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Lithium-ion energy storage battery in PV-smart building application

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Abstract

Photovoltaic (PV) panels with energy storage batteries represents a feasible solution for powering domestic loads. The service life of the batteries and the power management are the main challenges by developing the energy supply system of smart homes. Therefore, in this paper an efficient algorithm is developed in order to power a house by extracting the maximum power from the PV panels, enhancing the battery service life and minimizing the power supply from the smart grid. The smart metering, advanced inverter and rule-based energy management strategy ensure safe and optimal operation of the energy supply system. Matlab/Simulink model of typical PV array, lithium-ion battery, inverter with the associated controllers are developed to evaluate the performance of the proposed system. Starting from the actual solar irradiance data, the maximum power of PV array will be extracted as a function of the available irradiance and ambient temperature. The daily battery state of charge (SOC) and its internal temperature are calculated depending on the load, PV power and the battery charge/discharge modes. Simulation results show that the proposed algorithm can enhance the performance of energy supply system, extract the maximum solar power and minimize the power from smart grid.

Key words

PV array, MPPT controller, Li-ion storage battery, energy management, hybrid power system.

1. Introduction

The utilization of renewable energy such as solar energy to supply the domestic loads will reduce the power supply from the grid that depends on burning fossil fuels. This will result in minimization of the harmful emission released to environment. However, the use of renewable energy is costly at present and the generated energy has an intermittent nature depending on the variable weather conditions. Thereby, part of the load demand is covered during low solar irradiance by only installing PV array, and the remaining load is supplied from the grid. On the other side, large amount of generated solar energy is not utilized during off-peak hours due to lack of storage devices. Therefore, energy storage can provide a back-up to the intermittent nature of solar energy, facilitate increased penetration of distributed PV arrays and ensure the continuity of load supply in smart homes. Mainly, the energy storage devices are the rechargeable batteries of various types such as lead acid, sodium sulfur, nickel cadmium and lithium ion batteries. Recently, lithium ion batteries are relatively safe for the environment, low self-discharging rate and higher energy denisty compared to other types. The integration of PV panel and lithium ion battery resources in smart grid requires efficient energy management system (EMS). One of the key features of the smart grid is to enable consumers and distribution system to communicate with each other to manage the power flow and consumptions [1-5].

Recently, various researchers have developed EMS for smart home applications using real time data [6, 7] based on distributed generation within the grids. Thereby, the energy storage devices are modeled using simple equivalent circuit with constant elements. These models require small computational requirements but deliver inaccurate results by neglecting the effect of temperature on the electrochemical process of the lithium ion battery [8]. In this paper, a new integrated model of PV array and lithium ion battery is proposed taking into account the thermal dependence of its parameters. In addition, system controllers are developed to extract the maximum power of the PV array and manage the battery charge/discharge under different operating conditions.

The paper is organized as follows: After the introduction, section 2 describes the smart home concept and its architecture for managing the generation from the PV array and energy storage batteries. In section 3, the PV array and lithium ion battery are modeled under different operating conditions. Section 4 formulates the proposed EMS steps and the associated rule-based control strategy. Section 5 displays the simulation results of a real case study to validate the developed algorithm. Finally, section 6 summarizes the paper conclusions and states the suggestions for future work.

2. Overview of smart home architecture

The smart home consists of main controller, smart inverter and micro web-server via the internet. Smart residential or commercial building integrates the solar panels, storage batteries, DC/AC inverter with the grid. A smart home utilizes different types of sensors to collect the information which is used to manage energy resources efficiently, as shown in Fig. (1). This includes data collected from weather station, solar panels, loads and storage batteries that is processed and analyzed in monitoring and control system to manage the energy supplied by the resources [1,9].

The smart meters, sensors and actuators are directly interfaced to the main controller. The solar irradiance, ambient temperature and electric loads are examples of the measurements in smart home. The smart home can be controlled from remote monitoring and control module which will communicate with the home server through internet as indicated in Fig. (1) [9,10].

