ISSN: 0976-3104
SUPPLEMENT ISSUE

ARTICLE

A COMPREHENSIVE BIDIRECTIONAL CONVERTER CONTROLLING ALGORITHM FOR ENERGY MANAGEMENT OF BUILDING PV SYSTEM APPLICATIONS

Sajad Maleki Varnamkhasti*, Mohammad Yasinzadeh
Faculty of Engineering, Shahed University, Tehran, IRAN

ABSTRACT
The main purpose of a smart energy management system as a high level controller is to provide an adequate coordination between battery, solar system and power grid. Taking maximum power from solar panels, minimizing the energy received from the network and the reduction of battery charging and discharging cycles are the other purposes of utilizing this controller. In this paper, a novel and comprehensive control algorithm for bi-directional converter has been proposed to provide the solar system of a building with predictive energy management. Despite the existing management methods, the proposed algorithm considers the Tariff variant dynamic besides load and generation changes and launches a predictive approach for a solar system of a residential building. The main aims of the proposed algorithm are to increase energy storage life time, reduce electricity invoices and protect batteries against overcharging. The proposed algorithm has been implemented on some real data obtained from a solar system of an inhabited building and the results have been illustrated in the paper. Having achieved all the objectives, the simulations assure the effectiveness of the proposed management system.

KEY WORDS
Energy Management System; Bidirectional Converter; Controlling Algorithm; Building PV System Applications; Battery Charge and Discharge.

Received: 5 Oct.2017
Accepted: 13 Nov.2017
Published: 16 Nov 2017

***Corresponding Author**
Email:
s.maleki@shahed.ac.ir

INTRODUCTION

Renewable energy systems have gained a lot of support from some governments and intermittency of PV power generation is the challenging issue for widespread public acceptance [1]. In order to improve intermittency problem, energy storage systems can be placed to store excess energy and provide it at times of deficiency [2] and improve stability of the micro grid [3]. In order to properly supply the load with a PV installation an energy storage system is required, such as a battery bank, and consequently a bidirectional power converter should be used as an interface between the DC link and battery storage. Such battery-based power converter should have high efficiency and provide smooth charging and discharging to extend the life-time of the battery bank. In addition to the power converter, a smart-energy management system is required to coordinate the power transfer from PV as well as the charging and discharging of the battery bank according to the demand and the grid state as well as energy cost. Energy storage systems have proven to be a vital part of any renewable energy system [2-3]. Batteries have been distinguished from other storage systems because of their unique features like high energy density and less volume and weight [4]. The lithium-ion batteries have more benefits in comparison to other batteries; hence, the largest volume of battery production in the world belongs to the production of the mentioned batteries [5]. One of the disadvantages of the lithium-ion batteries is low resistance against overcharging and full discharging; therefore one of the factors which should be considered in the energy management control algorithm of the system is to protect the battery against full charging and full discharging.

Energy management control systems

Having chosen the best converter fitting a residential application, a management system should be designed to make the power flow more efficient maximizing the PV power dispatch. The energy management system basically coordinates between three parts of the system, the PV converter, the battery converter, and the grid connected inverter. In the literature, there are basically two main approaches to manage and optimize energy of renewable energy resources.

The first approach

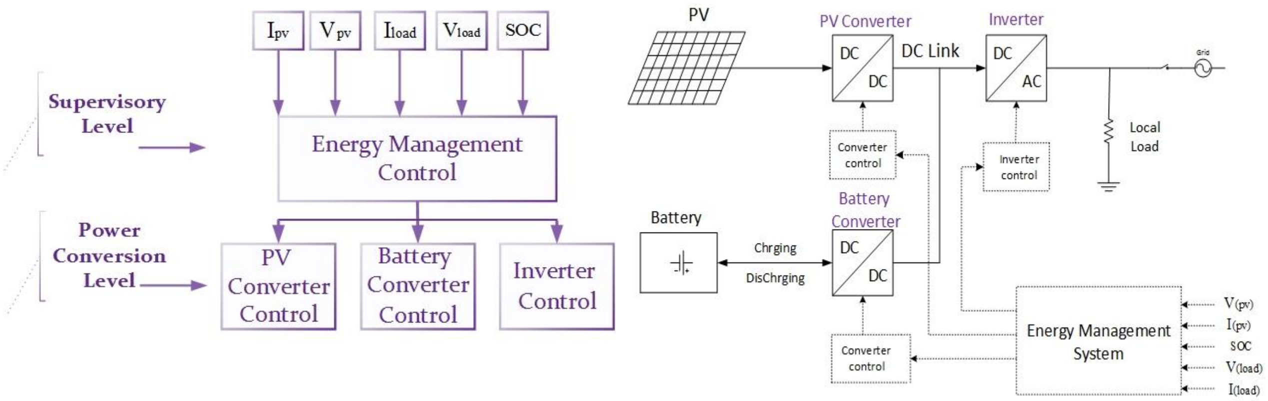
The first approach employs the use of a predictive control model to manage the system. It utilizes generation and demand forecast as well as market price prediction through statistical models and neuro-fuzzy networks. Such management systems can be found in [6-8], and [9]. These algorithms present many advantages for large scale integration of PV systems where optimization and response time are essential. However, these data may not be available for a small scale PV system. Therefore, the role of an energy management system in small scale PV systems is more concerned with maximizing PV power, minimizing grid power, extending the life of the energy storage system, providing backup using energy storage during islanded mode.

