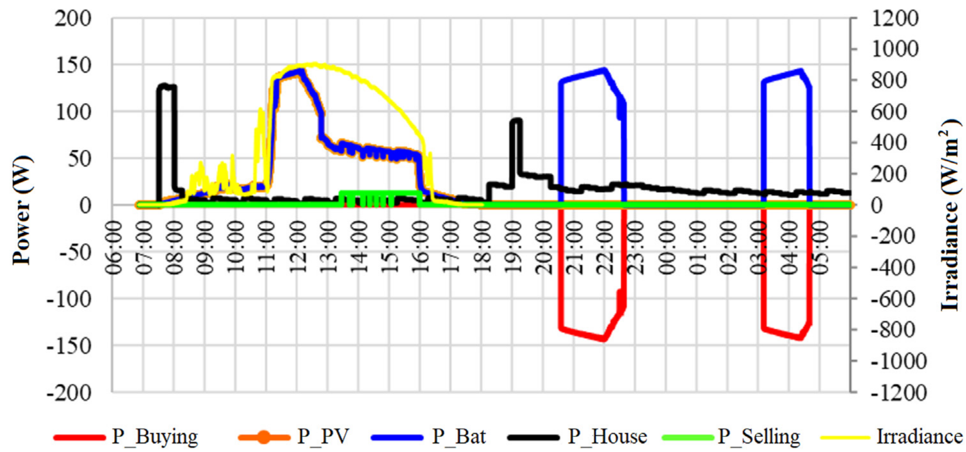

Fig. 6. *Working _Friday* experimental results.

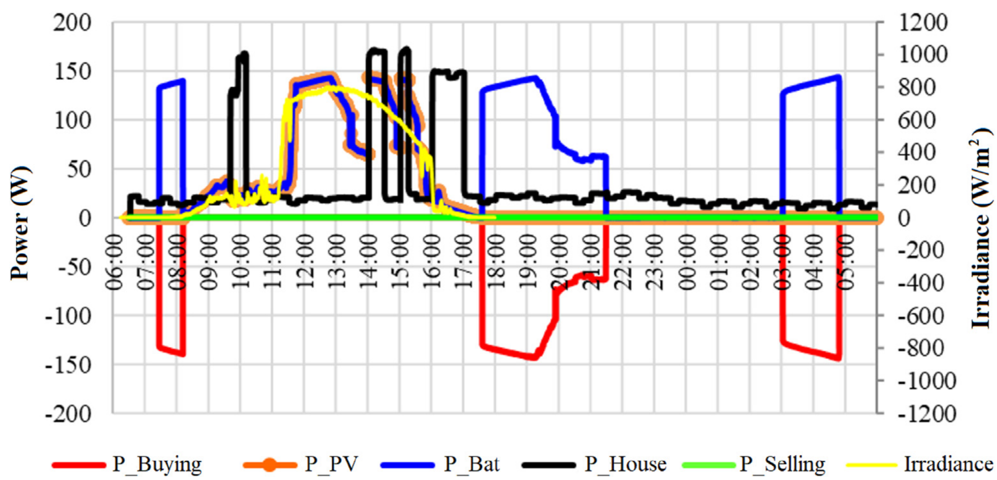

Fig. 7. *Working _Saturday* experimental results.

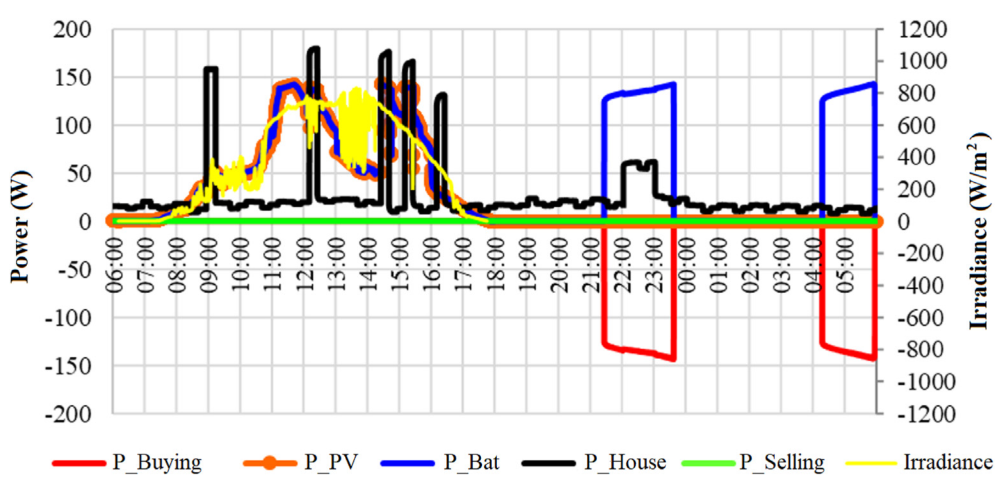

Fig. 8. *Working _Sunday* experimental results.

deactivated from time to time depending on the irradiation intensity and ended completely at 16.20. The power consumption of the house at night was met by batteries which was charged the twice from the grid.