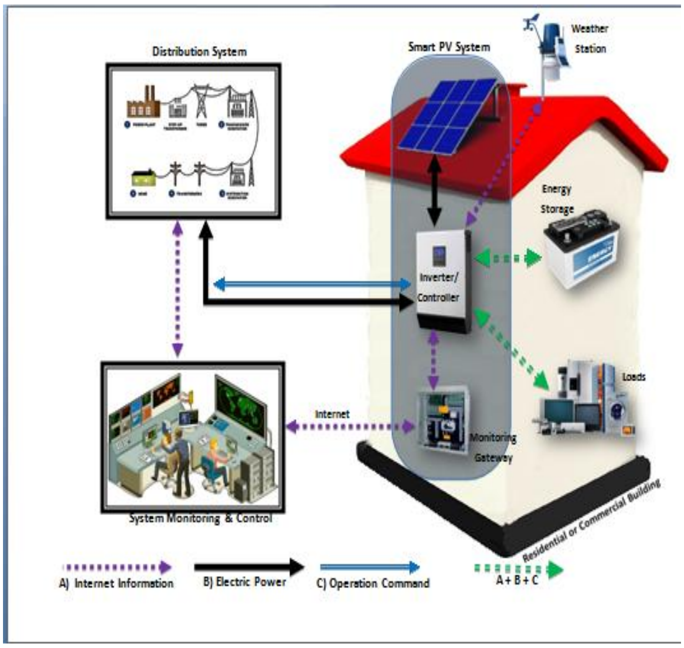

Fig. (1) Smart home architecture

3. Modeling of Energy Resources

3.1 Modeling of PV array

Generally, PV cells are grouped together in similar modules which are interconnected either in series or parallel to fulfill the load voltage and current. The current-voltage relation of PV array can be mathematically given by [11,12]:

$$I = N_p I_{ph} - N_p I_o [\exp^{\frac{qV}{A\,KT\,N_s}} -1] \qquad (1)$$

Where,
q: Electron charge.
A: P-N junction ideality factor
K: Boltzmann constant.
I: Array output current.
Iph: Photocurrent as function of irradiance level and junction temperature.
I_0: Reverse saturation current of diode.
T: Cell operating temperature.
V: Array output voltage.

Equation (1) is a non-linear relation of the I-V characteristics. The array output power is determined through multiplying equation (1) by array voltage. From P-V curve, there is a specific voltage level at which the generated power is maximum. Therefore, a continuous adjustment of the array terminal voltage is required to extract maximum power (MPP) from the solar array.

The main components of the PV system consist of the solar array and smart inverter. In this paper, the generated voltage of the PV panel is adjusted to the level of the maximum solar power using P&O method [11]**.** In P&O, the operating voltage of the studied PV array is perturbed by a small increment, and the resulting change of power, ΔP is used to update the array voltage as follows [12]:

-If $\Delta P < 0$ &$V(j) > V(j-1)$,then $V(j+1) = V(j) - \Delta V$
-If $\Delta P < 0$ &$V(j) < V(j-1)$,then $V(j+1) = V(j) + \Delta V$ (2)
-If $\Delta P > 0$ &$V(j) < V(j-1)$,then $V(j+1) = V(j) - \Delta V$
-If $\Delta P > 0$ &$V(j) > V(j-1)$,then $V(j+1) = V(j) + \Delta V$

3.2 Modeling of Lithium-ion Battery

3.2.1 Equivalent circuit model of the battery

State of Charge (SOC) is an important parameter for effective management of the battery operation. The extended Kalman filter has been reported as an effective technique [13, 14] for SOC estimation of a lithium ion storage battery. However, the estimated SOC using this technique strongly depends mainly on the accuracy of the battery model. Equivalent circuit model (ECM) is the most common approach for battery numerical analysis. Internal electrochemical reaction of Li-ion battery can be electrically modeled by resistance and capacitance [13], as shown in Fig.2. For lithium cells, a one or two *RC* block model is commonly applied [1-3]. The ECM includes the open circuit voltage (OCV) and the internal impedances represented by Ro, R_1 and C_1. Generally, ECM has the advantage of being computationally simple and is easily combined with an OCV / SOC correlation for real time etimation of battery energy exchange. The ECM parameters vary with the SOC, temperature and degradation. The circuit parameters are related to their respective electrochemical reaction of the lithium-ion battery as follows [8]:

- R_1C_1: Resistance and capacitance due to the low diffusion rate of the Li-ion cell.
- Ro: Resistance representing the power dissipated inside the cell.
- OCV: Open circuit cell voltage.

3.2.2 Discrete-time formulation of battery equations

The AC impedance of the battery is measured under different SOC and temperature conditions. A unity SOC represents fully charged state, while zero SOC means fully empty state. For battery capacity (Q) and coulomb efficiency (η), the discrete SOC at time instant k+1 can be expressed from its previous value at instant k by [8]:

$$SOC[k+1] = SOC[k] - i[k]\eta[k]\Delta t/Q \qquad (3)$$

where i is the battery current.

