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EXPERIMENTAL STUDY OF BATTERY STATE OF CHARGE EFFECT ON BATTERY CHARGING / DISCHARGING PERFORMANCE AND BATTERY OUTPUT POWER IN PV ENERGY SYSTEM

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ABSTRACT

The effect of battery characteristics on the performance of PV Energy System is experimentally investigated. The employed system consists of a number of lead acid storage batteries, a set of photovoltaic (PV) panels, a charge controller, DC/AC inverter and an electrical load. The system also employs a monitoring unit (MU) that consists of voltage and current sensors and data acquisition cards. The MU was specially developed to monitor energy system performance parameters; such as PV voltage and current, battery voltage, battery charging and discharging currents and inverter current. The monitoring unit is controlled through a specially developed, LABVIEW® based, computer program. In the study, the effect of battery SOC on charging and charging efficiency was investigated. Also, the effect of battery's loading conditions on its useful charge was investigated. Finally, the effect of battery SOC and supported load on battery performance was investigated. Results of the study showed battery's SOC had a minimal effect on charging efficiency. It also showed that higher discharge current (load requirements) leads to significant decrease in energy system performance caused by decrease of battery discharge efficiency by up to 50%. On the other hand, low batteries SOC proved to have insignificant effect on meeting load demand. The results emphasize the importance of proper selection of batteries size as well as characteristics including cost, to match load requirements, as those would highly affect renewable energy system's performance and feasibility.

Keywords: battery, battery SOC, battery efficiency, renewable energy, PV.

1. INTRODUCTION

Significant developments in the design, analysis and installation of PV based renewable energy systems have been achieved, offering a solution to power problems of remote sites. Renewable energy systems are either stand-alone or grid connected; in the case of grid connection they are considered as fuel saver. A range of renewable energy systems are mainly based on Photovoltaic combined with battery storage and supported by auxiliary petrol generator. Many of those are in operation for decades.

Although different types of energy storage are investigated for incorporation with renewable energy systems, batteries are still the most common storage media for PV electricity till now. Small and medium PV-battery stand–alone systems are widely functional for different remote applications. In these systems, batteries are the most sensitive equipment, often operating under severe conditions such as successive charge/discharge and long periods under deep discharge, which affect its lifetime, [1]. Lead-acid batteries are the most common battery type for renewable energy storage. The selection of proper number and size of batteries comprising the battery bank requires analysis of the battery's charge and discharge requirements, the load pattern and the pattern of solar irradiation in this specific region. As the average daily energy demand is approximately constant, when solar radiation decreases due to the weather conditions, less energy gets supplied by the PV array. Accordingly, the battery bank would support the load, get discharged and its SOC will be decreased, which would affect the system performance. Some believe that, energy losses occur mostly during battery bank charging, [2] however results of the current research proved different.

The SOC reflects the balance between energy stored and energy supplied at any instance and is a good parameter to evaluate the suitability of the storage size for the intended application involved. For optimum balance between daily charge and discharge, the SOC should be close to the upper limit (SOC = 0.97) at mid-day, and close to its lower limit (SOC = 0.3) at the end of most days, reflecting an optimum PV energy time-shift and demand management, [3].

Wen-Yeau Chang presented a review of developments in battery SOC estimating methods, focusing on both mathematical calculations and practical implementations, [4]. As battery SOC is an important factor that affects the battery performance, accurate estimation of SOC can protect battery, prevent over charge or discharge, and improve battery life. The paper presented an over view of the four categories of mathematical methods of estimating SOC such as; Open-circuit voltage, Terminal voltage, Impedance method, and Coulomb counting method.

Battery operating temperature and efficiency of charger and inverter also affects the PV system performance. The battery temperature and charge/discharge cycles would significantly affect batteries performance and lifetime, [5]. As expected, battery efficiency drops as it ages and it would age faster when not operated correctly.

