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Numerical modelling of the power pack system for remote islands electrification

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Abstract. Electricity is one of the indispensable elements in the daily life. From domestic to commercial sector, electricity has been used to provide a wide range of applications. However, access to electricity is only limited to the urban area while rural area electrification is always a challenge due to the geographical location and high cost of the electrification infrastructure. Therefore, electrification using solar energy is projected to be one of the feasible solutions in the rural area. A typical power pack system used for the rural area electrification consists of solar panels, voltage converters and battery pack. Although lead acid battery provides an economic solution for the energy storage system, they are also associated with other disadvantages such as low depth of discharge, bulky and low energy density. Li-ion battery is a new generation of battery technology with high energy density, light weight and high depth of discharge which offer a promising solution for an off grid power systems. In this study, an off grid power pack consists of Li-ion batteries, voltage converters and photovoltaic modules are modelled to evaluate the electrical performances of the system under Malaysia weather conditions. Then, the numerical modelling results are compared with experiments. It is found out that the numerical model correlated well with the experimental data with a relative error less than 5%.

1. Introduction

Electricity plays an important role in the country development especially in the industry, as well as an important energy source to power up electrical appliances for residential application. However, most of the electricity infrastructure, focuses in urban areas and those living in the rural areas are still lack of access to electricity. According to energy access outlook in the 2017, about 14% of the 1.1 billion populations in the world live without electricity. Around 84% of them living in the rural area and more than 95% of residents from countries in sub-Saharan Africa and developing Asia country [1]. The reasons that hindered the government from putting extended efforts to ensure access to electricity in rural area are low population, far from the national grid source, geographically inaccessible and poor funding from the government. Electricity provided to most of the remote areas are usually diesel generators which release harmful emission to the environment and subjected to volatility of the fuel price [2]. In addition, it is expected that global electricity demand will grow at 57% by 2030, the electrification gap between urban and rural areas will be widened further as more investment will be thrown into the electrification infrastructure surrounding urban areas. Therefore, remote residents are likely suffer from energy shortages or blackouts. In order to address these issues and reduce the harmful emission to the environment during electricity generation, it is appropriate to introduce renewable energy source power system for rural area electrification. Although there are various types of renewable energy source, the most suitable candidate of the power system for remote area is using solar energy [3].

A photovoltaic (PV) cell is an electronic device produce electricity through conversion of solar energy. There are different types of solar cell available such as crystalline silicon, monocrystalline silicon, polycrystalline silicon, multijunction cells, etc. Photovoltaic cell modelling is important in designing the rural area power system to determine its performance and efficiency. PV modelling can be classified into three different categories namely power model, single diode series resistance and single diode parallel resistance [4]. The power models estimate the power delivered during the optimum power point condition with the use of a single point efficiency to represent the PV module [5]. Most of the power models simulation software allow users to input various operating conditions to produce the results within an acceptable range. Ayvazogluyuksel and Filik used power model to forecast the output power of the solar based system in Eskisehir [6]. The study found out that global solar radiation in horizontal and tilted direction, PV cell temperature and ambient temperature are important factors affecting the power generation. Simulation results using Hybrid2 power model are compared with the experiment conducted in Xcalac [7]. It was found that there is about 18% difference on the PV array output with the experimental results. Besides, PV module can be modelled using a single diode series resistance model to predict the electrical characteristics of the PV under different operating conditions. Walker used the equivalent model proposed by Gow and Manning and simplified it by neglecting the shunt resistance to predict the electrical characteristic of the PV [8]. Walker model can be estimated from three initial conditions which are open-circuit, short-circuit and slope at open-circuit point. There are four parameters involved which is diode saturation current, photocurrent, series resistance and ideality factor. One of the drawbacks for the single diode series resistance model is the accuracy reduces when the PV module subjected to substantial temperature change. Therefore, single diode parallel resistance model with inclusion of shunt resistance which is equivalent to the leakage current in the p-n junction of the PV cell is proposed to improve the single diode series resistance model [9]. Shunt resistance, photocurrent, saturation diode current, diode ideality factor and series resistance are the parameters used in the single diode parallel resistance model can be obtained from open circuit point, maximum power point and short-circuit point using the I-V curve [9]. Moreover, it is observed that the single diode parallel resistance model with combination of HDKR model suggested by De Soto et al. will produce the best results for the PV array output with lowest mean bias error (0.89%) and mean absolute error (11.87%) [10].

Direct use of electricity generated by the PV system is often inconsistent as the solar radiation relied heavily on the meteorological conditions. Hence, energy harvested from solar radiation needs to be stored in the battery. Various types of battery used in the power system available in the market such as Li-ion battery, lead acid battery, NiMH, etc. Lead acid battery is commonly used as an energy storage system in the PV power system as it is cheap for bulk application. However, recent advancement in battery technology allows the development of Li-ion battery with high energy and power density and more lightweight compare to the lead acid battery [11]. Hence, Li-ion battery is the best energy storage system candidate for the solar power system. Establishing a precise battery model is important as the PV system is heavily depended on the battery performance to supply sufficient and uninterrupted power supply for household appliance during peak hours at night. Mathematical models have been applied to predict the I-V characteristic and temperature rise of the battery such as RC model, electrochemical model, empirical model and lumped parameter model [12]. Although electrochemical model gives the most accurate prediction, spatial partial differential equations coupled with time variant make it too complicated and required massive computational resources. Except electrochemical model, the second choice is using modified shepherd equation integrated with lumped thermal model. This battery model is also give a good prediction of the electrical and thermal behaviour of the battery [12].