In addition, the internal temperature can be computed by solving the following heat equation assuming uniform temperature distribution inside the cell [15]:

$$H_C\left(\frac{dT}{dt}\right) = -\frac{T-T_a}{C_r} + P_s \qquad (4)$$

where Ps is the power dissipated inside the cell (W), *Hc* heat capacitance (J m^{-3} K^{-1}), Cr convection resistance (W m^{-2} K^{-1}))

The change of the internal parameters follows the Arrhenius' equation. The general form of this equation is expressed by $Fe^{B/KT}$ where F is a function of SOC variable, K the gas constant and T absolute temperature). F and B are approximated by a least-squares technique using impedance measurements, which is the scope of another published papers in [8,13].

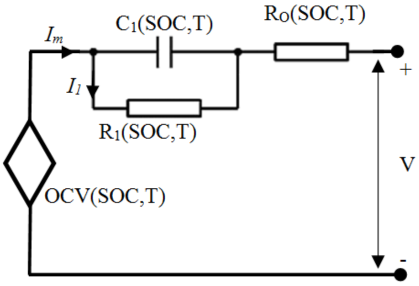

Fig.(2) general equivalent circuit model of Li-Ion cell.

$$v(t) = OCV - R_1 i_{R1}(t) - R_0 i(t) \qquad (5).$$

The respective ordinary differential equation of the ECM of Fig. (2) are converted to discrete-time ordinary difference for numerical simulation by [8]:

$$i_{R1}[k+1] = e^{\left(-\frac{\Delta t}{R_1C_1}\right)} i_{R1}[k] + (-R_1C_1)\left(e^{\left(-\frac{\Delta t}{R_1C_1}\right)} - 1\right)\left(\frac{1}{R_1C_1}\right) i[k]$$

$$= e^{\left(-\frac{\Delta t}{R_1C_1}\right)} i_{R1}[k] + \left(1 - e^{\left(-\frac{\Delta t}{R_1C_1}\right)}\right) i[k] \qquad (6)$$

The storage capacity of the battery can be estimated depending on the load demand and PV array generation. For stand alone system, the capacity depends on the number of continuous cloudy days. On the other side, for grid connected PV array, the main objective is to minimize the supplied energy from the grid. Li-ion batteries offer good charging performance at cooler temperatures and may even allow 'fast-charging' within a temperature range of 5 to 45 °C. Any operation outside this range may lead to battery degradation. The life cycle of the battery will be progressively decreased by working at lower temperature or slightly above 50°C. Therefore, Li-ion batteries require a battery management system to prevent the operation outside its safe operation range (minimum SOC and safe temperature range). This significantly improves battery efficiency, increases its capacity and life cycle.

4. Energy management strategy

For reliable and efficient operation of the smart home system, the proposed management strategy can be classified into 3 groups as follows:

4.1 Load sharing among all the energy sources:

The proposed PV/Battery system operates in any one of the five modes:

Mode 1: PPV > Pload. In this mode PV system generates excess amount of power than the demand. If the battery is not fully charged, then charge the battery by the excess power.

Mode 2: PPV < Pload. If the load exceeds PV generation and the battery SOC is above its minimum limit, then discharge the battery to cover the rest of the load.

Mode 3: PPV = 0. If there is no available energy from the PV panels, then Battery supplies the load.

Mode 4: PPV = Pload. In this mode, the PV array generate sufficient energy to feed the load without the intervention of battery.

Mode 5: PPV + Pbatt < Pload. If the available power from both PV panel plus battery is less than the load, then some devices have to be disconnected or the load deficit is covered from the grid.

4.2 Maximum power point tracking of PV panels

PV panel is an intermittent source and its output varies with measured irradiance and temperature. In this paper, P&O method is applied to extract maximum power from PV panels by sensing the PV voltage (Vpv) and PV power (Ppv) [11,12]. The inverter controller always regulates PV power to its maximum power (Pmpp) using the error signal of the panel voltage. The error signal driving the MPP controller is equal to the difference between the determined voltage V(j+1) of equations (2) and the actual measured voltage of the panel.