A modeling and optimization study of a stand-alone hybrid energy system was presented by Ghada Merei *et al.,* [6]. The system consists of a wind turbine,

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PV modules, batteries and a diesel generator for back-up. Three types of storage batteries were used in the simulation study, lithium-ion, lead-acid, and vanadium redox-flow individually or combined together. In case of using different battery technologies at the same time, a battery management system (BMS) is used. The developed BMS takes into account different battery operating points and ageing mechanisms. Battery ageing depends on two main processes: cyclic ageing and float ageing. Cyclic ageing takes place, while the battery is being charged or discharged. In this case thermal and mechanical stresses lead to a deterioration of battery properties. To estimate the effect of cycling aging, information about the average SOC is required. Float ageing generally depends on the state of charge (SOC) and the temperature the battery is operating at.

Batteries used in PV applications are working in harsh conditions compared with batteries used in more traditional applications. The PV charges battery randomly as the charge level is affected by the varying irradiation in addition to the intrinsically fluctuating loading conditions. This usually leads to charging the battery starting at any SOC and ending abruptly at any battery SOC. Also, the system would start withdrawing varying levels of energy from the battery to support the fluctuating load. Hence, the current work investigates, experimentally, the effect of battery SOC on charging efficiency and it also investigates the effect of discharging rate on the battery efficiency. Also, the effect of SOC on power losses and capacity of the battery to withstand different loading conditions was investigated.

2. BATTERY STATE OF CHARGE (SOC)

Battery state of charge SOC is defined as the ratio between the difference of the rated capacity and the charge balance divided by the rated capacity. SOC can be expressed by equation (1), [7]:

$$SOC = \left[\frac{C_{nom} - Q_{Bat}}{C_{nom}} \right] \tag{1}$$

Where:

C_{nom}: Nominal capacity of the battery (Ah)

Q_{Bat}: Ah-balance i.e. net Ah discharged or charged since the last full state of charge

When the battery SOC is low and the system attempts to supply the demand, daily charge and discharge would cycle close to the deep discharge threshold. More intelligent management system would monitor the SOC and gradually reduce the energy taken from the battery to help prevent continuous operation at a low state of charge. The minimum SOC or deep discharge protection (DDP) is often implemented by measuring the battery voltage. In the winter months the battery may experience a low SOC for extended periods due to the seasonal variation in solar irradiation. A sever low SOC affects system performance and reduces the life of the battery.

3. PV ENERGY SYSTEM CONFIGURATIONS

The system in the current research consists of PV modules, batteries, charge controller, DC/AC inverter and a dedicated adjustable load. The system is monitored through a specially developed monitoring unit (MU). The MU employs a number of sensors and signal conditioning devices and USB data acquisition cards (DAQ), connected to a PC to monitor and record the system performance, using a specially built LABVIEW software program. Figure 1, shows a schematic diagram of the employed energy system.

3.1. PV modules

The employed energy source is a number of twelve PVs from BIC Company, of Model: GP-75. The PVs were installed on top of a building (22 m height) in a totally sunny spot in Giza, Egypt. These PVs have a rated voltage of 12 volt, 21 open circuit volt, 4.8 short-circuit Amp and a maximum power of 75 watt each. Every pair of PVs are connected in series to supply 24 voltage required by the inverter, and then the pairs are connected in parallel, to supply a net of 24 voltage and 450 watt of power.