Although energy consumption is similar for retired people for whole weekday, there are some dissimilarities from the general situations mentioned above. in the *Retired_Friday* experiment (Fig. 11), the first remarkable point is that the irradiance is quite low

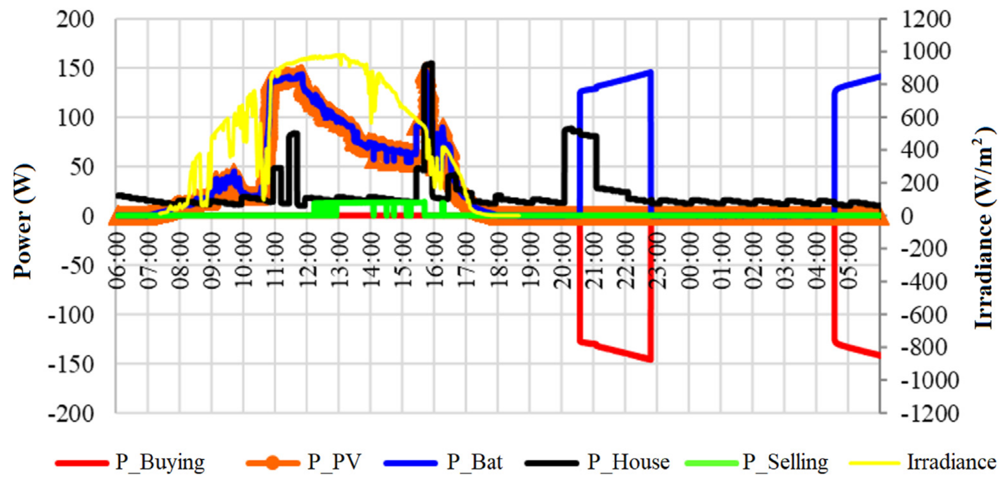

Fig. 9. *Retired_Monday* experimental results.

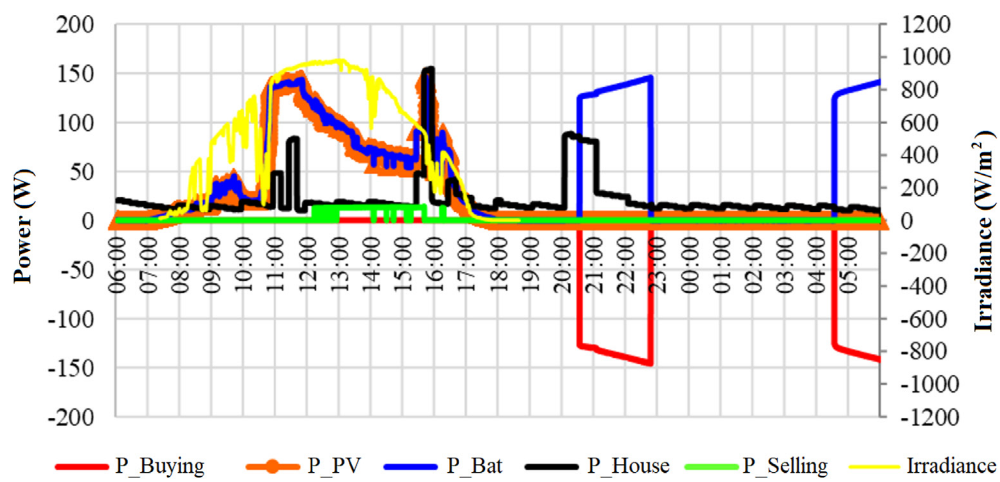

Fig. 10. *Retired_Tuesday* experimental results.

