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Adaptive Energy Management System for Smart Hybrid Microgrids

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Abstract
The energy management will play an important role in the future smart grid by managing loads in an intelligent way. Energy management programs, realized via House Energy Management systems (HEMS) for smart cities, provide many benefits; consumers enjoy electricity price savings, and utility operates at reduced peak demand. This paper proposed an adaptive energy management system for islanded mode and grid-connected mode. In this paper, a hybrid system that includes distribution electric grid, photovoltaics, and batteries are employed as energy sources in the residential of the consumer in order to meet the demand. The proposed system permits coordinated operation of distributed energy resources to concede necessary active power and additional service whenever required. This paper uses home energy management system which switches between the distributed energy and the grid power sources. The home energy management system incorporates controllers for maximum power point tracking, battery charge and discharge and inverter for effective control between different sources depending upon load requirement and availability of sources at maximum powerpoint. Also, in this paper, the Maximum Power Point Tracking (MPPT) technique is applied to the photovoltaic station to extract the maximum power from hybrid power system during variation of the environmental conditions. The operation strategy of energy storage systems is proposed to solve the power changes from photovoltaics and houses loads fluctuations locally, instead of reflecting those disturbances to the utility grid. Furthermore, the energy storage systems energy management scheme will help to achieve the peak reduction of the houses daily electrical load demand. The simulation results have verified the effectiveness and feasibility of the introduced strategy and the capability of the proposed controller for a hybrid microgrid operating in different modes.

KEYWORDS: Inverters, Converters, Micro-grid, Photovoltaics, Batteries, Utility Grid, House loads.

I. INTRODUCTION

The influence of renewable energy resources and units of energy storage in distribution systems can greatly alter the performance of the network grid [1], and integration in the distribution grid has positive effects such as improvement of reliability, bus voltage profile, and reduce grid losses. In addition to the benefits, unwanted management of simultaneous network operations can shorten its life. Therefore, an optimal management schedule is required for the proper operation of these units. One of the main goals of a distribution grid operator is to reduce operating costs, to reduces electricity bills [2]. Moreover, reliability is another important goal in studying power distribution networks, which play an important role in distribution studies that play a significant role in improving system performance especially in reducing subscriber blackouts and any operational program is not acceptable regardless of reliability indicators in modern power systems [3].

The incorporation of different distributed energy resources, energy storage system and electrical loads distributed into the renewable energy system is called microgrid [4]. Recently, there has been a lot of interest in using microgrids in power systems as it is considered to be a flexible and smart active energy grid. In addition, it can improve system reliability, efficiency, and safety, and promote the integration of renewable energy sources [5]. The microgrid can be connected to the grid or distributed energy resources can be used to deliver the load without the network. Incorporation of distributed energy resources and controllable load into the distribution network creates unique challenges for managing the energy management system. The main role of microgrid energy management system is to determine the optimal transmission of microgrid and main network energy independently every hour to meet the demand demands of the load. The literature offers different proposals for microgrid energy management systems with different algorithms and different microgrids such as in research [6]. The rest of this paper is organized as follows. Section II presents a description of the related works. Section III presents the overall energy management system. Section IV presents a description of the proposed system in this paper. Section V presents the mathematical model of the distributed hybrid generation system, section VI presents the control methods for photovoltaics and the battery system, section. Section VII presents the proposed houses energy management systems, the section VIII presents results of the proposed system, Finally, section IX concludes the paper.

II. Literature Review

The methods and models for implementing smart home energy management systems have recently received considerable attention. In this section, we review relevant research covering energy management strategies in the context of areas related to this work, namely: cost savings; load and PV generation forecasting; modeling complexity temporal resolution; and retail tariff settings, battery degradation, and computational feasibility. In [7] the authors propose optimal power management for grid-connected hybrid power generation systems, including photovoltaics, wind turbines, fuel cells, and electrolysis. The system trades electricity with the local network using real-time electricity pricing over a 24-hour horizon/period based on simulation results. The interior search algorithm was used to optimize energy management in the above case. In [8], the authors proposed a centralized system for energy management of microgrid in Island mode and grid-connected mode. In Island mode, the fuel cell will only work if the battery is less than 80%. grid connected mode requires a 60% threshold to ensure reliable operation. In [9], the authors suggested the energy management system to hybrid microgrid with wind-turbine, photovoltaics, and battery power. The control and data acquisition system work in real-time. The power management system is based on a set of rules that improve MG performance by controlling and monitoring power generation, loads, and storage items [10], the authors proposed an energy management system for the isolated microgrid. The isolated event was treated as a natural probability distribution of failure within the utility network. The aim was to reduce microgrid operating costs. This includes costs associated with running a small turbine, wind turbine, batteries, and loads. In [11], the authors proposed an energy management system to hybrid AC and DC Microgrid which guarantees economic transmission despite doubts associated with the use of renewable energy sources. the load control is on-demand, taking into account generators, controllable loads, and battery charge/discharge limits (thermal and electric vehicles).

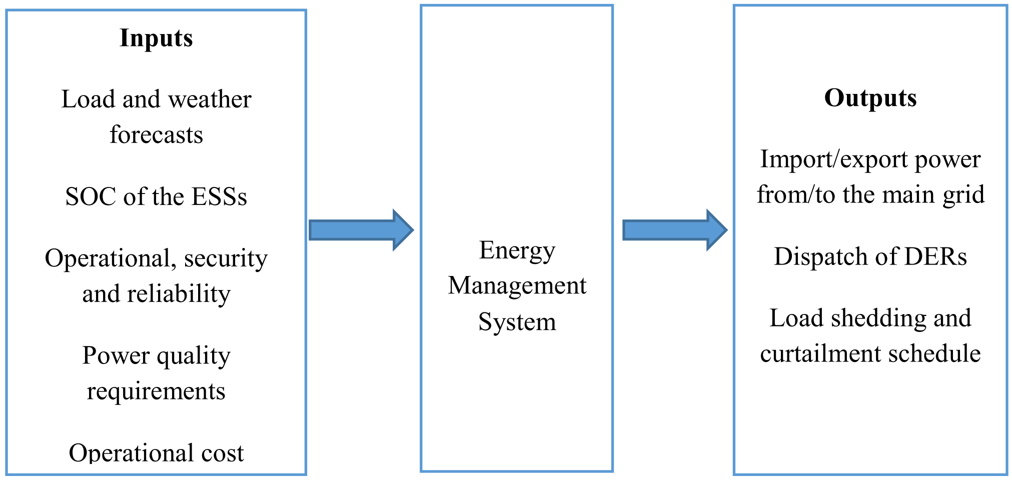
III. Energy Management System Overview

The system of energy management can be defined as an automated, real-time, and comprehensive, automated system used for optimum scheduling and management of demand energy response and manageable load and operating within the distribution system. The power management system provides data management, monitoring, and network information, and controls all automatic energy storage system(ESS) and distributed generation systems(DGS) that compose the microgrids [12].

