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Embedded control unit design for energy management in smart homes

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ABSTRACT

This paper deals with smart home energy management through load scheduling and optimal use of available energy sources. In this study, three energy sources were considered: the national electricity grid, photovoltaic (PV) energy, and the storage unit. The PV array can provide the maximum power to the load at a given operating point where the output power changes with temperature, radiation and load. Therefore, a real-time controller is proposed to track the maximum power. An energy management algorithm has been proposed in a smart home to achieve the main goal of making the electricity bill as low as possible. The algorithm involves scheduling loads by assigning a priority to each load. The loads are supplied with the required power according to their priorities and the available energy. The obtained results indicate that supplying the PV system with a fuzzy-based MPPT indicates an increase in system efficiency. The results also showed that the use of energy management based on load scheduling led to a significant reduction in the electricity bill.

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1. INTRODUCTION

In recent years, a great deal of interest in renewables for power generation due to the depletion of fossil fuels, their increasing cost, and growing environmental concerns [1]. Photovoltaic (PV) systems are used as one of the natural alternatives for generating electric power, which contributes significantly to reducing the cost of energy, as the fuel purchase bill constitutes a large percentage of Jordan's budget. Jordan's location makes it very suitable for the exploitation of PV energy in the generation and storage of electric energy and to benefit from it in strengthening the national economy [2], [3]. Jordan announced in 2012 the renewable energy law, which allows any company or facility to install a renewable energy system to generate electric power to cover the electricity bill [4]. The increasing demand for energy and the high cost of its generation led to a rise in its price, which was directly reflected in a noticeable increase in electricity bills [4], [5]. These factors have greatly aided in the investment in PV energy. The PV system can provide the maximum power at a certain operating point, so maximum power point tracking (MPPT) methods are used to maximize the output power of the PV array by continuous tracking of the maximum power point [6]. With these challenges, several companies and institutions, as well as homes, have taken the initiative to install PV systems to generate electrical energy. The existence of PV power generation units with the national grid requires an energy management system at the level of consumer, production and generation companies [7].

The rapid developments in internet of things (IoT) technologies have contributed to new research interests in the field of energy management [8]-[11]. In the residential sector, the energy management system plays a vital role in managing demand for achieving better energy efficiency through smart control of various home entities. This can be achieved by employing artificial intelligence (AI) concepts in managing energy sources and customers' demands. There are several research papers and studies published in the field of smart grids and the control and management of various energy sources. In a smart grid, each household may have renewable energy generation and energy storage in addition to the inflexible and resilient energy loads [9] [10]. The load service entity tries to coordinate the energy consumption of these households to reduce the total energy cost. The main objective of home energy management system is to reduce electricity cost and peak demand problem by controlling electrical appliances along with improving energy quality [11]-[17]. The smart home proposed by Rajalingam and Malathi [14] consists of a smart electrical device, a PV system with a battery, a smart communication network and a controller. The selected controller schedules the power units in response to the electricity price at the time of use. Yoo *et al*. [18] proposed an energy management scheme that has the ability to predict load forecasting capability based on the Kalman filter. It is designed to increase the predictability in controlling energy flows between power system components and controllable electrical appliances in a building to provide electricity by taking into account critical peak prices for grid power. Guo *et al*. [19] developed an online control algorithm to reduce the average total energy cost of households within a neighborhood without knowing the relevant random model statistics. The proposed lyapunov algorithm is a very long analytical method that takes a lot of time. A fully centralized system introduced by Bellido-Outeirino *et al*. [20] to manage home appliances via a wireless sensor network. Management algorithms are based on consumption models along with a schedule of timing, power, temperature or ambient light measurements and priority plans.

There is a great trend in Jordan to use renewable energy sources to address the problems of generating power and obtaining clean energy while reducing the electricity bill. It is useful for consumers and service providers to analyze energy supply and demand. Muralitharan *et al*. [21] proposed an intelligent optimization approach to predict the energy demand of consumers. At the consumer end, a neural network-based forecasting method is used to understand consumer behavior in different weather patterns for a year, helping to maintain the lowest cost strategy in energy bills for their energy use. Mahmoud *et al*. [22] proposed an algorithm to reduce the local peak load for better use of the electricity infrastructure. It has been reported that under realistic conditions, the peak demand can be reduced by up to 96%. This approach would be useful in managing peak loads under different load dynamics and weather conditions.