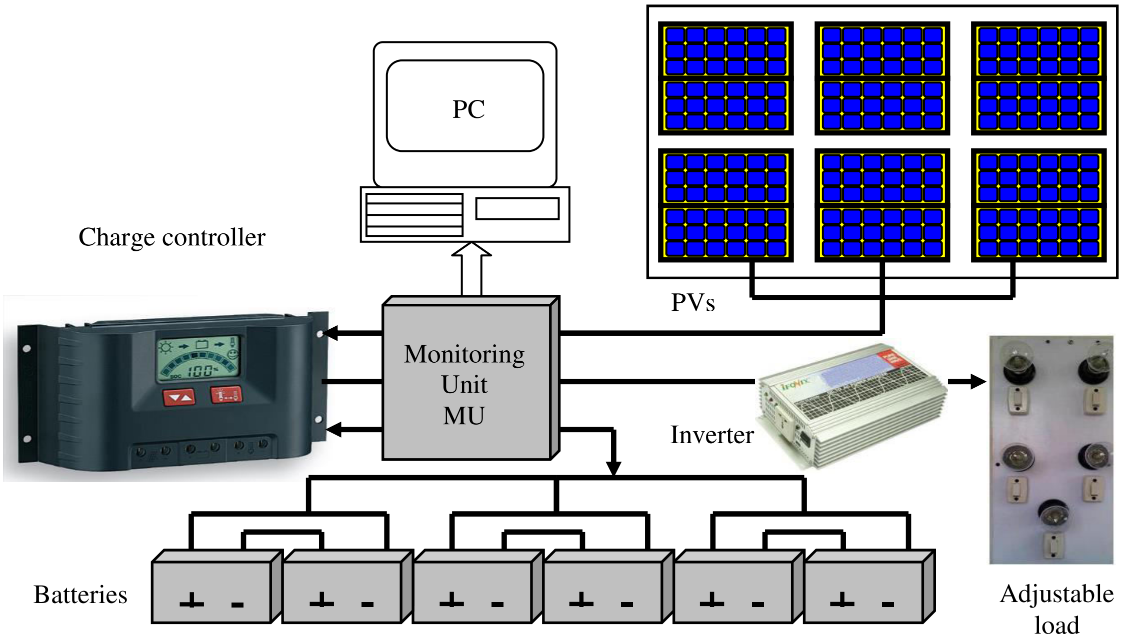

Figure-1. Schematic diagram of the employed energy system.

3.2. Lead-acid storage battery

Different battery types are used with PV system such as lead-acid and nickel cadmium batteries. The most commonly used is the lead-acid battery with its different technological solutions (e.g. flooded-vented, valve-regulated (VRLA) in adsorbed gel form. The 12-volt and 6-volt batteries are the most common blocks [6]. In the current research a set of six batteries, are employed. The batteries are Lead Acid based Gel type modules from Dyno EUROPE ® Company of Model DGY12-100EV. Each battery is 12 volts and 100 Ah/ 20 hrs. Batteries were connected in pairs to provide 24 volts required by the inverter then the pairs were connected in parallel.

3.3. Charge controller

The employed charge controller is from Steca ® Company and it is Model PR3030. The charge controller has the capacity to supply the PV energy to the load and charge the batteries using any excess energy until it is fully charged. In case of shortage it would withdraw energy from batteries to feed the load until SOC of 35%, where it cut off the battery current to protect it from deep discharging, which would destroy it.

3.4. DC/AC inverter

The employed DC/AC inverter is from IFONIX ® Company and its Model No. is IC-1200 It receives an input of 24 DC volts and employs switching mode technology to convert it to 220 V AC, to match domestic load requirements. It has the capacity to support continuously a load of 1200 watts and a peak of 2400 watts of energy.

3.5. Adjustable load

The dedicated adjustable load is comprised from five posts each would accept a domestic tungsten lamb. During the test these posts were filled with tungsten lambs, either 100 watts lambs or by four 100 watts lambs and one 50 watts lamb. In the first case a maximum load of 500 watts with a step of 100 watts was attainable, while in the second case a maximum load of 450 watts with a step of 50 watts was attainable.

3.6. Current measurements

Current is measured, by MU unit, through a number of current sensors; signals are converted to digital data using the data acquisition cards (DAQ) and fed to the PC. For the MU system, the same transducer measures both batteries charge and discharge currents. The discharge current has a positive sign and the charging current has a negative sign.