4.3 Charging/discharging of the battery.

Batteries can operate in high power charging/discharging mode as long as it does not exceed its physical limitations. Battery life will be rapidly decreased under uncontrolled charge or discharge of its stored energy. In the proposed energy management strategy the SOC is estimated in real time based on the battery current, as described in equation (3).

Therefore, there are some constraints to be taken into account during charging and discharging of the battery. When the battery is being charged, the charging will be stopped if the voltage reaches its high limit or the battery is at its 100% SOC. The deep discharge will affect the battery's life cycle. Hence, the discharging process goes on until the SOC reaches 80% (DOD of 20%). It should be noted, as this charge/discharge cycle is repeated, the battery age increases whereas its capacity decreases [14].

In smart home, the installed sensors provide the actual status of voltages, currents and temperatures within the battery as well as its SOC. Moreover, they can also provide alarm functions indicating out of safe range conditions. This intelligent system also contains a memory with information about the battery upper and lower voltage limits, maximum current limits, temperature limits and how many times the battery has been charged and discharged [14-16].

5. Simulation Results:

The numerical simulation starts by calculating the daily energy output of a solar pannel as a function of the measured solar irradiance and ambient temperature. Then, the daily PV array energy output is compared with the connected load demand, the battery storage energy and the battery charge/discharge energy are used to estimate the daily battery state of charge (SOC). Matlab Simulink model of the PV panel, lithium ion battery with the DC/AC inverter is developed to evaluate the performance of the proposed algorithm. The PV panels and battery data are taken from the technical manuals of the manufactures. Due to lack of space, the performance is evaluated for typical sunny and cloudy daily curve with maximum irradiance of 1000 and 450 W/m^2, respectively. However, this algorithm can be also applied on different load patterns with other weather conditions.

The behavior of the PV output power during sunny day is represented in Fig. (3) together with the corresponding solar irradiance. It is observed from the curve that its shape is the same as the irradiance curve. It is also clear that the output power changes according to the available solar irradiance and the controller tracks the MPPT. The battery voltage and currents are illustrated in Fig. (4 and 5) for three different daily load curves low, average and high with peak value of 1700, 2300, 2700 W, respectively. Fig. (4) indicates that the battery voltage over the 24 hour of the day and its variation is within the specified limits of 9.2 V and 12.8 V. The battery voltage is decreased to its minimum value of 10.15 V during the discharging mode and is increased to a maximum of 12.1 V during charging mode. The battery current in Fig. (5) is positive and reaching a maximum value of 120 A during discharging to cover the high load demand and negative with minimum value of 38 A during charging mode at high solar irradiance.

Fig. (6) indicates the SOC of the battery for sunny day under the three load levels. The behavior of SOC depends on charging/discharging of the battery. It is clear from Fig. (6) that the minimum SOC will not exceed its 80% limit irrespective of the insolation variation during the day. For the three load levels, the SOC starts from 95% and decreases when the battery is at its discharging mode and increases during excess PV generation for low and average load, respectively. During discharging mode, the SOC is decreasing again until 94.5 % and 93 % at the end of the day for low and average load, respectively. It is observed from SOC curves, that the battery is discharged to 90.5 % at the end of the day and cannot be recharged for high load level as there is no excess power during the whole sunny day time to charge the battery.

Fig. (7) displays the battery temperature for the considered three load levels. As illustrated in this figure, the temperature is continuously increased either during discharging or charging mode. The temperature curves start at ambient temperature of 25 ^{o}C and increase to 28.5, 33 and 38 ^{O}C for low, average and high load level, respectively. It should be noted that the maximum temperature at the end of the day for the three load levels is within the safe rang of 5 - 45 ^{O}C.

Simulation was also carried out for another three different load levels corresponding to the cloudy day. Similarly, the battery voltage and currents are illustrated in Fig. (8 and 9). The variation of the battery voltage is within the specified limits of 9.2 V and 12.8 V. During discharge, the battery voltage is decreased to its minimum value of 10.2 V, while at charging mode it is increased to a maximum of 12.8 V. The battery current has the same response of Fig. (5). The current is positive and reaching a maximum value of 120 A during discharging and is negative with minimum value of 71 A during charging mode.

The SOC of the battery is illustrated for cloudy day in Fig. (10). The behavior of SOC depends on charging/discharging of the battery and will not exceed its 80% limit during the day. At night and early morning, the load is supplied by the battery. Then, as the PV power increase and when solar power exceeds the load, this excess power is delivered to the battery. For the three load levels, the SOC starts from 95% and decreases to a value of 95 % , 92 % and 89.5 % at the end of the day for low, average and high load, respectively.