It is clear that the power management system plays an important role in managing the electrical loads to ensure the optimal and safe performance of the smart grid. Therefore, the main objective of this research is the precise regulation of load consumption for all household appliances. This is done through optimal scheduling based on the load requirements and time of use of all household appliances, to ensure the lowest costs and high reliability. The rest of the paper is organized as follows; the PV system sizing calculation is given in section 2. The smart grid modeling in MATLAB/Simulink environment is illustrated in section 3. The design of the fuzzy controller of the MPPT is discussed in section 4. The energy management and load scheduling algorithm is given in section 5. The obtained results are discussed in section 6. Finally, the most important conclusions are given in section 7.

2. PV SYSTEM SIZE

The general layout of the proposed energy management of a smart home is illustrated in Figure 1. There are three sources of energy: the national electricity grid, PV energy, and storage unit (battery). The power supply to the loads is controlled by the power management algorithm. A fuzzy-based MPPT control algorithm is implemented to generate the maximum power from the PV array by adjusting the duty cycle of the PWM signal applied to the dc-dc converter. The fuzzy-based controller can track the maximum power much faster than other types [6]. In this section, the optimum size of the PV systems to meet the load requirements will be determined. Study the system productivity to works on load scheduling energy management in the right way, so the system must be chosen adequately in terms of size and characteristics, with the lowest cost and highest reliability.

An on-grid system was taken for this study; it increases the efficiency and quality of the whole system, so that it avoids any power outages as there is a backup storage with the battery. The proposed grid has three energy sources: photovoltaic, battery, and electric grid. With power management and load scheduling, the supply from the PV system will be the basis to cover the required loads to ensure that the bill is reduced to minimum for the consumer. The following steps were applied to determine the number of PV panels required (parallel and serial) to achieve the required power as well as the selection of the suitable inverter and the MPPT algorithm.

Step 1: determine load demand (consumption rate): this is done according to the monthly bills or according to the user's desire to cover a specific value for these bills.

Step 2: determine power to cover the demand of the loads: it is calculated by measuring the ratio between the average monthly consumption and the rate of production of the solar cells at the peak time.
Step 3: calculate the number of PV panels: the number of panels is calculated by dividing the required power by the power produced one panel.
Step 4: ensure that the space is sufficient for the number of panels calculated. If this is not enough, the calculations are repeated to match the area with the number of panels and the required power.
Step 5: inverters: the panels are distributed according to the inverters and maximum power point tracking inputs, and here it is possible to re-select the number of cells in proportion to the inverters.
Step 6: simulation: at this stage, a special design software such as "PVSyst" has been used to determine the geographical location of the installation site of the PV system.

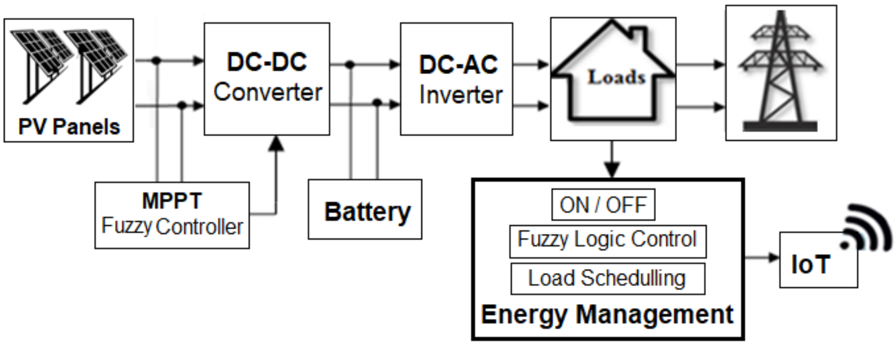


Figure 1. General layout of the proposed grid

3. SIMULATION OF A SMART GRID

A smart grid is an electrical grid that includes a variety of operating and energy procedures including renewable energy resources, battery storage unit, smart meters, smart distribution panels, circuit breakers and load control switches [13], [23]. This section deals with smart grid modeling in a MATLAB/Simulink environment. It covers simulation of proposed smart grid components of PV modules, DC-DC inverter, MPPT controller and load scheduling methodology. The energy sources in the proposed smart grid include PV systems, a storage system (battery).