3.7. Voltage measurements

The voltages of different system components are measured in order to evaluate the system's energy flow and to batteries output energy. The voltage by nature is detectable and easy to convert to digital data by the means of DAQ. The employed DAQ measures the voltage and converts it to digital data and feed it to the PC. The batteries are arranged to provide a voltage of 24 volts as required for inverter input voltage. As the measuring range of employed DAQ, and most available DAQs, is ±10 volts, a special arrangement of resistors was used in voltage divider configuration to adapt the measuring levels. To measure inverter output voltage; which is in the range of 220 AC volts, a step-down transformer was used to reduce the level of the signal to 12 AC volts, and then a voltage divider was employed to adjust the level to the DAQ range.

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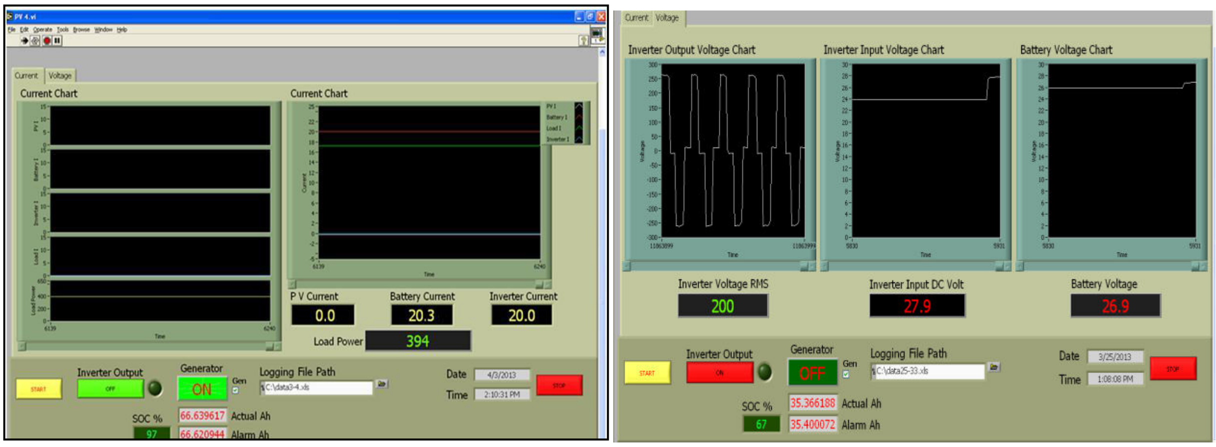
3.8. Data acquisition cards (DAQ)

Two identical DAQ cards from National Instrument ® Company, Model USB 6008 were employed in the current system. Each has eight channels and can deliver up to 12 bits A/D conversion.

3.9. LABVIEW® software program

The program was specially developed to communicate with the monitoring unit to display and record renewable energy system performance parameters. Figure-2 shows sample of system performance screens.



(a) Current monitoring screen (b) Voltage monitoring screen

Figure-2. Sample of system performance screens, a. Current, b. Voltage.

4. SYSTEM OPERATION

Through the employed system, PV, inverter and battery's voltages and currents are monitored, displayed and recorded.

4.1. System calibration

Performing the first test run, the results of battery voltage; showed a high level of signal noise that was attributed to the noise generated by the switching mode technology of the inverter unit. To suppress this noise a small capacitor (0.1 µf, 50 V) was connected to DAQ port parallel to the voltage sensor.

For the purpose of system calibration, a set of measuring devices were employed and the test was conducted at fixed and known conditions. The test results were compared to measured levels and the monitoring system was adjusted to reflect the true energy system signals. The control scheme was calibrated for different values of; PV current, battery current, inverter current and load.

4.2 System configuration

To carry out the different tests, the system was configured differently for each test. This configuration changes involved the number of batteries constituting the storage battery bank and the connection pattern (serial/parallel). The PVs were employed as the only means of battery charging. After the batteries were charged the PVs were covered with thick cloth to ensure that PV would not supply any current to the system.

5. RESULTS AND DISCUSSIONS

A set of experiments were performed using the developed experimental setup. The results are presented and discussed in the following sections.