The main features of the energy management system are [13]:

1. Maximize energy availability for each customer and increase system reliability.
2. Reducing energy loss, operating cost.
3. Maximizing the usage of renewable energy resources.
4. Reduced energy purchased outside the microgrid.
5. Manage all distributed generators, energy storage systems, and controllable load when resynchronization with the utility grid.

The energy management system requires data input such as the forecast of the non-dispatchable generation unit, electrical/heat load forecast, energy price, the state of charge (SoC) of the energy storage system, energy prices, forecasts of the thermal or electrical loads, operational reliability and security constraints of the grid, and information about the PCC (common coupling point) operation with the utility grid [14]. All this data is collected by the energy management system and develops a series of control procedures. The purpose of these actions is to reduce the total operating cost of the microgrid network and the energy bill paid by consumers, while reducing the network losses and emissions, and increasing the energy quality and reliability experienced by consumers [15]. Therefore, the energy management system provides output level information on utility (export / import power to main network), DER level (disconnection / connection or dispatch scheduling), and to the loads level As illustrate in Figure 1 [16].



Figur.1: Input and output data in the energy management system

IV. PROPOSED SYSTEM DESCRIPTION

Figure.2 illustrates the overall configuration of the proposed system which includes a photovoltaic system with maximum power point tracking control, inverter and battery control, and control. The system integrates battery power as a backup unit to run critical loads and maintain voltage and frequency microgrid in emergency situations. The battery is usually placed in parallel with the photovoltaic system. The battery is usually placed parallel to the photovoltaic system. The batteries either absorbs or injects real power via a converter. The converter operates in boost mode when the battery supplies power to the network or load and operates in buck mode when the battery draws power from the photovoltaic. The battery injects or absorbs real power via a converter. The batteries are usually placed in parallel with the photovoltaics system. The converter operates in boost mode when the battery provides power for load or the grid and is on when the batteries feeds the power to load or grid and operates in buck mode when the batteries draws power from photovoltaic. The lead-acid batteries are commonly selected for photovoltaic application.

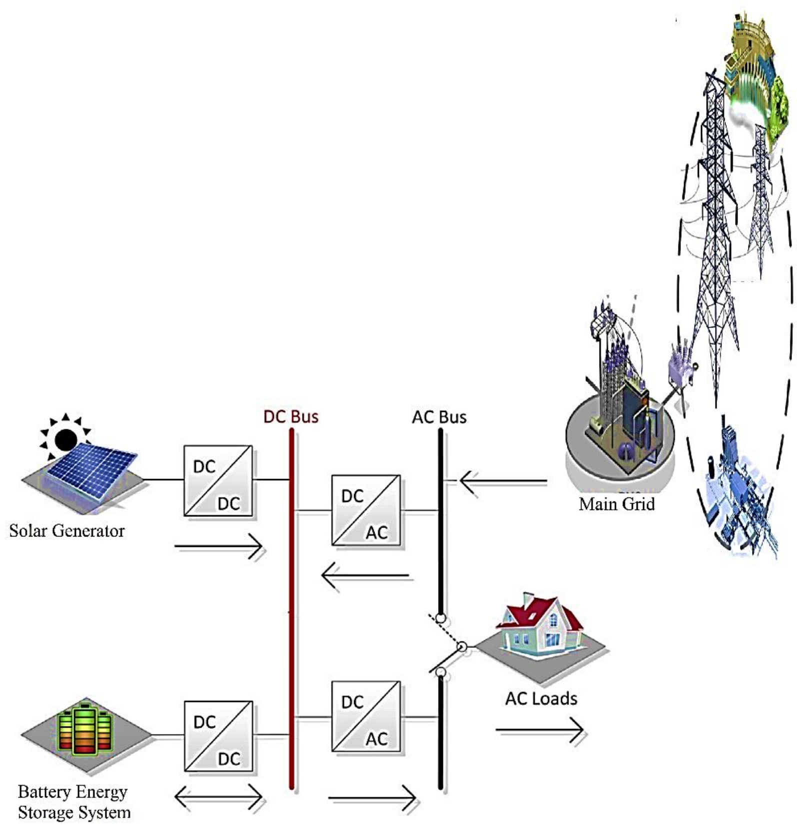


Figure.2: The proposed system structure

V. Distributed Hybrid Energy Generation System

A. Modeling of PV Cell

Figure.3 illustrates the equivalent circuit based on the single diode model of PV cell which can be represented as a current source, diode, series resistance, and parallel resistance. The I-V characteristics of PV cell are described by the mathematical standard equation which is [17]:

$$I = I_{ph;cell} - I_{0;cell}\left[\exp\left(\frac{q(V+IR_{s;cell})}{akT}\right) - 1\right] - \frac{V+IR_{s;cell}}{R_{p;cell}} .. (1)$$

Where:
I_{PH}, *the cell* is the photocurrent (A) of the PV cell which represents the current source,
Id, the cell is the current (A) computed by the Shockley diode equation of PV cell,
I_o, *the cell* is reversed leakage or the saturation current of the PV cell diode,
q is the electron charge ($1.602 \times 10^{-19}\ C$),
k is the Boltzmann's constant ($1.38 \times 10^{-23}\ J/K$),
T is the temperature of the diode measured in Kelvin (K),
R_s, the cell is the series resistance of PV cell (Ω),
R_p , the cell is parallel resistance of PV cell (Ω) and

If the series and parallel resistances of PV cells are not taken into account, then the model of the PV cell is the ideal model. Figure 4 illustrates the I-V curve derived from Equation (1) for the ideal PV cell. It is noted that the net output cell current (I) results from the difference between I_{PH}, cell and I_d,cell of PV cell [18,19].

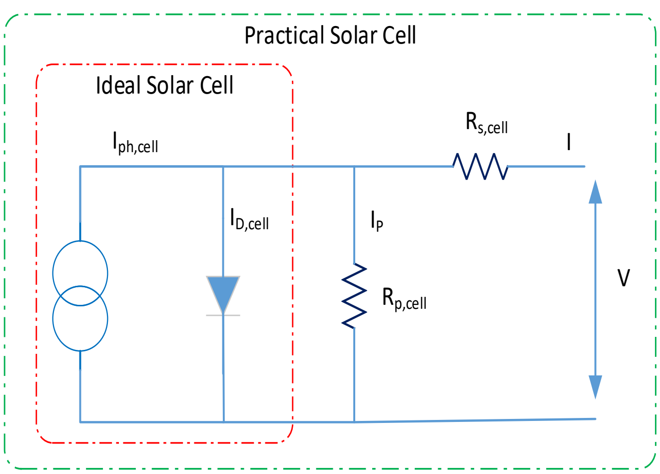


Figure 3: The equivalent circuit of the PV cell

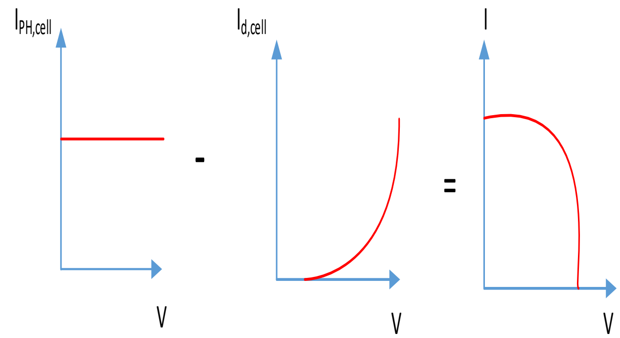


Figure 4: A typical I-V curve of PV cell

B. Modeling of PV Module

As stated earlier, a PV module is composed of PV cells jointed in a series and parallel forms. Therefore, the mathematical standard Equation is derived from Equation (1) and the description of the I-V characteristic of the PV module becomes [20]:

$$I = I_{PH} - I_O\left[exp\left(\frac{V+IR_S}{a\,Vt}\right) - 1\right] - \frac{V+IR_S}{Rp} \qquad \ldots\ldots (2)$$

where:
I_{PH} is the photocurrent (A) of the module
Vt is the thermal voltage of the module which is equal to $NskT/q$ where *Ns* refers to the number of series-connected cells,
I_O is reverse leakage current of the module,
R_S is the series resistance of the module and
R_p is the parallel resistance.
Equation (2) produces the I-V curve as indicated in Figure 5, where three salient points are bolded:

1. Short circuit current point (0, I_{sc}).
2. Maximum power point (MPP) (V_{mpp}, I_{mpp}) located at the V-I curve.
3. Open circuit voltage point (V_{oc}, 0).

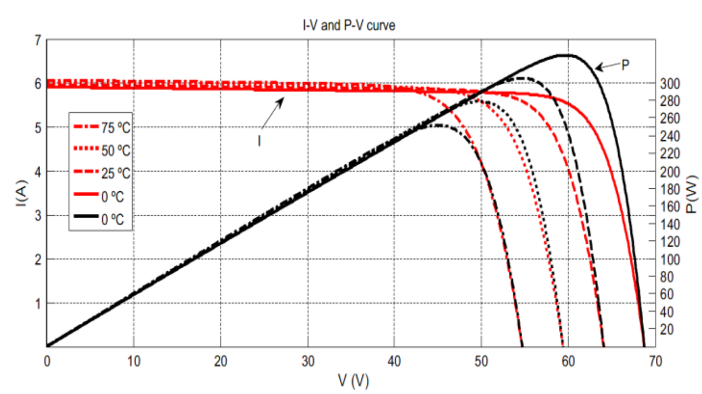


Figure 5: I -V, P - V curves of a practical photovoltaic module at different temperature levels and constant insolation

The photocurrent of a PV module (I_{PH}) depends on the amount of the solar irradiance falling on the module and the PV cell temperature corresponding to the below Equation [21]:

$$Iph = \frac{G}{Gn}(I_{ph;n} + Ki\Delta T) \quad \dots (3)$$

where:

$I_{PH.n}$ is the photocurrent under the nominal condition (usually $25C^{O}$ temperature and 1000W/m2 irradiance), ΔT is the difference between the actual temperature (T) and the nominal temperature (T_n) of the PV cell and they are measured in°C,

G_n is the nominal irradiance (1000 W/m2).

G is the solar irradiance measured in W/m2,

Ki is the temperature coefficient.

While the open voltage circuit (V_{oc}) depends on the cell temperature corresponding to the below Equation:

$$V_{oc} = V_{oc;n} + K_v \Delta T \quad \dots (4)$$

where:

K_v is the temperature coefficient of the open-circuit voltage and $V_{oc;n}$ is the open-circuit voltage under the nominal conditions. The diode saturation current (Io) can be obtained according to the below Equation:

$$I_o = \frac{I_{sc;n} + K_i \Delta T}{exp\left(\frac{V_{oc;n} + K_v \Delta T}{a\,V_t}\right) - 1} \quad \dots (5)$$

where $I_{sc;n}$ is the short circuit current under the nominal conditions [19].

B. Battery Storage System

Battery storage systems store the extra energy generated by renewable energy generation systems. However, if there is a lack of energy from the renewable energy generation system, the battery bank will be discharged to meet the demand for the load. the model of the battery as follows [22]:

$$SOC_{bat} = 100\left[1 - \left(\frac{1}{Q_{bat}} * \int_0^t i_{bat}(t)dt\right)\right] \quad \dots (6)$$

$$B_{AH} = \frac{1}{3600}\int_0^t i_{bat}(t)dt \quad \dots (7)$$

where SoC_{bat} is the battery state of charge (%), Q_{bat} is the maximum battery capacity (Ah), i_{bat} is the battery current and B_{AH} is the battery ampere-hour. The battery's initial state-of-charge (SoC) is set to 80%. In this system, the battery is modeled according to the characteristics of deep-cycle lead-acid batteries with discharge efficiency assumed to be 90%.

C. Loads

The loads consist of residential and commercial loads. Commercial loads appear on asynchronous devices to show the effect of commercial inductive loads, such as air conditioning systems, on the Microgrids. Residential loads are designed according to the daily non-seasonal consumption profile of the resort island. Residential loads are simulated according to the actual difference in the specific load profile for the specified resort island.

VI. The Proposed Control method for photovoltaics and Battery system

To ensure a stable response in the hybrid microgrid network during normal operation, figure 6 and figure 7 illustrates two news proposed control methods. In this paper, the investigation is carried out to choose the state which has a major influence on the DC-link voltage state. This will lead to reducing the controller effort needed to limit the DC-link voltage and thus using a small controller gain, which preserves the stability.

A. The Control of the converter interfaced Photovoltaics

A single-phase boost phase is used to boost the voltage from the panel and maximum power point tracking. The input current (I_{PV}) is sensed before the input capacitance along with the panel voltage (V_{PV}). These two values are used in the maximum power point tracking algorithm. The maximum power point tracking algorithm calculates a reference point the panel input that needs to be maintained at to be at the maximum powerpoint. The maximum power point tracking is realized using an inner current loop and an outer voltage loop, as shown in Figure.6. Therefore, the sign for the outer voltage compensator reference and feedback are reversed. Note that the converter output has not been adjusted. To prevent the output voltage from rising higher than the rating of the components, the voltage feedback is mapped to the internal comparators, which can do a cycle by cycle trip of the PWM in the case of overvoltage.