The second approach

The second approach is a direct approach that evaluates the state of the system instantaneously, decides the operation mode, and generates control signals to the converters in the system. Typical tasks of such a management system include maximum power tracking, state-of-charge (SOC) estimation, battery dispatch optimization, and inverter control. Typical systems can be found in [10-14]. These systems share a common management structure which consists of a higher level controller that decides the mode of operation and generates reference signals to lower level controllers of power converters. In [Fig. 1(b)], the

IIOAB JOURNAL
ISSN: 0976-3104

general structure of a residential solar system is displayed, as it can be observed in the structure of the energy management system in [Fig. 1(a)], the low level control is made up of three parts in which the PV inverter controller has the task of performing the MPPT algorithm in order to use the maximum power. The battery inverter controller has the task of controlling the charge and discharge of the battery by performing two functional modes of buck and boost on the inverter. And the inverter controller has the task of controlling the voltage and also controlling the active and reactive power. In this paper, it has been supposed that there are three distinct convertors. However, they can be packed in one device if required. Also, authors want to clarify that the proposed algorithm is launch on the battery convertor with is in charge of charging and discharging the battery. When it attempts to charge the battery, it will work in buck mode and when it attempts to discharge the battery it will work in boost mode.



a. Energy Management Structure.

b. General structure of a residential solar system.

Fig. 1: General structure

PROPOSED ENERGY MANAGEMENT CONTROL SYSTEM

The proposed management system is similar to the previously mentioned systems. However, the existing predictive algorithms don't have the simplicity required for a residential application and on the other hand, the existing instantaneous algorithms don't have the estimation focus. Therefore, the proposed algorithm will combine simplicity of application and apply estimation that suits the residential application. The proposed system will not discuss island detection techniques and will assume the state of the point of common coupling (PCC) will be given by a binary integer (one/zero). The proposed energy management algorithm is similar to the one in [13]; however, power limitations and economic considerations are added. The energy management algorithm presented in [13] is shown in [Fig.2(a)]. The three main purposes of the energy management control system are consisted of reducing electricity bills, observing the charge and discharge modes (SOC) of the battery and reducing the number of charging and discharging cycles. The second and third cases increase the battery life. In [Fig. 2(b)], power functions of each part of the system are shown in which P(pv) is the productive power of the photovoltaic system, P(bat) is the transitional power of the battery, P(inv) is the transitional power of the invertor, P(load) is the power consumed by the load and P(grid) is the transitional power of the network. In this paper, grid characteristics is as follows: 220AC, 50Hz, Single phase.

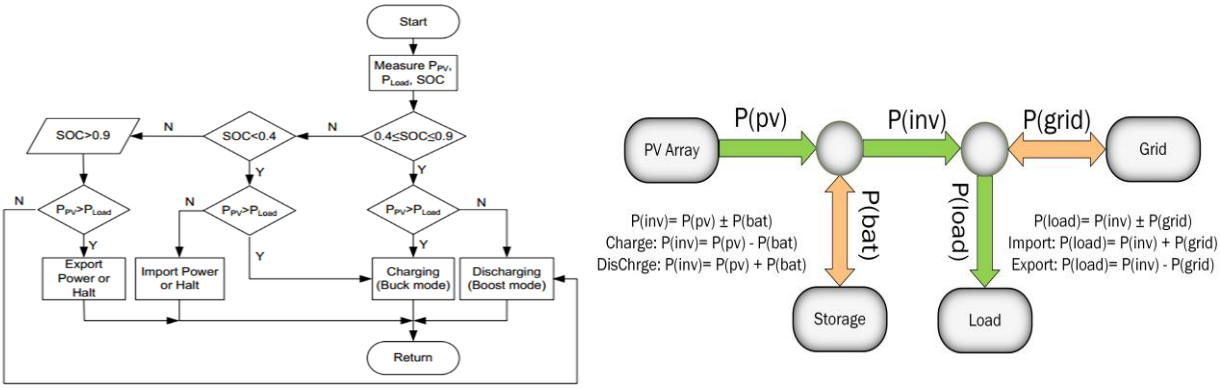
Transitional power of invertor is obtained from equation 1 in which the P(bat) sign is distinguished by the charge and discharge of the battery. As it is obvious in [Fig. 2(b)], when the battery power is finished or the so-called battery is discharged, positive sign is chosen in equation 1 and P(bat) is added to p(pv). And when the battery is charged, negative sign has been chosen and P(bat) is subtracted from P(pv).