5.1. Effect of SOC on battery's charging efficiency

In this test PV modules were employed to charge a single battery from 35 % SOC to 100% SOC and charging current was recorded. The total Ah consumed during charging was calculated as the integration (summation) of charging current measured multiplied by charging time, using equations (2 & 3). The results were collected using the MU and the software, where the current is measured every time interval (Δt) that is equal to two second.

$$\text{Battery Charging Ah} = \int I\,dt \qquad (2)$$

$$\text{Battery Charging Ah} = \sum_{SOC=35\%}^{SOC=100\%} I.\Delta t \qquad (3)$$

Where; I Charge current of interval
Δt Time of interval

The results, shown in Figure-3 and Table-1, show the linear relation between SOC and charging Ah, which indicates that SOC has no effect on the charging Ah. This result proves that equal Ah diverted to the battery at different SOC will contribute equally to battery's charge. This result shows that frequent charging of battery at different SOCs will not affect the charging efficiency, which is a positive outcome. Also, the result showed that charging efficiency was higher than 90%, as less than 70 Ah were consumed to charge the 100 Ah' battery from SOC 35% to SOC 100%, that corresponds to 65 Ah battery charge.

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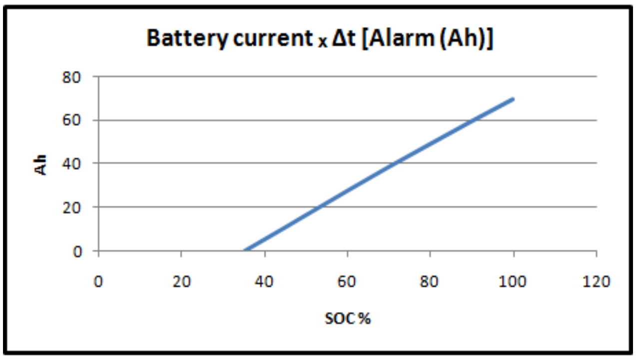

Figure-3. Battery charging energy at different SOC.

Table-1. Charging Ah used to charge battery from 35% SOC to 100% SOC.

SOC (%)	Battery current × Δt [Alarm (Ah)]
35	0
40	5.498
50	16.602
60	27.764
70	38.672
80	49.152
90	59.56
100	69.646

5.2. Effect of discharge current on battery's efficiency

To evaluate the effect of discharge currents on batteries discharge efficiency, a special test was carried out. In this test two batteries were connected serially to deliver the 24 volts required for the AC/DC inverter. Then the inverter AC output was connected to adjustable load. Each 100 Ah battery would theoretically deliver 65 Ah when discharged from 100% SOC to 35% SOC at 5 Ah discharge current. The theoretical 130 Ah for the bank of two batteries was considered the base for discharge efficiency calculation.

The PV modules were employed to charge batteries to 100% SOC then the PV modules were covered ensure zero PV current and the batteries were discharged to 35% SOC, as measured on the charge controller, using different load for each run. During these runs the summation of the discharged current (Actual Ah) were calculated for the batteries. At 50 watts of load (around 2 Amps of discharge current) the two batteries delivered 90 Ah that when compared with theoretical capacity of the batteries translates to 70 % of battery discharge efficiency. At 400 watts of load (around 17 Amps of discharge current) the two batteries delivered around 66 Ah, which translates to around 50% of battery discharge efficiency. Figure-4 shows the significant decrease in batteries useful capacity at higher load demand (discharge current). It also shows the linear relation between the load and the batteries useful capacity. This linear relation would facilitate simulation studies.

The poor battery performance when discharged at higher rates emphasizes on the need to properly consider adding extra batteries to support higher load requirements. Although more batteries translate to more system cost, the higher running efficiency of the system translates to higher system capacity. The results show importance of simulation study of the load pattern and its effect of system performance as means to decide on the proper size of storage batteries.