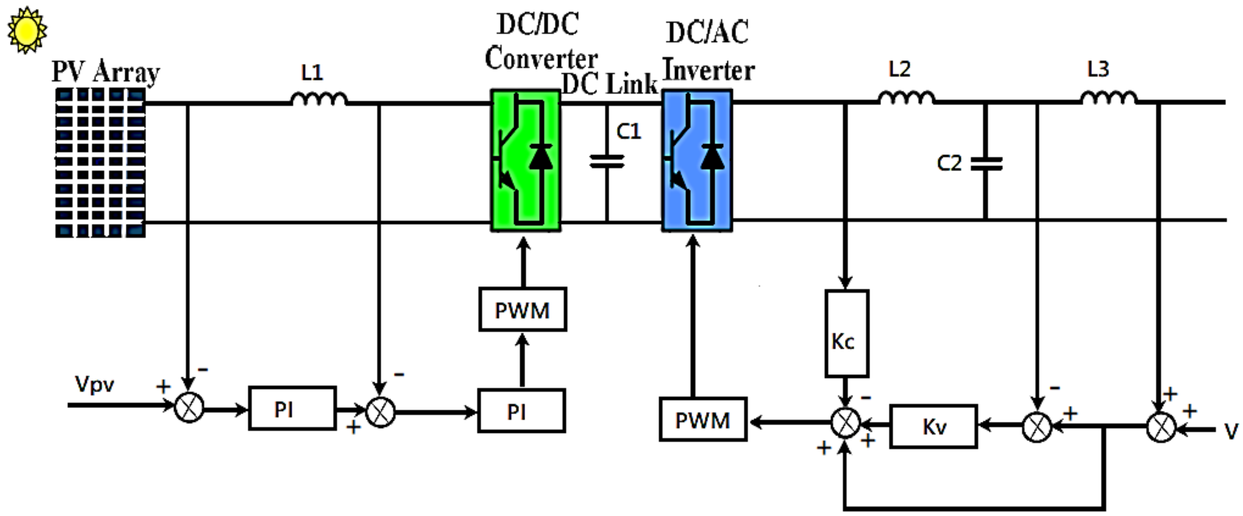


Figure.6: The proposed controller of the converter with maximum power point tracking

B. The Control of bidirectional-converter interfacing battery

In the proposed system, as shown in Fig.2, the bidirectional converter consists of the high-frequency inductor and the output filter capacitor and two switches that allow bidirectional current flow. In the power management method, there is a two-voltage controller with adequate limitation blocks to achieve the required power flow under different conditions. These controllers produce a reference current for energy storage. The first control unit is to regulate the DC-Bus voltage, and the second controller is to control the battery voltage. In order to improve the power management in the hybrid microgrid, backup energy storage is included. It consists of a battery connected to a DC bus with a bidirectional converter. This converter performs multiple functions: it acts as a battery charge regulator in grid-connected operation, and a boost converter to deliver energy from the batteries to the microgrid when the fuel cell and photovoltaics sources have insufficient power to feed the loads (AC loads and DC loads) in islanded operation. In island mode operation, the most favorable operating conditions occur when the load energy and the photoelectric extracted power agree, that is when the converter does not process power. Figure.7 shows a simplified phase of the converter power and its bidirectional control structure.

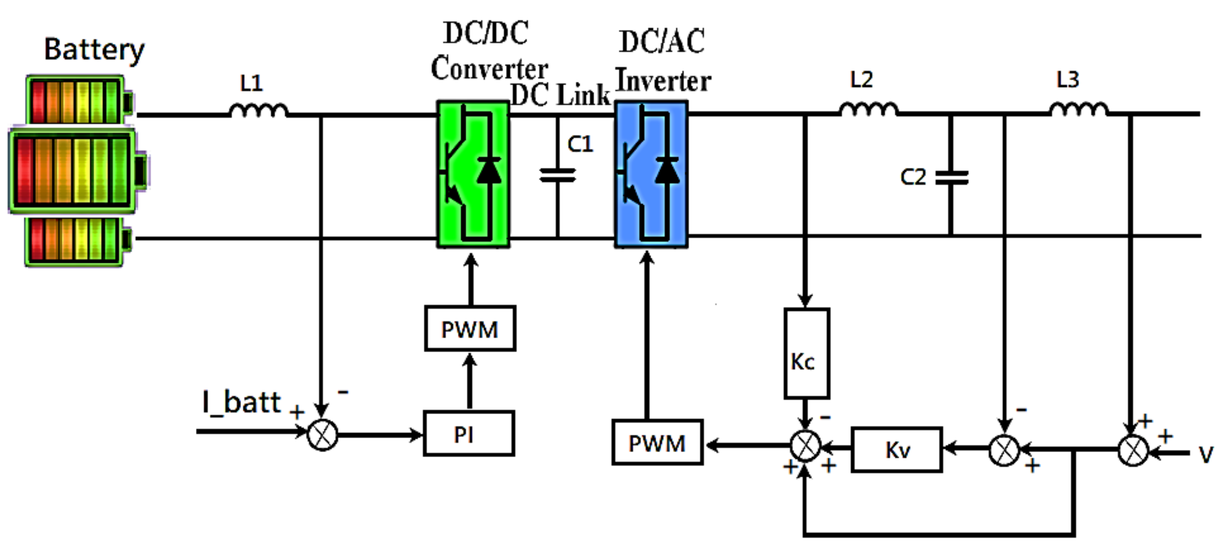


Figure.7: The proposed controller of battery storage

VII. THE PROPOSED HOME ENERGY MANAGEMENT SYSTEM

In islanded mode, the battery is used as a backup power source when the photovoltaic generated power is less than the customer's energy demand. In this mode, when the photovoltaic source produces more power than that of connected loads, then the excess power is stored in the battery. The energy stored in a battery is used whenever the power demand of consumption exceeds the actual photovoltaic power generation. In the mode of grid-connected operation, the battery is enabled to charge from utility power and photovoltaic. In this operating mode, the energy generated by the photovoltaic cells is delivered to the batteries at a constant rate. At the time of beginning, photovoltaic array produces lower power from which the battery can't charge. During this condition, grid power is taken by the inverter as supplementary energy. As soon as the battery charge power reduces, the inverter begins to supply power into the grid. Once the battery gets fully charged, all the generated power from photovoltaic delivered to the grid.

The hybrid microgrid real power exchanged with the grid $P_{grid}(t)$ is the sum of the photovoltaic generation system P_{PV} , the $P_{Batt}(t)$ and loads (Figure.2).

$$P_{grid}(t) = P_{PV}(t) + P_{Batt}(t) - P_{Load}(t) \qquad \ldots(8)$$

During such a long time, the fast power variations exchanged with the battery $P_{Batt}(t)$ can be neglected. Equation (8) is expressed over a long range of time as follows:

$$\{P_{grid}\}T = \{P_{PV} - P_{Load}\}T \qquad \ldots(9)$$

During such a short time, the batteries masters the power flow thanks to its fast response time. The power reference of the battery $P_{Batt}(t)$ can be calculated by the inversion of the Equation (8) as:

$$P_{Batt}(t) = P_{grid}(t) - P_{PV}(t) + P_{Load}(t) \qquad \ldots(10)$$

The battery has an extremely fast charging and discharge response, and so in this study, Batteries are used for the DC-Bus voltage control of the hybrid microgrid. The storage capacity of battery is subject to the following constraints:

$$E_{Batt\,min} \le E_{Batt}(t) \le E_{Batt\,max} \qquad \ldots(11)$$

where $E_{Batt\,min}$ and $E_{Batt\,max}$ are the minimum and maximum allowable storage capacities of batteries. $E_{Batt\,min}$ is determined according to the following equation.:

$$E_{Batt\,min} = SOC_{Batt} \times E_{Batt\,max} \qquad \ldots(12)$$

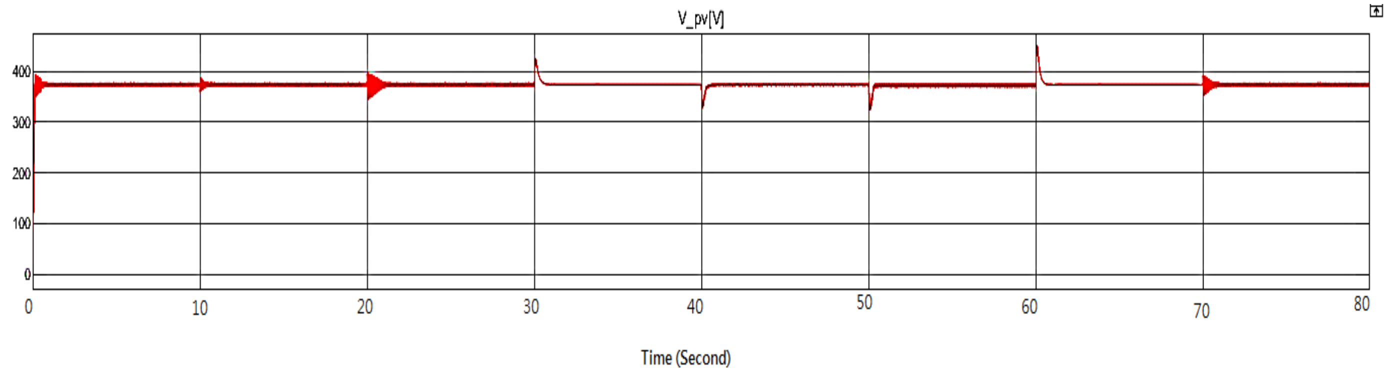
The houses microgrid can exchange power with local grid. The surplus produced power of the photovoltaic after charging batteries is sold to the grid. If the total produced power of the hybrid microgrid cannot satisfy the demand, power will be purchased from the utility grid.

VIII. THE RESULTS OF THE PROPOSED SYSTEM

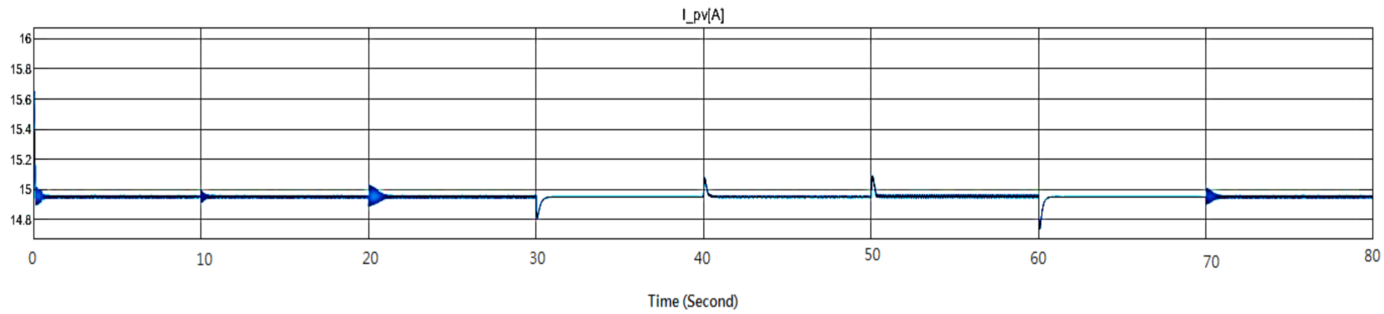
To show the effectiveness of the proposed control method, a proposed microgrid is simulated using Matlab/Simulink to validate the performance. This microgrid consists of photovoltaic and battery units. The parameters are listed in Table I. The performance has been tested in both grid-connected and island mode during unintentional islanding. In grid-connected mode, the photovoltaic generates MPPT reference and the battery generates reference sent by control. At first, the batteries are assumed to be fully charged and the load is not connected to the system yet. The power grid is connected to domestic from the distribution transformer. The surplus power from the home energy management system is fed into the power grid. Also, it can supply power to the home energy management system in the case of a shortage of power generation in the photovoltaic system. This transfer of power between home energy management system and power grid takes place with the help of a bidirectional DC to AC inverter. The photovoltaic is allowed to operate at its standard test condition with an operating $1000\,W/m2$ Irradiation and $25C^{o}$ temperature. The simulation is carried out for 80 seconds. The total power generated by the photovoltaic is maintained constant at 6 kW by the MPPT controller. Figure 8 shows the output current and voltage for the photovoltaic power generation.

Table 1: Simulation Parameters

Parameter	**Value**
k_p	25
k_i	60
ω	$2\pi \times f$
f	*50*
V	220 V
X	1 mH
R	0.08Ω



(a)



(b)

Figure.8: (a) the photovoltaic voltage at MPPT and (b) the photovoltaic current at MPPT

System load will take effect at the specified time interval. In this study, two rated PQ loads with the real power of 4 kW and 100 AVR are connected to the home energy management system. Figure 9 shows the time interval when loads are being connected to the home management system