$$P(inv)=P(pv)\pm P(bat) \tag{1}$$

The transitional power of the network is also obtained from equation 2 and as shown in the [Fig.2(b)], the power sign taken from the network is positive and the power sign given to the network is negative.

$$P(grid)=P(inv)-P(load) \tag{2}$$

IIOAB JOURNAL
ISSN: 0976-3104



a. Proposed Energy Management Algorithm in [13] b. Power functions of each part of the system.

Fig. 2: Proposed system.

The two main objectives of this Energy management control system are to reduce the electricity bill and reduce number of charging / discharging cycles off the battery. The number of charging and discharging cycles will in fact effect the life time of batteries. Lithium-ion batteries for example, are typically used and have got high price, having decreased the charging and discharging cycles, it will save the costs. When PV generation, for example, excels the local load and when it is possible to charge the battery, the algorithm decides whether to charge the battery or not. Having analyzed PV generation, loads' energy consumption and Tariff values, the algorithm might conclude that no charging shall happen at instant. This will reduce the unnecessary charging cycles. In this system, charging and discharging decisions will be made every three hours based on averaged measurements for one hour. The energy function of this system is expressed as follows:

$$E_{grid}(t) = E_{load}(t) - E_{pv}(t) - E_{bat}(t) \quad (3)$$

And the price of electricity can be expressed as follows:

$$price(t) = E_{grid}(t) \,.\, C(t) \quad (4)$$

$$price(t) = \left(E_{load}(t) - E_{pv}(t) - E_{bat}(t)\right).C(t) \quad (5)$$

And c(t) is the cost for electricity function. From this equation it can be observed that the load cannot be changed and the only way to control PV energy is to apply MPPT algorithm. Therefore, optimizing this function relies on optimizing the battery energy with respect to the cost. Since battery can give or receive energy, price function should be reduced at charging the battery and increased at discharging the battery. Maximizing the battery life has many parameters but in this system only the number of charging and discharging cycles is included. According to [5], the lithium-ion batteries have low resistance in front of overcharging and full discharging, therefore it is important to observe the charging mode for these batteries, providing charging mode (SOC) and minimizing the number of charging and discharging cycles have been considered in this algorithm. According to the mentioned items, for designing the algorithm, supply priorities should be distinguished and these priorities are given in [Table 1].

Table 1: Priority organization

Priority step	Priority
Priority 1	Energy will be obtained from PV
Priority 2	Energy will be obtained from grid if (Tariff(now) < Tariff(later))
Priority 3	Energy will be obtained from battery if (Tariff(now) > Tariff(later))

According to the priorities of the mentioned [Table 1], battery charging and discharging algorithm by bidirectional dc-dc converter in the energy management control system was designed as [Fig. 3]. In which P(pv) is the productive power of the photovoltaic system, P (bat) is the transitional power of the battery, P(inv) is the transitional power of the invertor, P(load) is the power consumed by the load and P(grid) is the transitional power of the network. In the following algorithm, SOC, BCN, P (PV-f) and P (load-f) stand respectively for state of charge, bidirectional convertor, PV energy generation prediction and load prediction. For tariff, two other concepts have been defined. Tariff (n) reports the tariff at the existing time and Tariff (later) reports the tariff at the later time.