The battery temperature is continuously increased either during discharging or charging mode, as shown in Fig. (11). The temperature behavior is within the safe range of 5 - 45 ^{O}C. The temperature curves start at ambient temperature of 25 ^{O}C and increase to 30.5, 32.5 and 40

^{O}C at the end of the day for low, average and high load level, respectively.

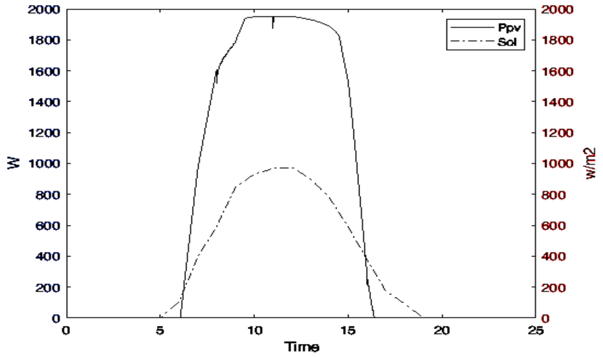

Fig. (3) Variation of PV generated power corresponding to solar irradiance for sunny day

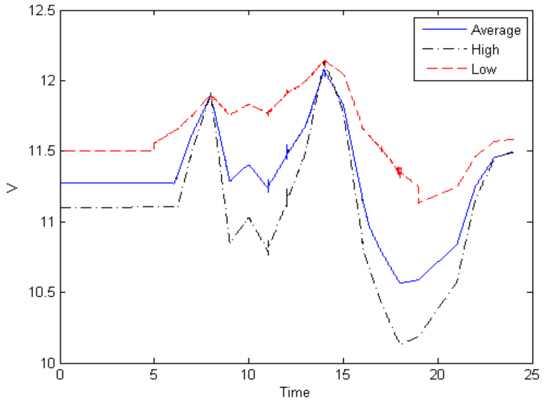

Fig. (4) Variation of battery voltage for average, low and high load during sunny day

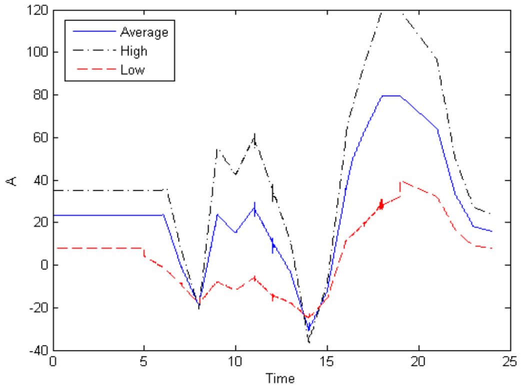

Fig (5) Variation of the battery current for average, low and high load during sunny day

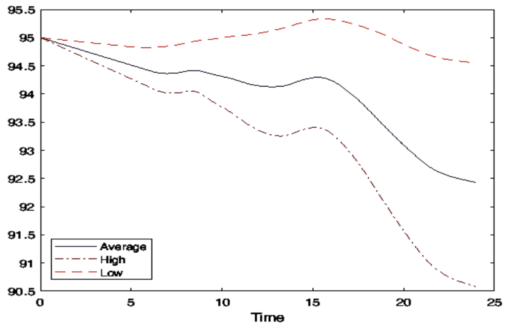

Fig. (6) Variation of batter SOC for average, low and high load during sunny day

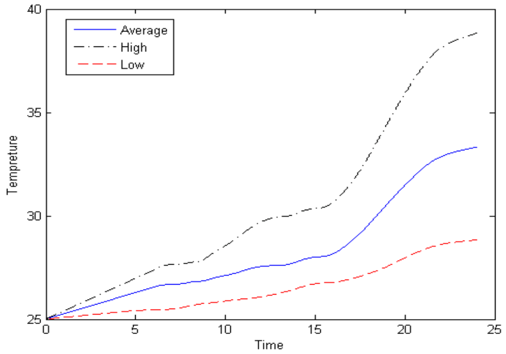

Fig. (7) Variation of battery temperature for average, low and high load during sunny day