3.1. PV power simulation

The amount of energy derived from the PV units depends on solar radiation and temperature. These two parameters are used in the simulation of a PV array. Figure 2 shows the theoretical I-V and P-V curves for the PV array at 25°C and 1000 W/m^2. The rest of the properties of the PV array worked on in the simulation are given in Table 1 in terms of the model and the number of parallel and serial strings.

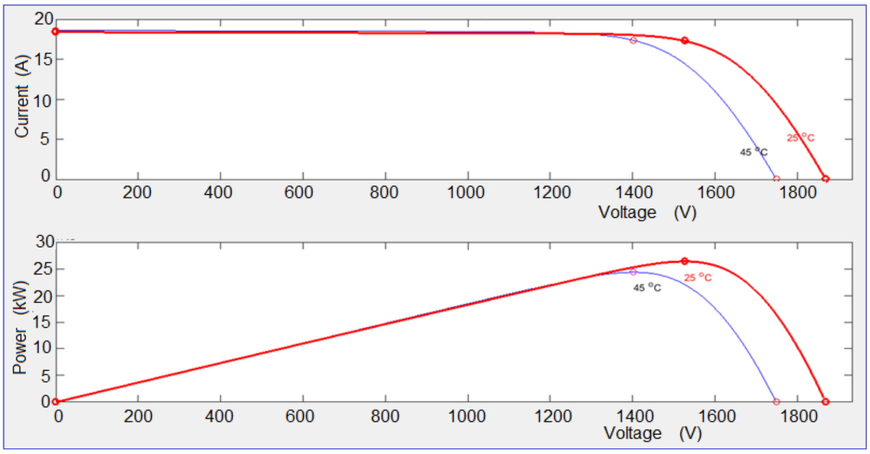


Figure 2. I-V and P-V curves of PV array

Table 1. Properties of the PV array

Array Data		PV Module Data	
Parameter	Value	Parameter	Value
No. of series connected modules/string:	40	Max. power (w):	329.9975
No. of parallel strings:	2	No. of cells/module:	72
		Open circuit voltage Voc (V):	46.72
		Short circuit current Isc (A):	9.19
		Voltage at MPP (V):	38.15
		Current at MPP (A):	8.65
		Temp. coefficient of Voc (%/deg.C):	-0.31999
		Temp. coefficient of Isc (%/deg.C):	0.055996

3.2. Battery simulation

When the generated photoelectric power is less than the power required for the loads, the battery must supply the load. As another case, when it generates more power than the power consumed on load, the batteries will be charged to keep the two voltage points constant. The battery side parameters are made up in the simulation are: charge state (SOC), current (A), and voltage (V).

The battery is connected with a bidirectional commemorative for charge and discharge. A gate of bidirectional has been connected with positive side switch (PSw), and negative side switch (NSw), as illustrated in Figure 3. For the battery controller, there is a pulse width modulation (PWM) signal applied to both switches (PSw and NSw). The duty cycle of the PWM signal is adjusted by the fuzzy controller. The battery controller will be divided into two stages; when there is excess in the solar array where the battery is charged, and when the loads increase and the energy generated from the solar system is not enough. As a result, when the radiation is zero, the PV power side is zero, as shown in Figure 4. The battery current is going around 15 A, the charge state (SOC) will decrease so that the battery is discharged. When the radiation rises to 300 W/m^2, the battery will start charging, the SOC will increase, and the PV power will be greater than the consumer power required for the load.