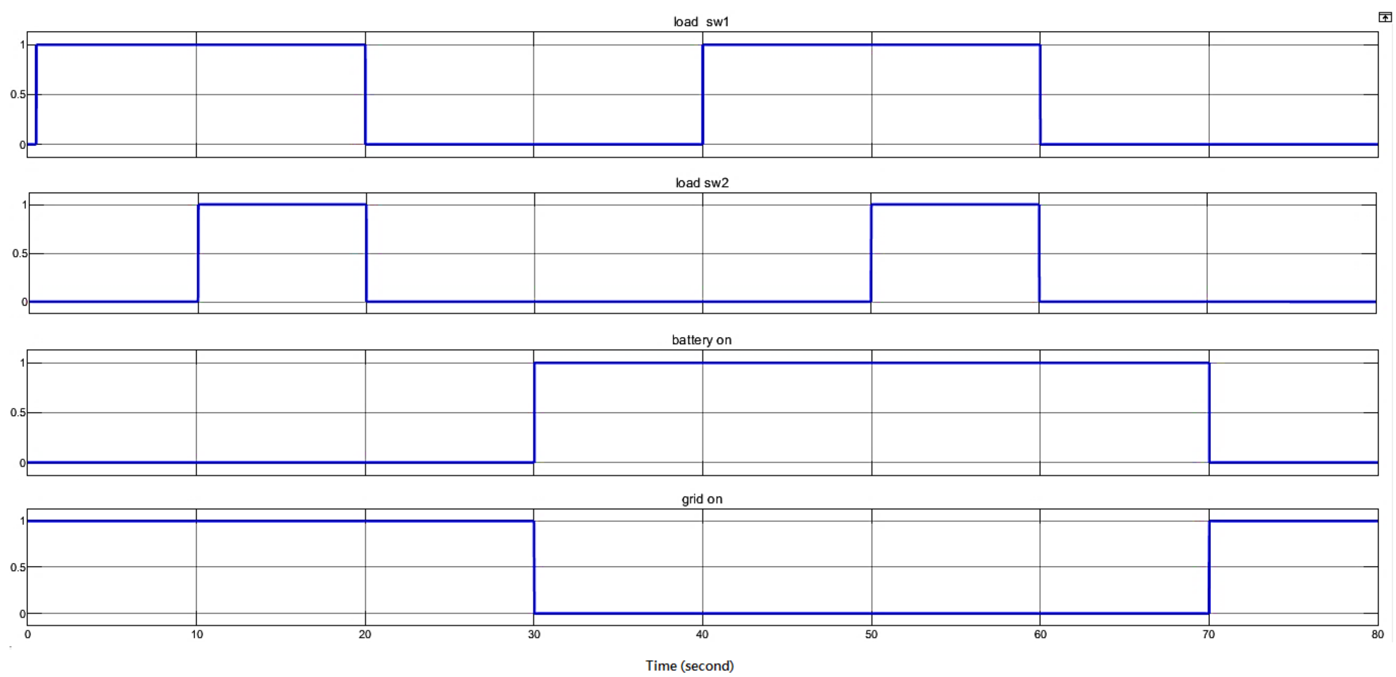


Figure.9: Switching between island, grid operations modes and loads

Consider operating in grid-connected mode, where the first load of 4KW is connected at time t=0.75 second. The load consumes more than half the power generated from the photovoltaic, and the remaining power is returned to the power grid. At time t = 10 seconds, second load (also 4KW) is connected. Currently, the system has a total system load of 8,000 watts (4kw+4Kw), which is more than the power generated by the photovoltaic system. Hence, the shortage of power is supplied to the consumer by the utility power. Therefore, the grid will help to balance the power demand of consumers along with the photovoltaic system. Figure 10 shows the residential load at different times.

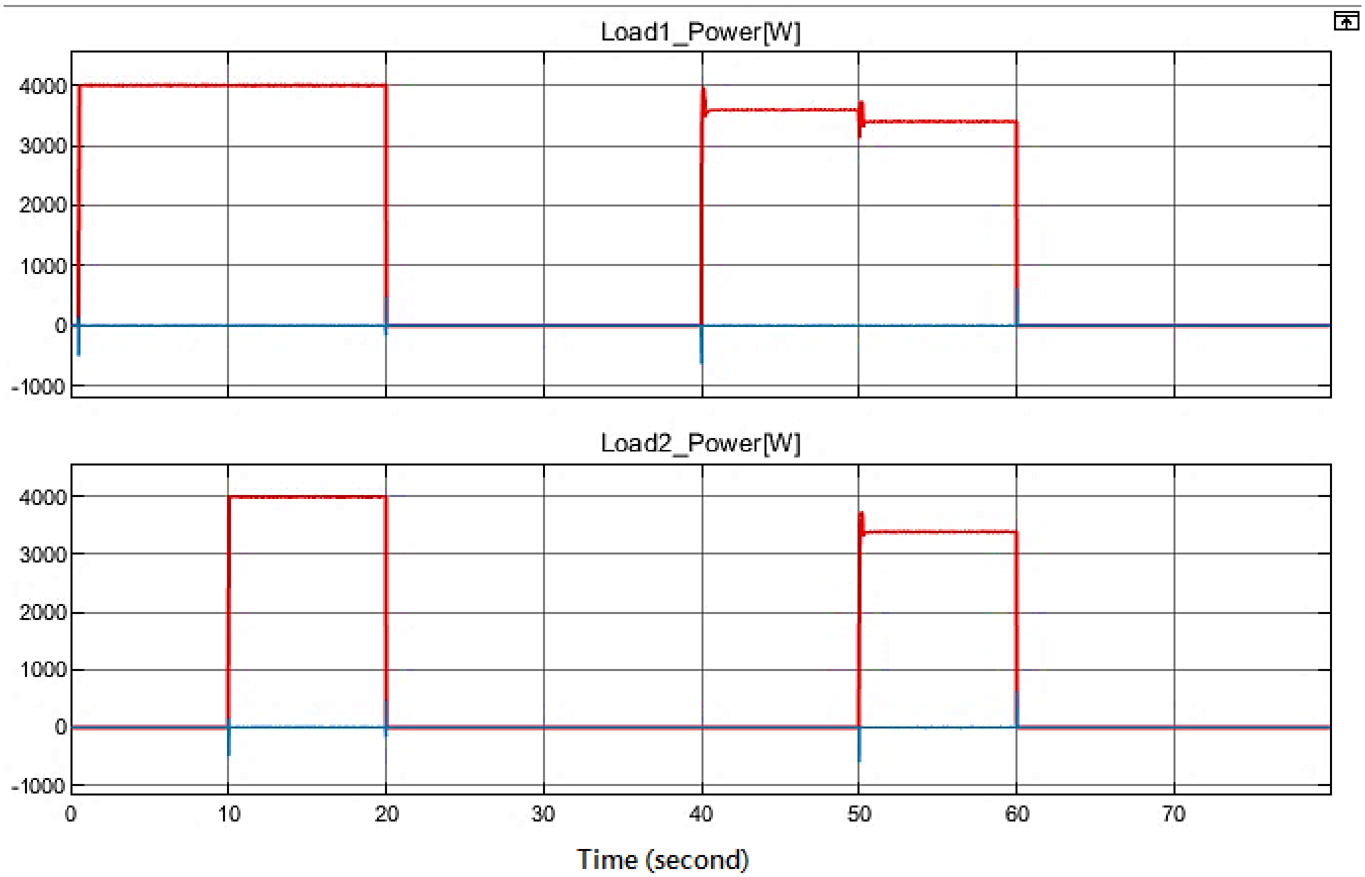


Figure.10: Load variation at home for many time

Then, to test the proposed system behavior in the transition condition, the grid is now disabled at time t=30 seconds. Now the microgrid operates in an island mode of operation. Figure 9 shows the system's response to loading changes from 4 kW to 8 kW. In this mode, the photovoltaic system is allowed to generate its maximum power of 6 kW. The battery operates in the islanded mode. The battery will supply the complementary power required to meet consumer power demand. The output of inverter decreases or increases based on the requirement of load power, while the DC-link voltage is kept constant. The maximum power point tracking controller provides the reference value for DC link voltage and is maintained constant by the battery DC to DC converter by absorbing or delivering adequate power.

Figure 9 shows the transition from the grid to the island operating mode. Here again, the first load and second load of capacity 4 kW each is connected to the home energy management system at time t=40 second and t=50 second respectively. During the connection of the first load, the photovoltaic supplies the required power as the power demand is below the photovoltaic generated power. When the second load is connected to the home energy management system, the total load becomes 8 kW is higher than the photovoltaic generated power. The battery power is enabled to provide this power difference to make power balance. The following Figures illustrate the various parameters home energy management system in the grid-connected and islanded mode of operation.