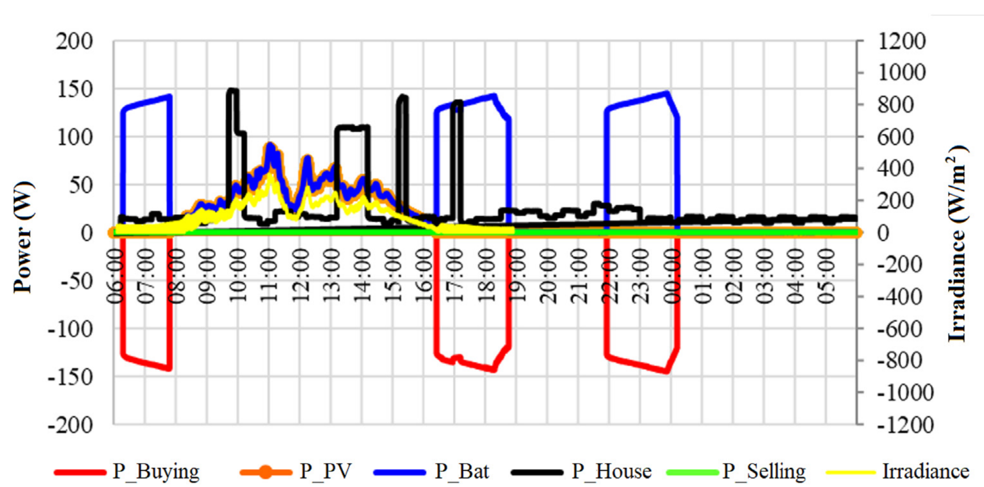

Fig. 11. *Retired_Friday* experimental results.

during the day. It is clearly seen that the batteries are charged from the PV system in proportion to the irradiation intensity during the day.

In Figs. 12 and 13, *Retired_Saturday* experiment has been repeated to see the effect of irradiation in the same consumption profile. On the day with high irradiation level, the batteries were

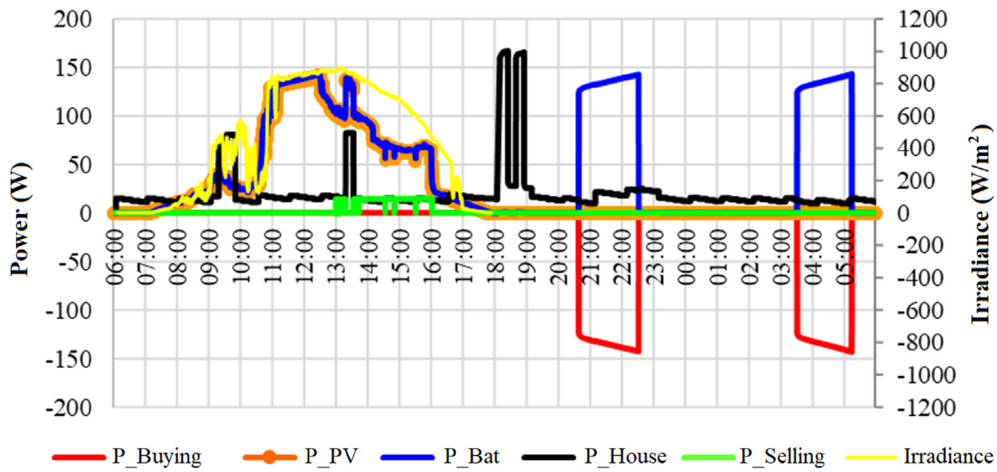

Fig. 12. *Retired_Satuday* High Irradiance experimental results.

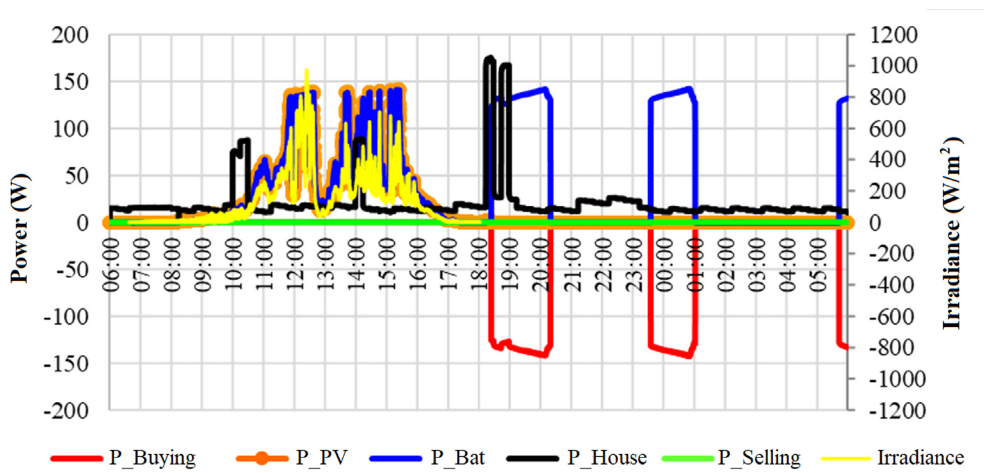

Fig. 13. *Retired_Satuday* Low Irradiance experimental results.