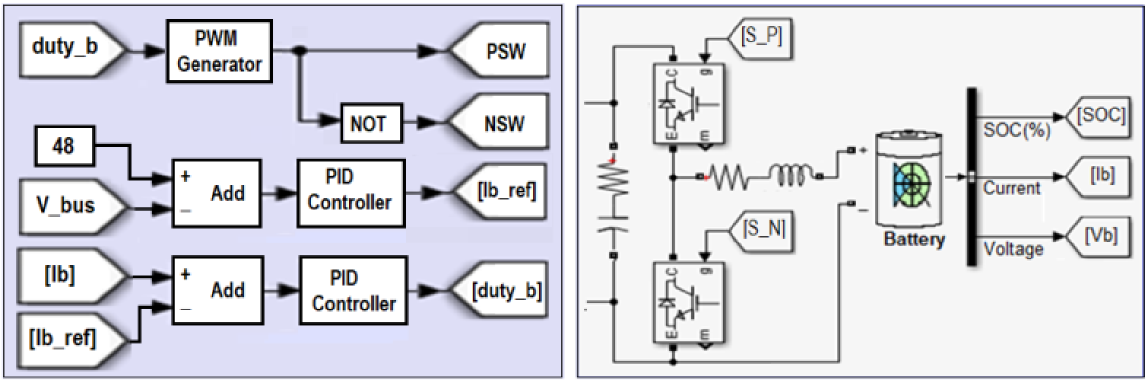


Figure 3. Battery side simulation

3.3. Utility grid simulation

In this simulation, the utility grid is expressed as a backup storage. In the absence of PV output and when the battery is empty, the loads will be fed from the electrical grid.

3.4. Boost converter simulation

The boost (step up) converter is a class of switched-mode power supply. It is a DC to DC converter that increases the voltage while the current is stepped down from the input source (solar panels). The output will be greater than the source voltage. The MOSFET gate of the boost converter is controlled by a pulse generated from the MPPT controller. Figure 5 shows a simulation of both the boost converter and the MPPT controller. It is used to check the PWM signal generated by the MPPT and the interest gained from the converter using a fuzzy controller.