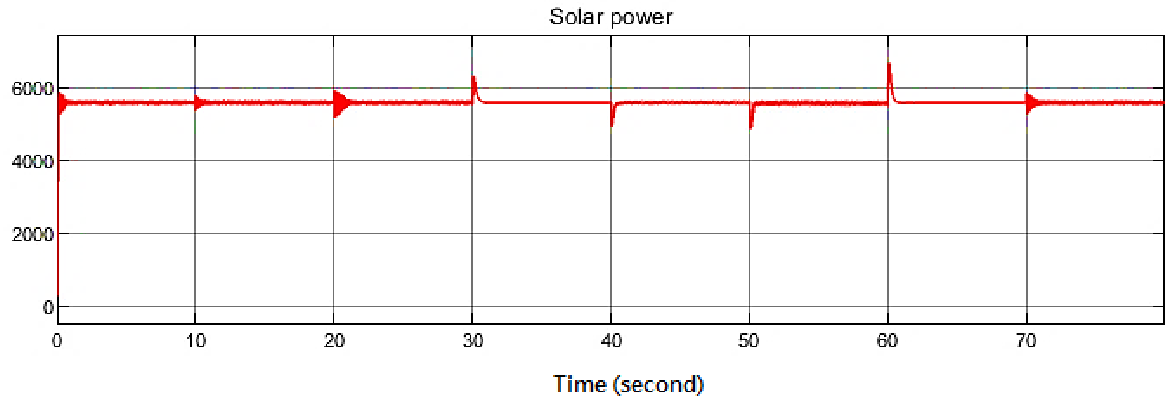


Figure.11: The photovoltaic power during island and grid modes

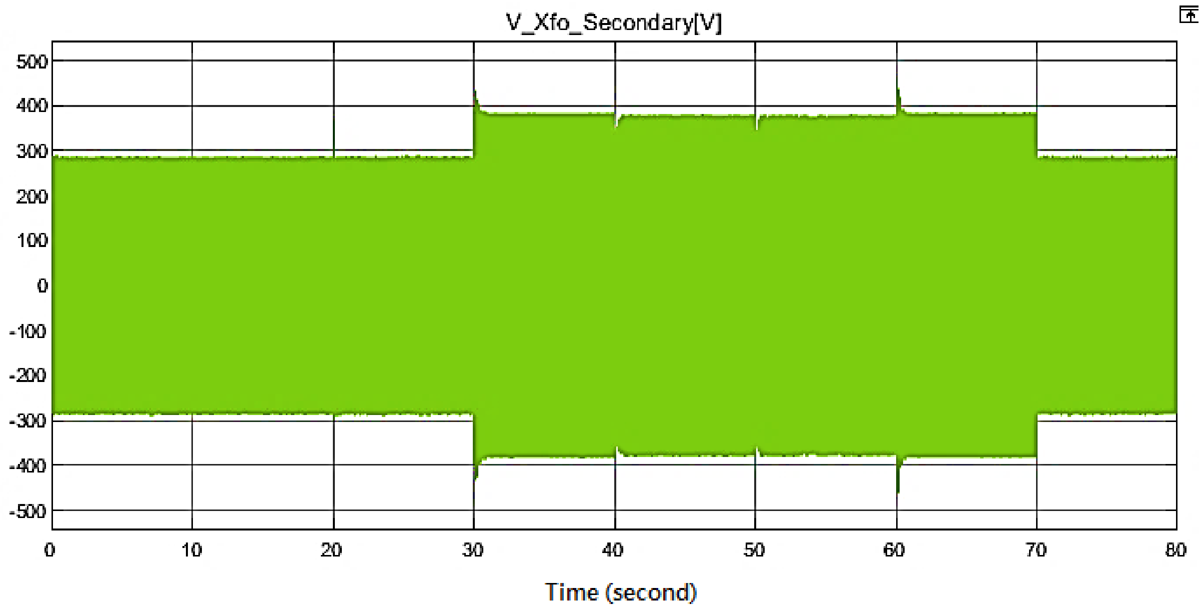


Figure.12: Load voltage during both island and grid modes of operation

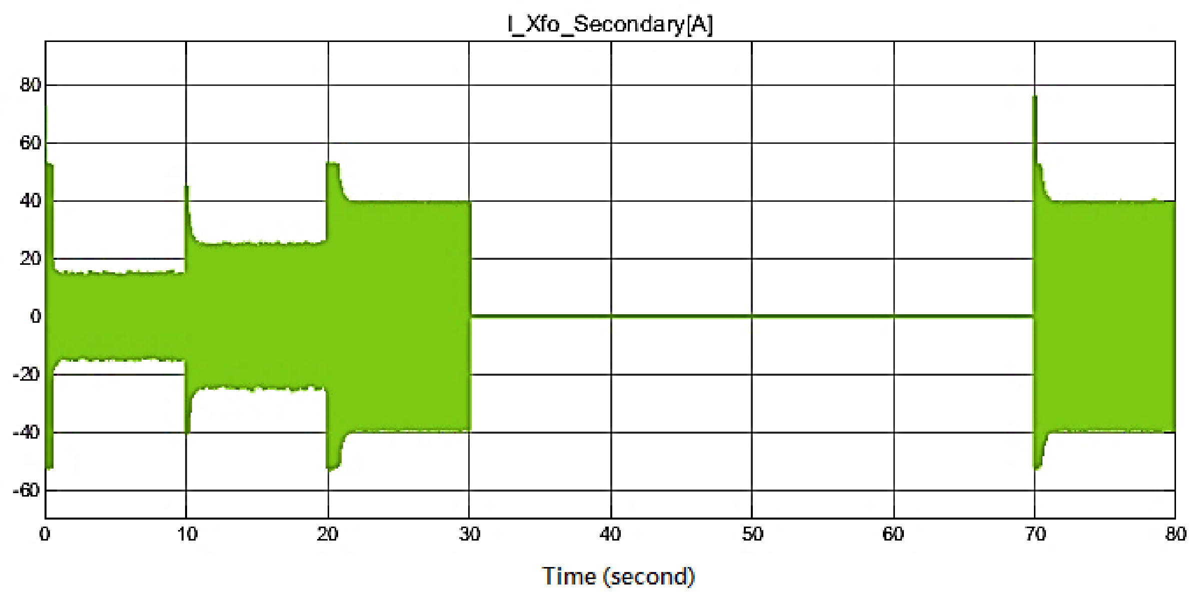


Figure.13: The contributed via the grid for island and grid modes

Figure.11 shows the power generated by the photovoltaics. The total power generated remained almost constant at 6 kW throughout the simulation. Figure.12 illustrates the load voltage during grid operated mode and islanded mode of operation. Obviously, for the time interval from t=0 second to 30 seconds, the system operated in grid-connected mode drawing power from both grid and photovoltaic systems. From time interval t=30 second to 70 seconds, the grid is disabled and now the system is operated in islanded mode feeding power to loads from both photovoltaic system and battery. Figure 13shows the current drawn from the utility grid. It is evident that the grid does not contribute to load during the interval of time t=30 to 70 seconds, as the grid is disabled. Figure14 replicates the power drawn from the grid to meet the demand power of residential homes. The Figure15 shows the battery parameters, state of charge, voltage, current and power during island operating mode at the time of transfer from the grid to island mode, the battery starts to discharge energy into an inverter for meeting the insufficient power that is not been ably met by the photovoltaic system.