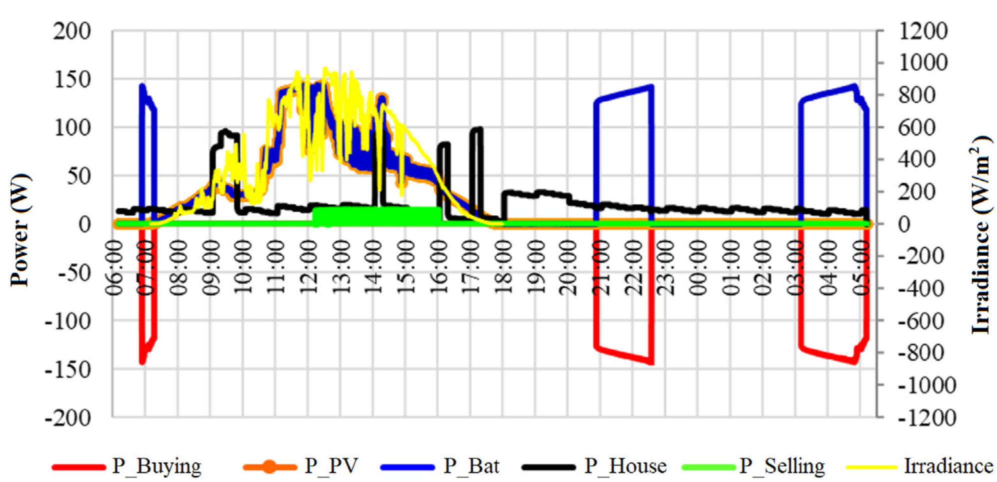

Fig. 14. *Retired_Sunday* experimental results.

charged totally around 13.00, the energy transfer process to the grid started at this time and continued until 16.15, whereas the irradiation was low, there was no energy transfer to grid. In the evening, when the irradiation level was low during daytime, the batteries will not be charged enough via PV modules, so the power will be supplied from grid to batteries earlier (18.15) than on the day when the irradiance was high. On the day when the irradiation intensity is sufficient, the batteries were charged from the grid only two times after the sunset (Fig. 12). On the contrary, when the irradiation was low, the batteries were fully charged twice, then the third charging process started in early hours of the morning (Fig. 13).

4. Conclusion

In this study, not only a BMS but also an EMS has been designed, implemented and tested for a grid-on PV system with battery in order to meet the electricity needs of single-family house.

Designed BMS successfully fulfilled the functions of measuring accurately the voltages of each battery and the battery block, the charge/discharge current of the battery block, and the temperatures of the battery block, balancing between series connected batteries. Thus, it has been seen that Li-ion batteries can be used as an ideal energy storage for high and suddenly changing household energy consumption by preventing misuses which will have a negative impact on the battery performance. All the data of the BMS were recorded on the SD card in real time for 24 h at intervals of 8–10 s in order to examine the performance of the PV system and batteries, to analyse the system and to carry out future system development studies. EMS had been designed, to provide and control the energy flows successfully between PV system, battery block and grid. With this aim, an experimental test setup which includes the 400 Wp PV system, the 300 W power supply acting as the grid and 24 V lambs acting as selling energy to the grid, a programmable DC electronic load, was proposed and constructed successfully as a prototype. Due to the programmable DC electronic load, 24-h various energy consumption profiles have been generated as a reduced modelling of household load profiles and the energy flows between PV system, battery, load and grid can be investigated for various situation. By using this test setup 24-h real time experiments carried out for various load profiles, so varies EMS strategies have been tested to investigate energy flow between PV system, batteries and grid.

As a result of experimental studies, we demonstrated the suitability of the proposed strategy for efficient management of battery and energy system. This proposed BMS/EMS can be easily adjusted to larger-scale energy storage system by mainly increasing the number of battery blocks, and considering a new hardware/software design for the data transfer between units. Thus, this energy storage system created can easily be used in homes, offices and living spaces with PV-battery systems connected to the grid or not.

Thanks to designed prototype BMS/EMS that provide flexibility to investigate the optimum design of various PV module and battery combinations for different load profiles, and also to give an opportunity to analyse the system as an economic aspect considering the energy selling/buying to/from grid as future work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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