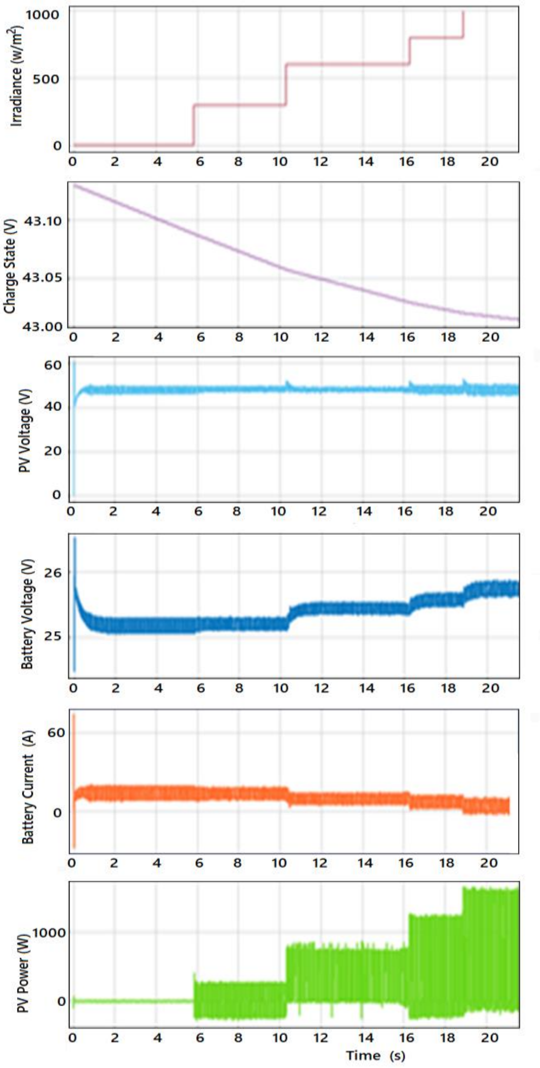


Figure 4. Battery controller result

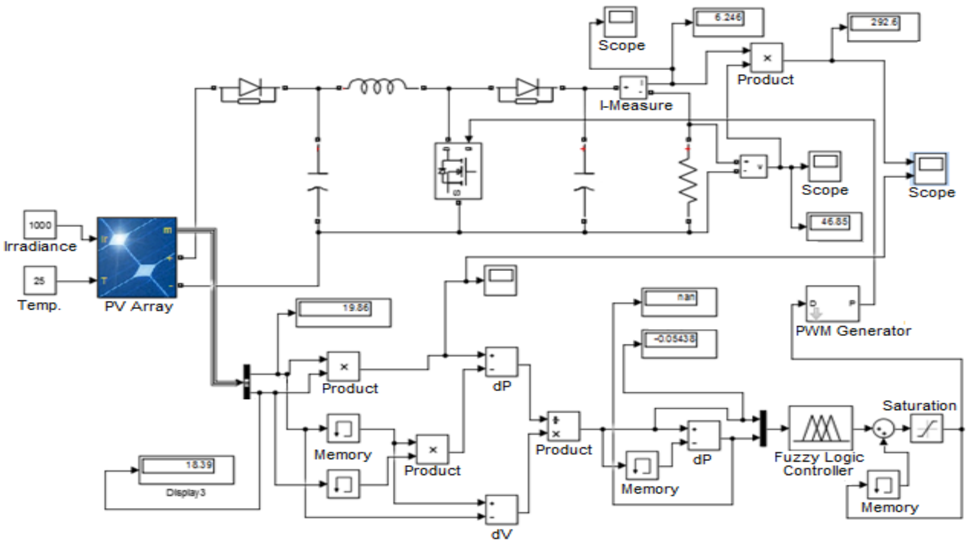


Figure 5. Simulation of a MPPT and boost converter

4. FUZZY-BASED CONTROLLER FOR MPPT

Fuzzy logic is widely used in AI applications as it is an effective tool for dealing with ambiguous and vague information [24], [25]. In this paper, fuzzy logic concepts were employed in MPPT design for tracking, capturing and delivering the largest capacity of a network PV system. The fuzzy controller does not require accurate mathematical models and deals very well with nonlinear systems. Such a controller can provide powerful performance under parameters and loads variation. The inputs of the MPPT logic controller are error and change in error. This control method is simple and allows the PV generator voltage to be regulated regardless of the weather variation to obtain the most power.

The fuzzy controller is adopted to assist the conventional MPPT technique to obtain the maximum power operating point faster. The general layout of the proposed fuzzy logic controller is given in Figure 6, it consists of four main components: fuzzification, fuzzy rules, fuzzy inference engine and defuzzification. The implemented fuzzy controller is based on Mamdani's fuzzy inference method, and the centroid method was used as a defuzzification process. The input variables are the error (E) and change in error (ΔE). The error input variable (E) represents the derivative of the change of power with respect to change of voltage.

$$E(n) = \frac{\Delta P}{\Delta V} = \frac{Ppv(n) - Ppv(n-1)}{Vpv(kn) - Vpv(n-1)}. \text{and } \Delta E(kn) = E(n) - E(n-1)$$

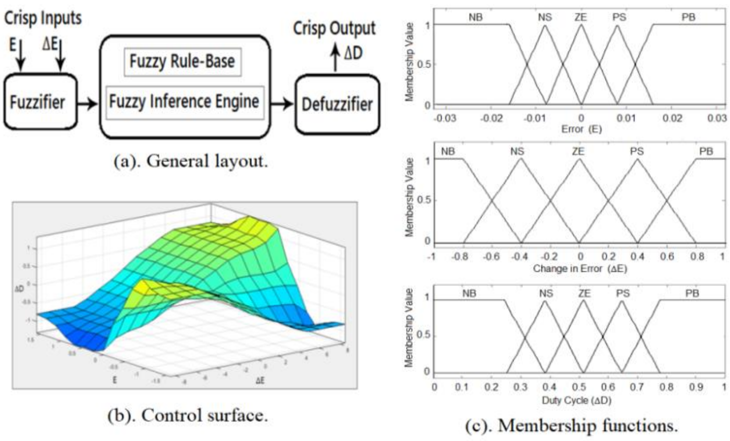
The input and output variables are represented by linguistic variables using five fuzzy subsets; negative big (NB), negative small (NS), zero (Z), positive small (PS) and positive big (PB) have been chosen. Figure 6 illustrates the membership functions used for the input and output variables. The main function of the implemented fog controller is to select the appropriate duty cycle (D) of the PWM signal to adjust the operation of the boost converter. Since five fuzzy sets are used to represent each of the input variables, there are 25 rules to explain the relationship between the input variables (E & ΔE) and the output variable (D), as shown in Table 2. Each rule is represented by an IF-THEN statement such as;

If EPS and ΔENB then ΔDNS

This means that if error is positive small and change in error is negative big, then the change in duty cycle is negative small. The control surface that displays the relationship between the inputs (E and ΔE) and the output (ΔD) is given in Figure 6. Hence, the fuzzy logic controller will update the duty cycle of PWM according to the measured voltage and calculated power of PV array.