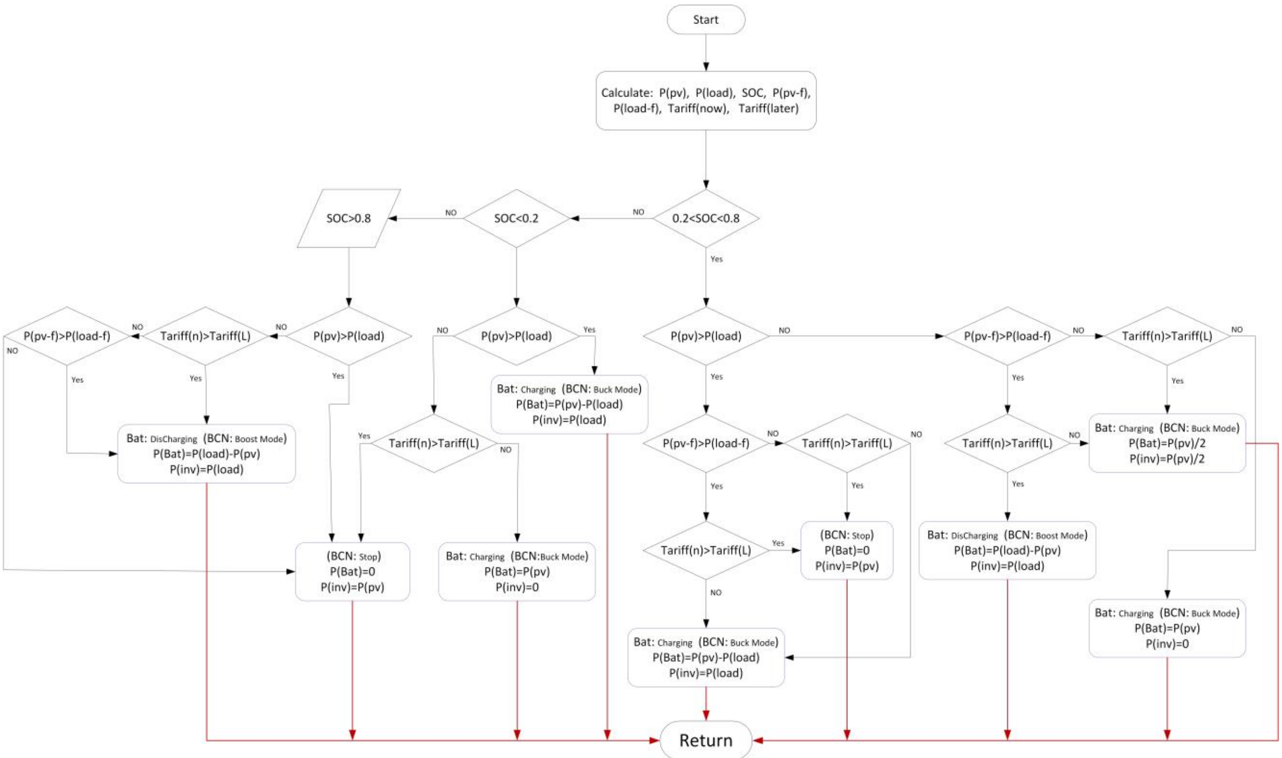


Fig. 3: Proposed battery charging and discharging algorithm by bidirectional dc-dc converter in the energy management control system

LOAD PREDICTIVE MODEL

There are many load predictive models in the different literatures. The simplest forecast models are linear regression models such as [15]. Linear regression models are simple to implement and have many forms. However, they are known to have consistent, over-estimating or under-estimating, errors. Nonetheless, the amplitude of error is considered acceptable in a residential energy management application especially when its main function is to determine the state of the battery. The Chosen model for this system is a linear model that predicts a residential load based on its past history for the last four days. The model is expressed as [15]:

$$d(t) = [d(t-1)\ \ d(t-2)\ \ d(t-3)\ \ d(t-4)] \times \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} \tag{6}$$

To find the (a) parameters, a set of at least 8 days of load data is needed and parameters a1 to a4 can be found as follows:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} d(4) & d(3) & d(2) & d(1) \\ d(5) & d(4) & d(3) & d(2) \\ d(6) & d(5) & d(4) & d(3) \\ d(7) & d(6) & d(5) & d(4) \end{bmatrix}^{-1} \cdot \begin{bmatrix} d(5) \\ d(6) \\ d(7) \\ d(8) \end{bmatrix} \tag{7}$$

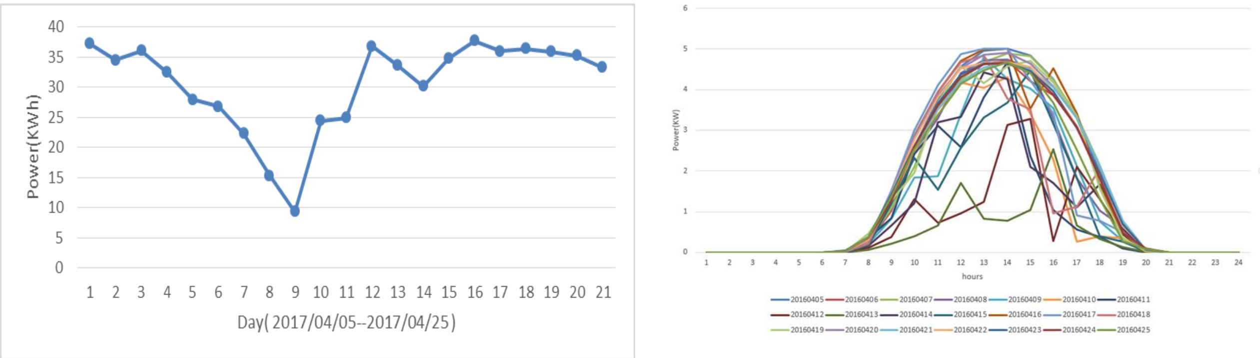
After finding these parameters, the load can be predicted by simply providing load consumption for the last four days.