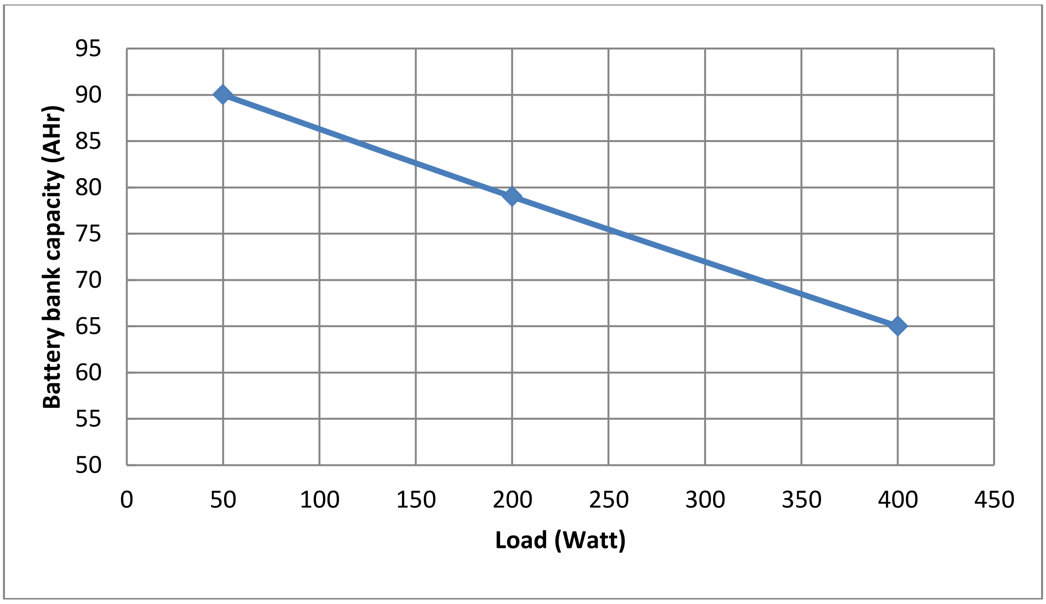

Figure-4. Variation of battery bank capacity at different consumption rates.

5.3. Effect of battery state of charge on battery's output power

The effect of SOC (%) of batteries on the capacity of the system to supply a load was evaluated. A special test was carried out in which two serially connected batteries (to supply 24V) were charged to 60%, the PV modules were covered by an opaque sheet to ensure zero PV current and the system was loaded; load was supported only by the batteries. The power delivered to the load was evaluated at different loads and different battery states of charge. The results of this test, as shown in Figure-5 shows that battery SOC doesn't significantly affect the capacity of the battery to support the load, down to 35% SOC. Figure-5, also, showed increase of consumed power in a rate higher than the load increases, leading to decreased efficiency.

To further investigate the system performance, consumed power losses was derived and plotted against loads, as shown in Figure-6. The results showed a nonlinear trend of losses that features a characteristic bend at the recommended maximum load. This load is calculated as the product of nominal Amber hour of the battery (100Ah), no. of batteries (2) and the voltage of the battery (12V) divided by the recommended hours of discharge (20hrs). For the current system, recommended load could be evaluated as following:

Battery's recommended load = Battery Ah ×No. of Batteries × Battery voltage / Discharge hours
= 100 × 2 × 12 /20 = 125 Watt