Table 2. Fuzzy rules for MPPT controller

		Error (E)				
		NB	NS	Z	PS	PB
Change in Error (ΔE)	NB	PS	PB	NB	NB	NS
	NS	PS	PS	NS	NS	NS
	Z	Z	Z	Z	Z	Z
	PS	NS	NS	PS	PS	PS
	PB	NS	NB	PB	PB	PS



(a). General layout. (b). Control surface. (c). Membership functions.

Figure 6. Fuzzy logic controller

5. ENERGY MANAGEMENT

The scheduling of appliances in the home is according to the priority given to each appliance and peak hours to reduce energy consumption as much as possible. Work begins by prioritizing appliances in the home and then prioritizing that over peak hours for renewable energy production. All devices were divided according to priority into three categories:

- High priority loads; such as lighting, refrigerator, and air conditioner
- Medium priority loads, such as TV and computer
- Low priority loads, such as iron, water heater and vacuum

High priority loads are activated instantly, and other loads are scheduled according to their priority. Figure 7 represents the flow diagram of the proposed power management scheme. Load scheduling is achieved according to the operating load methodology based on their priority and availability of energy production from renewable energy. Figure 8 shows a simulation of loads scheduling and supplying from the available energy source according to the energy management algorithm in order to make the electricity bill as low as possible. Energy management is realized by making use of the energy sources available in the grid. If the load consumes more power than the PV output, the load will be fed from the electrical grid, while if the battery output covers the loads being fed, the switch will be closed for feeding from the PV modules.

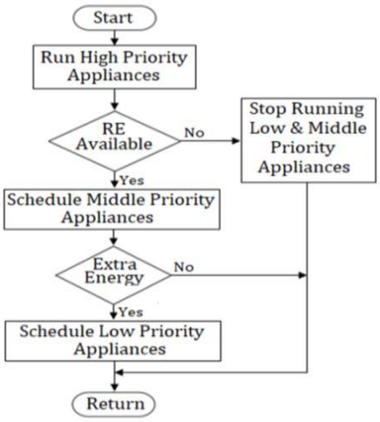


Figure 7. Load scheduling flowchart

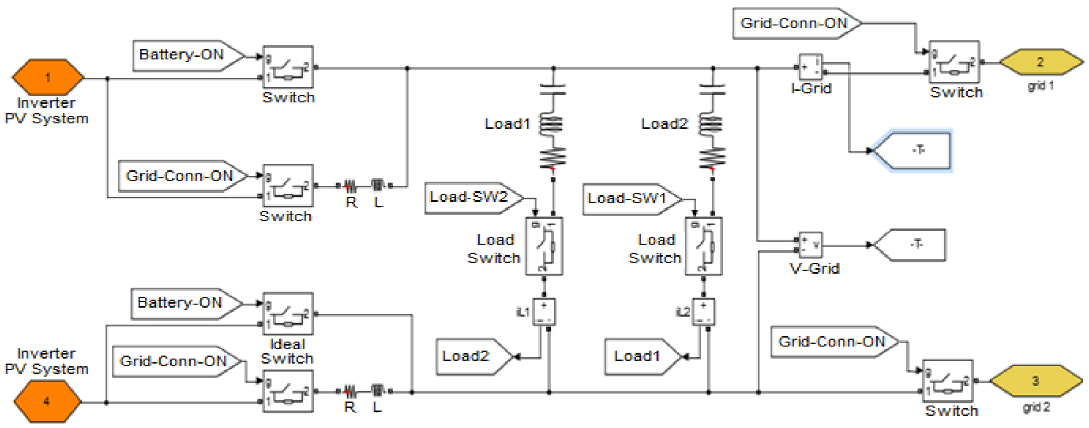


Figure 8. Home loads control in MATLAB tool box

6. RESULTS AND DISCUSSION

MPPT has a clear impact on power management, and without it the system will take the required voltage to charge the battery or feed the system from the solar cells and leave the excess voltage without investment, and as a result there is a massive waste of energy. But with MPPT, it takes every point of maximum power in every signal. This seeks to conserve energy from wastage and exploitation as large as possible, and to preserve battery life. As given in the results, the boost converter worked to increase the value of the voltage from 300 V to 600 V. Obtaining the maximum power point automatically based on fuzzy logic controller of the MPPT had a big impact on the obtained results.