PRODUCTIVE POWER OF THE PHOTOVOLTAIC SYSTEM

Depending on the weather conditions, temperature and radiation, it is different in various days; for testing the proposed algorithm, the data of a 5-kW inverter of the SMA Company (Sunni boy 5000 TL) which was installed in a residential building, was used. For the forecast model of the production, the linear regression method which was mentioned in the load forecast model section has been used. In [Fig.4(a)] and

IIOAB JOURNAL
ISSN: 0976-3104

[Fig.4(b)], general production diagrams of a solar system in one day and system production at different hours of the day in a 21 day period of the year are presented, respectively.



a. Daily production diagram of the photovoltaic system in a 21-day period

b. Production diagram of the PV system at different hours in different 21 days.

Fig. 4: Productive power of the photovoltaic system.

Tariff Model

As previously pointed out one of the main aims of the proposed control algorithm is to reduce the consumed electricity bill of a residential building equipped with solar system and storage system; in this system, dynamic pricing is applied to the energy management algorithm. The price of electricity varies during the day and the highest price is related to the highest demand or the peak consumption. Electricity pricing varies in different parts of the world, but by checking several sites that included electricity prices during different hours of the day, an electricity tariff model based on prices at different hours was extracted without considering any specific currency. The extracted model is shown in [Fig. 5].

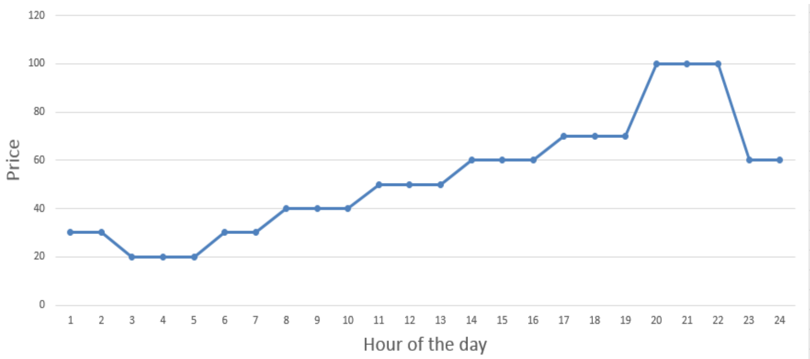


Fig. 5: The electricity tariff model based on different hours of the day

CAPACITY OF THE PHOTOVOLTAIC SYSTEM AND THE STORAGE SYSTEM

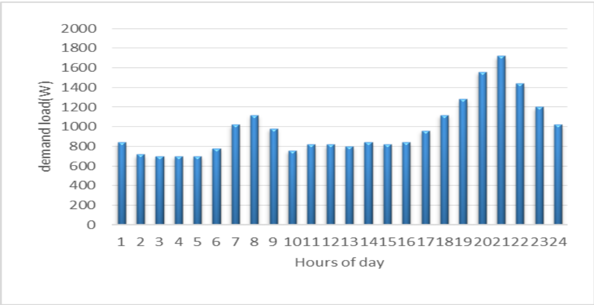
For testing the proposed algorithm for the bidirectional converter in the energy management control system, the capacity and size of the photovoltaic system and the storage system should be specified. It should also be notified that the proposed algorithm can work with any size and capacity and can provide the desired items such as reducing the electricity bill and increasing the battery life time. In [16], a general analysis about the optimum capacity of these systems is presented for several scenarios and in different years. In 2017, the capacity of the photovoltaic system in the optimal mode is 3.75 kW and the capacity of the storage system is 5 kWh.

RESULTS OF EVALUATING THE PROPOSED ALGORITHM

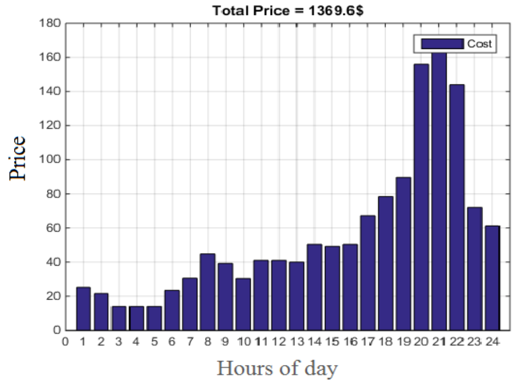
In this section, the proposed algorithm for the bidirectional converter in the energy management control system is evaluated. For this reason, the results are compared with the results of the algorithm in [13]. The bidirectional converter was considered as a 1 kW converter. To make the comparison simple in different situations, evaluation was used for a sample of load profile in a day. In [Fig. 6(a)], the diagram of a sample load consumed for a residential building at different hours of the day has been represented. According to