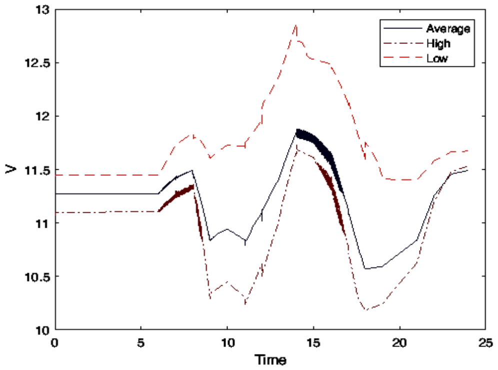

Fig. (8) Variation of battery voltage for average, low and high load during cloudy day

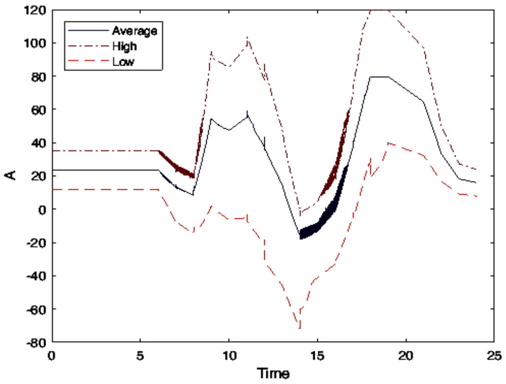

Fig. (9) Variation of battery current for average, low and high load during cloudy day.

6. Conclusions

Integrating storage batteries in smart homes can facilitate the efficient utilization of solar energy by installing PV panels. With this PV penetration, the harmful emissions related to conventional generation are drastically decreased. The configuration of studied system consists mainly of Lithium-ion storage battery, PV panel and smart meters. The mathematical model of the system is developed and simulated using Matlab/Simulink. Also, efficient energy management algorithm was developed to regulate the power form PV panels and lithium-ion battery. The inverter is controlled to track the available maximum power of the PV panel. Battery is bi-directionaly connected to the system to enable charge/discharge of its energy.

The algorithm has the capability to manage and organize the different modes of operation in smart homes. Simulation results show that the proposed algorithm can improve the life cycle of the battery by controlling its SOC and cell temperature within the safe range. The minimum SOC will not exceed its limit under different load levels irrespective of the irradiance variation during the sunny and cloudy day. The battery temperature is continuously increased either during discharging or charging mode and is kept within the safe temperature range during the different operation conditions. The simulation result shows the energy management algorithm will operate correctly for the battery charging/discharging mode to minimize the power exchange by the grid.

The impact of storage batteries on the electricity bills has to be studied in future. First, the cost saving due to reduction in peak demand charge and the participating in regulation market will be estimated. Second, as electric vehicle number continues to increase, the proposed model needs to be extended to consider the additional constraints by charging and discharging of electric vehicle batteries.

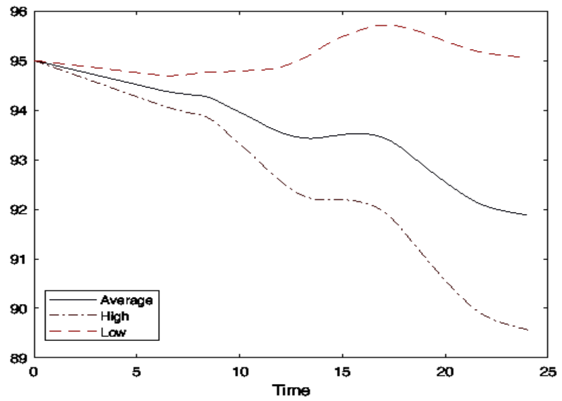

Fig. (10) Variation of battery SOC for average, low and high load during cloudy day

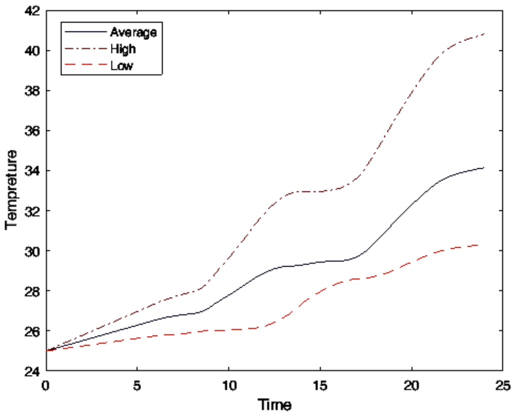

Fig. (11) Variation of battery temperature for average, low and high load during cloudy day

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