This algorithm takes into account the variation in radiation and temperature over time as well as the impedance of the load. These factors affect maximum power point and are reflected in the amount of generated electricity. The results indicated in Figure 9 illustrate the other side of the energy management algorithm by scheduling the loads according to the peak times and the power available to feed the loads in the house. Figure 10 shows a more detailed explanation of the energy management aspect of available energy sources. It shows whether the energy source is PV, battery or grid and the amount of power consumed by the loads from the grid. It also shows how the charge and discharge movement, battery consumption and the latest graph represent the amount of PV output.

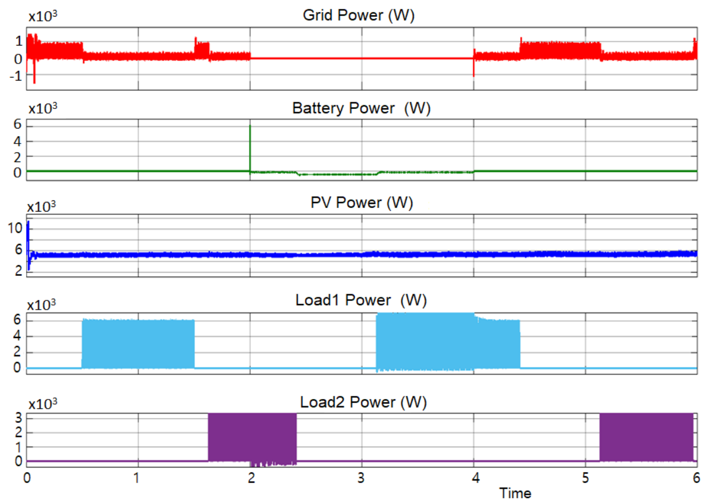


Figure 9. Results of energy management

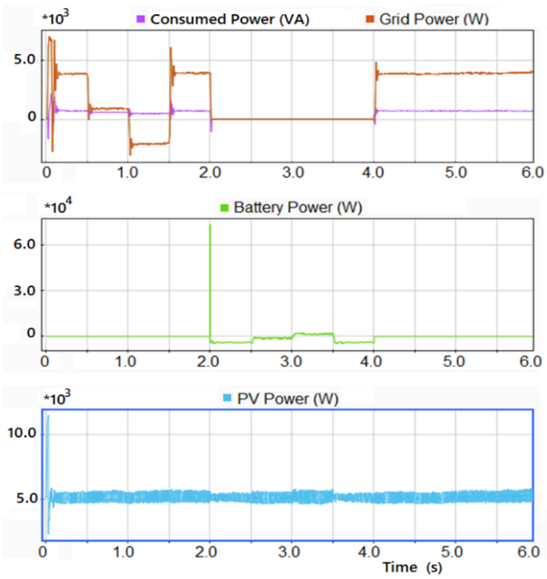


Figure 10. Energy management aspects of the existing energy sources

7. CONCLUSION

Rapid developments in computer and communication technology have contributed to the employment of AI concepts in the processes of controlling power generation and distribution, as well as scheduling loads in homes. A smart grid containing a PV system, a storage unit and a national grid was considered in this study. An energy management algorithm has been implemented to achieve the main objective of reducing the electricity bill as much as possible. The algorithm involves scheduling the loads by giving priority to each load. The loads are supplied with the required power as per the priorities and available power source. A simulation of smart grid and home loads was implemented on MATLAB/Simulink to analyze energy management and load scheduling. The obtained results indicate that providing the PV system with MPPT based on fuzzy logic indicates an increase in system efficiency more than without it. The results also indicated the effectiveness of the proposed energy management algorithm in scheduling loads and ensuring the lowest electricity bill.

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