IIOAB JOURNAL
ISSN: 0976-3104

the presented sample tariffs [Fig. 5], the electricity bill without the solar system is 1369.6 dollars and the bill is also calculated and represented in [Fig.6(b)] according to the tariff per hour. Two evaluations of two samples have also been provided in two different days which are as follows:



a. The diagram of the load sample consumed for a residential building at different hours

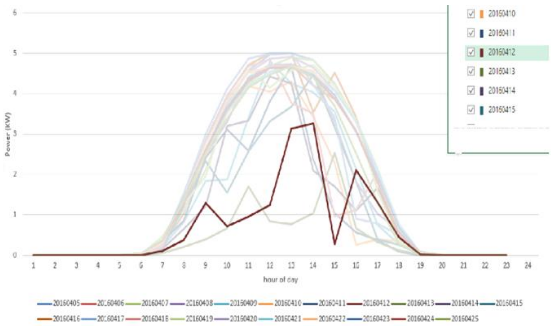


b. The diagram of the electricity price based on the diagram of the load sample consumed at different hours without the solar system

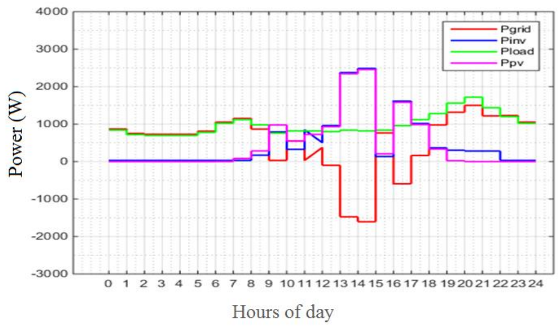
Fig. 6: The diagram of the load sample consumed and the diagram of the electricity price

The first sample

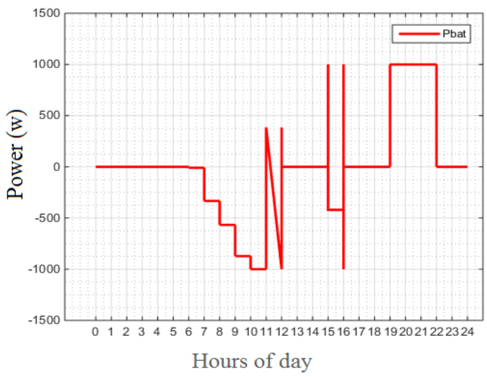
In [Fig.7(a), (b), (c), (d), (e)] the production diagram of the photovoltaic system on 12.04.2017 and general values of the system parameters, the amount of battery charging and discharging, battery charging mode and the electricity bill will be represented. In [Fig. 7(e)], positive values express the scenario in which energy is obtained from grid. Also, negative values express the scenario in which energy is exported to grid.



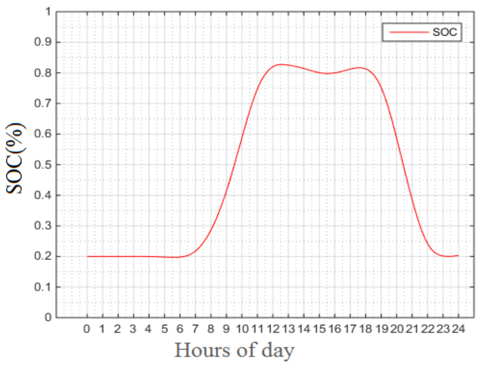
(a)The production diagram of the photovoltaic system on 12.04.2017.



(b) The changes diagram of the network power, invertor, load and PV by implementing the proposed algorithm for the first sample.

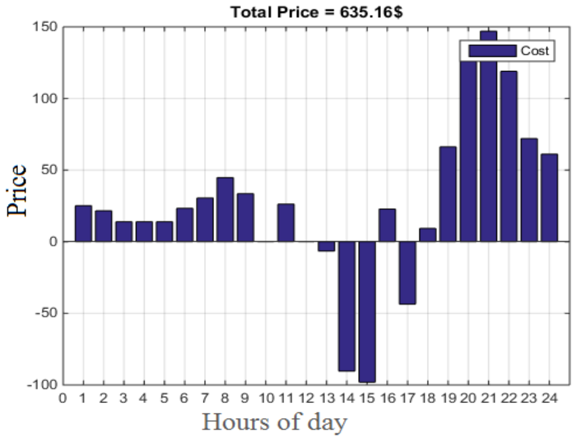


(c) Battery charging and discharging diagram using the proposed algorithm for the first sample.