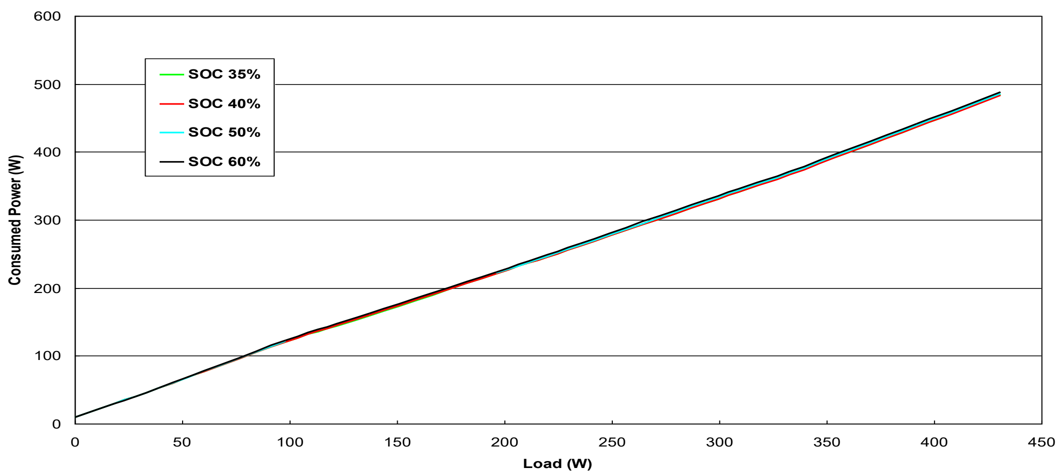

Figure-5. Power consumed by different loads at different battery's SOC.

Finally, the decreased loss rates at higher loads should be viewed as decrease in batteries useful capacity at high load current. The results show that battery bank selection should favor useful capacity unless other economical goals such as reducing number of batteries to reduce cost are pressing.

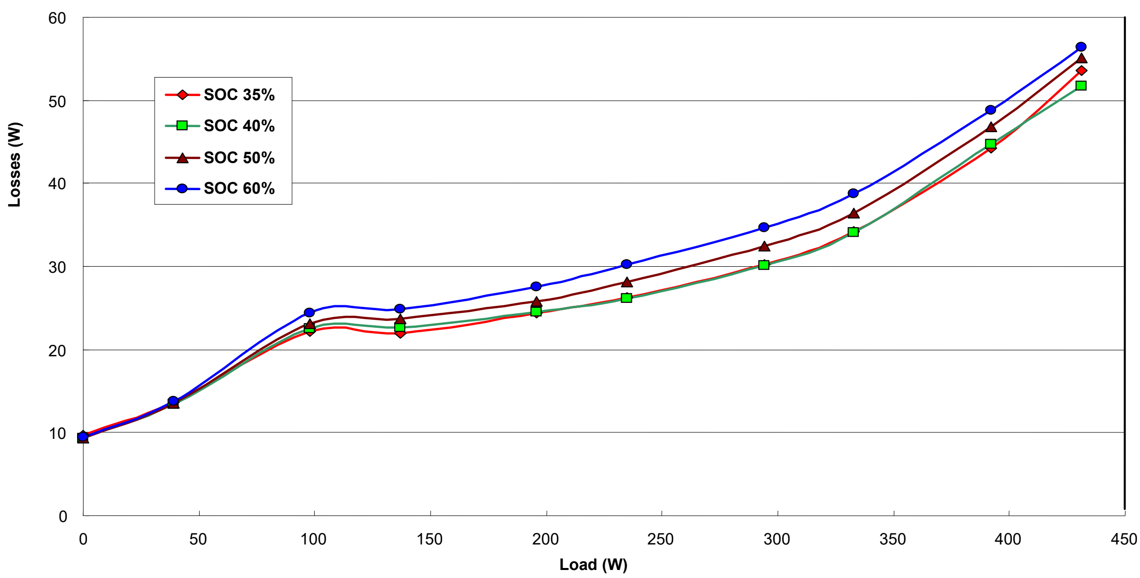

Figure-6. Power losses at different battery's SOC and different loads.

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6. CONCLUSIONS

The current study investigated the battery's effect on fitted PV energy system. The effects caused by battery's capacity and performance under different SOC and load demand could be concluded as following:-

- Battery SOC does not affect battery charging efficiency, consequently does not reduce energy system performance.
- Batteries suffer from significant decrease in its useful capacity at higher discharge current (load requirements). This indicates a poor efficiency of the batteries when supporting larger loads, leading to degraded energy system performance.
- Battery losses is nonlinear that increases by increase of batteries SOC and load.
- Lower battery's SOC has insignificant effect on the capacity of battery to supply the load demand.

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