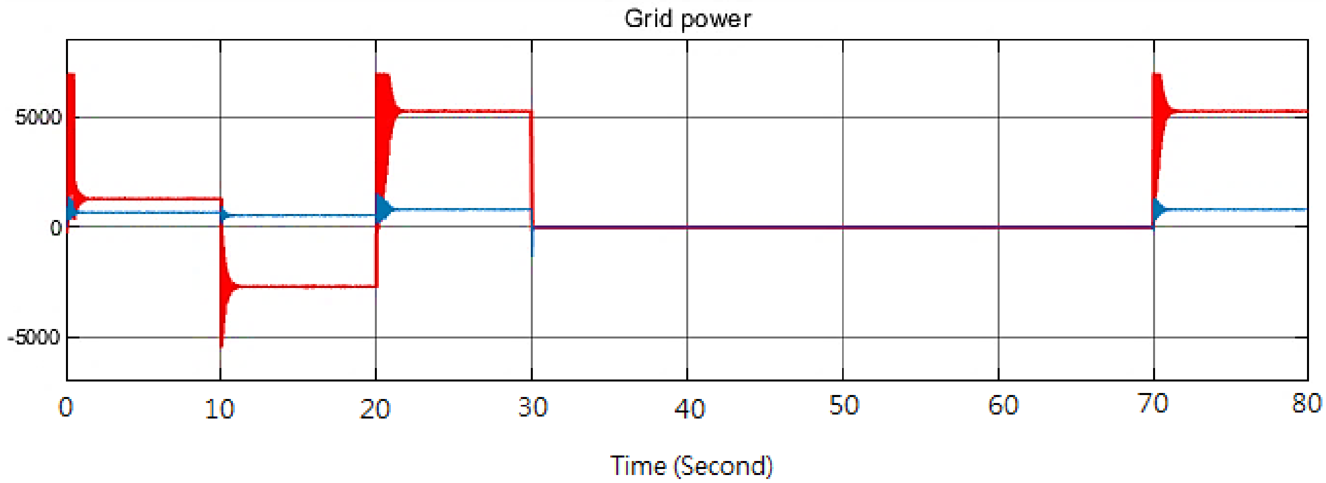


Fig.14. The active and reactive power of utility grid

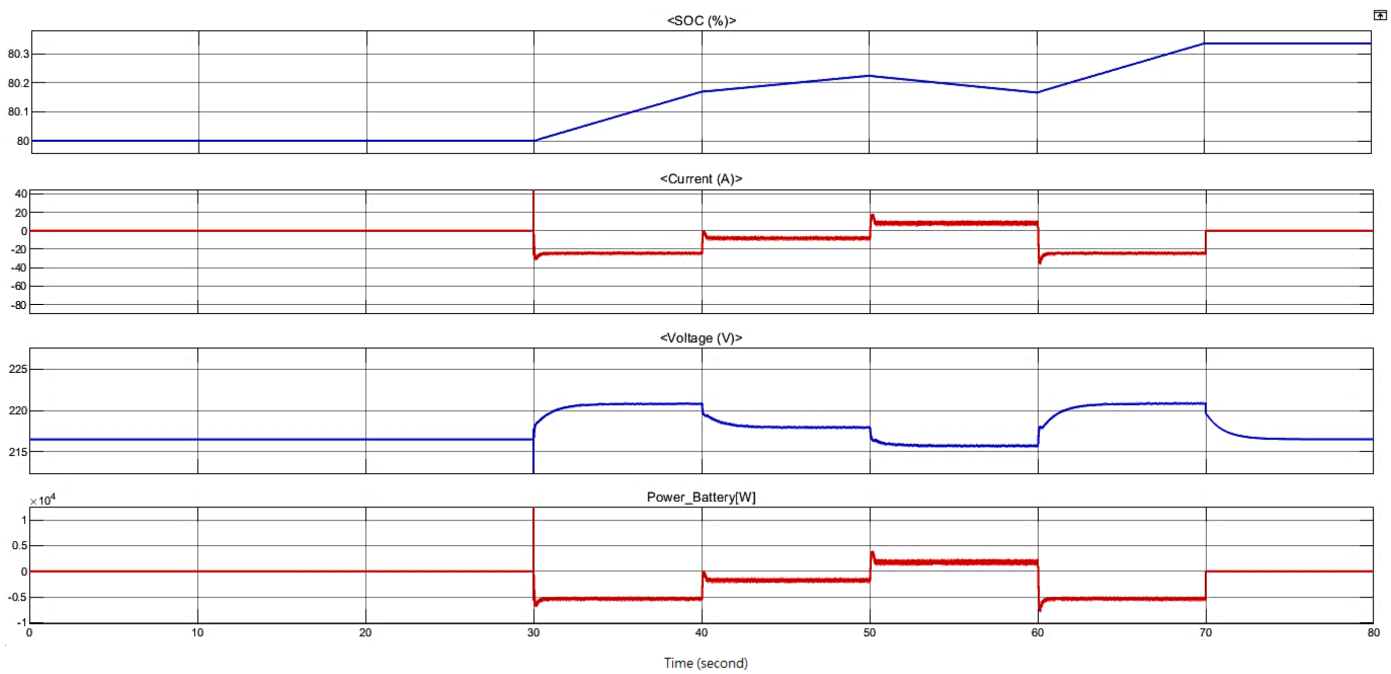


Fig.15. Battery discharge and charging during the transfer of grid to island operation

IX. CONCLUSIONS

In this work, a home management system shows the effectiveness of such a technique to deliver uninterrupted power to the consumer through various controller designs. Also, this paper proposes an effective control strategy for smooth transition from grid-connected to islanding mode due to unintentional islanding. Using the energy management system as part of the control design of a grid-connected microgrid can minimize the total operating cost. The supervisory control has been added to the control model to adjust any deviation between the main grid power and the scheduled reference power by modifying the reference set-point of the battery power given by the energy management system. The results show that the proposed adaptive energy management system for smart hybrid microgrids based on green energy supports the minimal use of power of utility grid. The proposed strategy is able to share the power among the distributed generator units even under unbalanced conditions. Also, results reveal that the incremental conductance method collects more daily energy than the constant voltage method when the ambient temperature is high. However, the irradiation and load variations tests show that the incremental conductance method is more oscillation, less dynamic response, and less stable about the maximum power point than conventional methods. Hence, the proposed method is more responsive and efficient than the conventional method.

CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

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