(d) The (SOC) diagram using the proposed algorithm for the first sample.

IIOAB JOURNAL
ISSN: 0976-3104



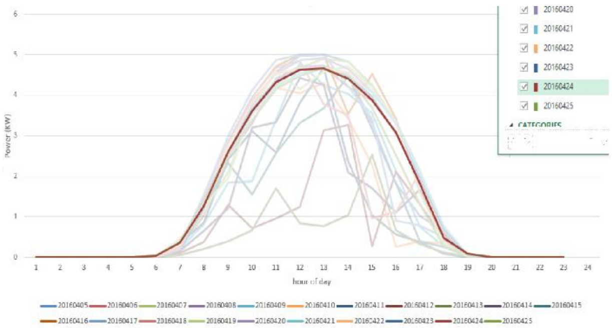
(e) The cost of electricity per hour and the electricity bill using the proposed algorithm for the first sample.
Fig. 7: The first sample

....

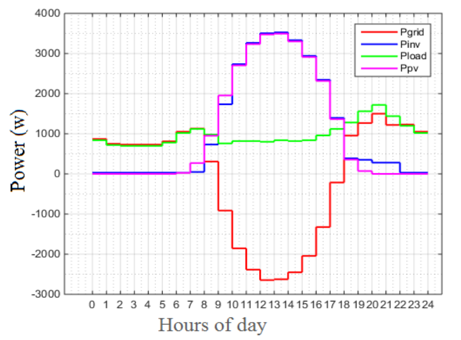
The electricity bill in the indicated day is equal to 737 by implementing the algorithm in [13] and it is equal to 635 by implementing the proposed algorithm and for this day, considering the production of the PV system, the bill is decreased by 14 percent compared to the algorithm [13] using the proposed algorithm. Also, the parameters of maximizing the battery life can be seen in the algorithm in which (SOC) is about 20 to 80 percent in all the process of charging and discharging the battery and the number of charging and discharging cycles is minimal.

THE SECOND SAMPLE

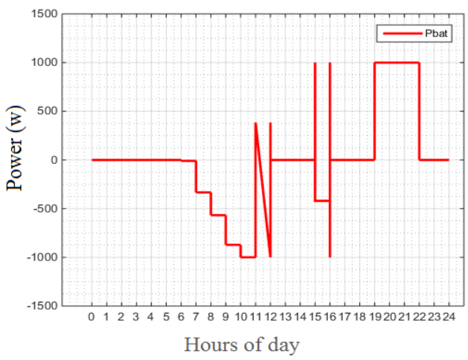
In [Fig. 8(a),(b),(c), (d), (e)], the production diagram of the photovoltaic system on 14.04.2017 and general values of the system parameters, the amount of battery charging and discharging, battery charging mode and the electricity bill will be represented.



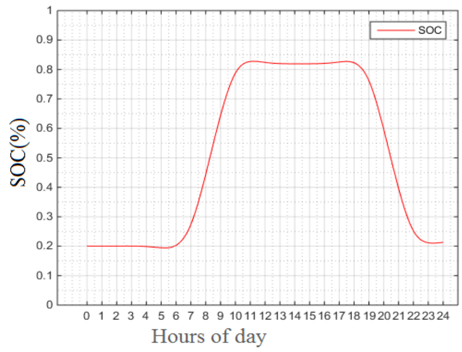
(a) The production diagram of the photovoltaic system on 24.04.2017



(b) The changes diagram of the network power, invertor, load and PV by implementing the proposed algorithm for the second sample

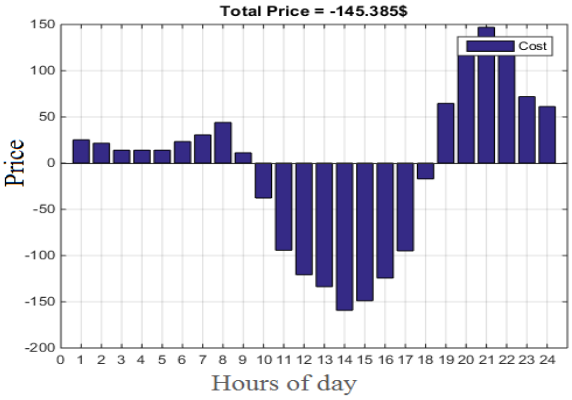


(c) Battery charging and discharging diagram using the proposed algorithm for the second sample



(d)The (SOC) diagram using the proposed algorithm for the first sample

IIOAB JOURNAL ISSN: 0976-3104



(e)The cost of electricity per hour and the electricity bill using the proposed algorithm for the first sample

Fig. 8: The second sample

The electricity bill in the specified day in the energy management control system is equal to the negative 108 by implementing the algorithm in [13]. In fact, the amount of 108 units has been sold to the electricity network. And it is equal to the negative 145 by implementing the proposed algorithm that for this day, considering the production of the PV system, the sold electricity to the network is increased by 34 percent compared to the algorithm [13] using the proposed algorithm. By evaluating the proposed algorithm for the 21-day data from the production of the photovoltaic system and comparing the results with the algorithm [13], the proposed algorithm will have in an average of 23 percent profitability, while in this algorithm, the desired parameters for increasing the battery life are also considered.

CONCLUSION

In this paper, a control algorithm was proposed for a bidirectional dc-dc converter in the energy management system of a residential building equipped with solar and storage systems. The algorithm is in fact a predictive algorithm and its main purposes are to increase energy storage life time, reduce electricity bills and protect batteries against overcharging. The decision maker algorithm pays a serious attention to state of the charge (SOC) to minimize the charging and discharging cycles which subsequently increases the life time of storage system. Having used the real data of a residential building solar system, the simulations assure the effectiveness of the algorithm as all the desired purposes can be achieved. Having analyzed the results, it has been concluded that the proposed algorithm would be beneficial for all the residential building equipped with solar and storage systems.

CONFLICT OF INTEREST
There is no conflict of interest.

ACKNOWLEDGEMENTS
None

FINANCIAL DISCLOSURE
None

REFERENCES

[1] Wang L, Zhang H, Chen D. [2013] Intermittency indexes for renewable energy resources. In Power and Energy Society General Meeting (PES), 2013 IEEE:1-5

[2] Qian K [2009] Benefits of energy storage in power systems with high level of intermittent generation. Electricity Distribution-Part 1. 20th International Conference and Exhibition on. IET.

[3] Lamichhane Sumiti, H Nazaripouya, S Mehraeen. [2013] Micro grid stability improvements by employing storage. Green Technologies Conference, IEEE.

[4] Kiehne, Albert H. [2003] Battery technology handbook. Vol. 118. CRC Press.

[5] Shaw S, [2013] Graphite demand growth: the future of lithium-ion batteries in EVs and HEVs, 37th ECGA General Assembly, Roskill Information Services.

[6] Valverde L, Bordons C, Rosa F. [2012] Power management using model predictive control in a hydrogen-based microgrid, IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society.

[7] Garcia F, Bordons C. [2013] Regulation service for the short-term management of renewable energy microgrids with hybrid storage using model predictive control. Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE.

[8] Yubin J, Liu X [2014] Distributed model predictive control of wind and solar generation system. Control Conference (CCC),33rd Chinese.

[9] García P, García CA, Fernández LM, Llorens F, Jurado F. [2014] ANFIS-based control of a grid-connected hybrid system integrating renewable energies, hydrogen and batteries. IEEE Transactions on Industrial Informatics, 10(2):1107-1117.

[10] Choi SC, Sin MH, Kim DR, Won CY, Jung, YC. [2014] Versatile power transfer strategies of PV-battery hybrid system for residential use with energy management system. In Power Electronics Conference (IPEC-Hiroshima 2014-ECCE-ASIA), 2014 International: 409-414

[11] Trifkovic M, Sheikhzadeh M, Nigim K, Daoutidis P. [2014] Modeling and control of a renewable hybrid energy system with hydrogen storage. IEEE Transactions on Control Systems Technology, 22(1): 169-179.

IIOAB JOURNAL
ISSN: 0976-3104

[12] Khanh LN, Seo J.J, Kim YS, Won DJ. [2010] Power-management strategies for a grid-connected PV-FC hybrid system. IEEE transactions on power delivery, 25(3):1874-1882.
[13] Zamora R, Srivastava AK. [2014] Energy management and control algorithms for integration of energy storage within microgrid. In Industrial Electronics (ISIE), 2014 IEEE 23rd International Symposium: 1805-1810
[14] Hasan KN, Haque ME, Negnevitsky M, Muttaqi KM. [2008] Control of energy storage interface with a bidirectional converter for photovoltaic systems. In Power Engineering Conference, 2008. AUPEC'08. Australasian Universities: 1-6
[15] Soliman SAH, Al-Kandari AM. [2010] Electrical load forecasting: modeling and model construction. Elsevier.
[16] Hoppmann J, Volland J, Schmidt TS, Hoffmann VH. [2014 economic viability of battery storage for residential solar photovoltaic systems–A review and a simulation model. Renewable and Sustainable Energy Reviews, 39: 1101-1118.