Shukla et al. evaluated the feasibility of grid-connected rooftop solar photovoltaic system which supplies electricity for a hostel in India [13]. Performance of various PV systems is evaluated using Solargis PV planner. Among four types of PV system, only amorphous silicon (a-Si) and crystalline silicon (CdTe) PV systems provide performance ratio higher than 75%. Bouzguenda et al. presented an economic and technical analysis of an off-grid solar PV system with power rating of 2 kW. The effect of the PV panel orientation, tilt angle, spacing between panel, energy demand of the user, site specifications and urban settings are taken into consideration to compute the energy cost [14]. A techno-economic analysis of the commercial solar home lighting system (SHLS) with polycrystalline silicon photovoltaic as an energy harvesting source and lead acid battery is also evaluated [15]. Besides, the performance of the SHLS is also evaluated using different types of lithium-ion battery and compared with commercial SHLS. It was found that lithium manganese oxide cathode, lithium iron phosphate, and Lithium Nickel Cobalt aluminium oxide battery are practical choices for energy storage system concerning economics and performance metrics.

It is found that most of the reported work in the literature primarily focus on the economic-techno analysis, while study related to the modelling of the PV power system is rare. In view of this, an empirical based battery model is developed to forecast the I-V characteristic of the PV power system under various operating conditions. The validated PV model and Li-ion battery model are then combined to investigate electrical response of the solar power pack system for rural area electrification.

2. Numerical model for the solar power system

2.1. Photovoltaic model

A PV cell model is used to simulate the power output of the PV panel under different metrological conditions. HDKR model coupled with De Soto et al. model is used for this study [10]. Equations 1 to 6 are used to describe the electrical behavior of the PV cell. The PV cells are assumed to be identical and there is no variation between PV cells.

$$I = I_{pv} - I_o\left\{\exp\left[\frac{q(V+IR_S)}{nkT_cN_s}\right] - 1\right\} - \frac{V+IR_S}{R_p} \quad (1)$$

Photo-current, I_{pv}

$$I_{pv} = \frac{S}{S_{STC}}\left[I_{pv,STC} + \mu_{I_{sc}}(T_c - T_{c.STC})\right]$$

Diode saturation current, I_o

$$\frac{I_o}{I_{o,STC}} = \left[\frac{T_c}{T_{c,STC}}\right]^3 \exp\left[\frac{q}{nk}\left(\frac{E_{g,STC}}{T_{c,STC}} - \frac{E_g}{T_c}\right)\right]$$

Shunt resistance, R_p

$$R_p = \frac{S}{S_{STC}}\left\{I_{sc,ref} + I_{sc,ref}\left[exp\left(-\frac{V_{oc,ref}}{a_{STC}}\right)\right] - \frac{V_{MPP,STC} + I_{MPP,STC}R_S - V_{oc,ref}}{a_{STC}} - \frac{P_{max,exp}}{V_{MPP,STC}}\right\}$$

Total irradiance using HDKR model, $I_{T,\,HDKR}$

$$I_{T,HDKR} = I_b r_b + I_d\left\{(1-A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + r_b A_i\right\} + I_H\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (2)$$

2.2. Lithium-ion battery model

Eq. 3 & Eq. 4 represent the modified Shepherd equation used to model the charging and discharging behavior of the Lithium Iron Phosphate ($LiFePO_4$) battery [12]. The battery internal resistance is taken as 0.0034 Ω regardless of the operating condition.

Discharging (i* > 0)

$$V_{batt} = E_o - i.R - K\frac{Q}{(Q-it)}it + Aexp(-B.it) - K\frac{Q}{(Q-it)}.i^* \quad (3)$$

Charging (i* < 0)

$$V_{batt} = E_o - i.R - K\frac{Q}{(Q-it)}it + Aexp(-B.it) - K\frac{Q}{(Q-it)}.i^* \quad (4)$$

2.3. Voltage converter

There are two different types of voltage converter modeled in this study namely DC to DC Converter and DC to AC inverter. DC to DC buck converter is used to step down the voltage generated by the PV module from 30 V to a compatible voltage rating of the battery pack at 24 V. On the other hand, DC to AC inverter is utilized to change the DC voltage of the battery pack to AC 230 V for household application in Malaysia.

2.4. Experimental setup and parameter extraction

A commercial polycrystalline PV cell panel (MSR MYS-60P/B3/CF-260) and 20 Ah $LiFePO_4$ battery (A123 Systems) is used as the energy storage system. The details of the PV cell and battery parameters are tabulated in Table 1. The discharging data of the battery at various C-rates is extracted using the battery cycler (Maccor Instrument 4000). Impedance analyser (Solartron analytical 1400) is used to analyse the internal resistance of the battery.

Table 1. Specifications of the PV cell and $LiFePO_4$ battery.

PV cell		**Li-ion battery (A123 system, AMP20M1HD-A)**	
Parameters	**Value**	**Parameters**	**Value**
Rated maximum power, W	260	Nominal voltage, V	3.3
Short circuit current, A	8.987	Nominal Capacity, Ah	20
Open circuit voltage, V	38.329	Pouch cell length, m	0.227
Current at MPP, A	8.563	Pouch cell width, m	0.160
Voltage at MPP, V	30.878	Pouch cell thickness, m	0.00725
Overall system efficiency, %	50	Pouch cell weight, kg	0.496
Discharge efficiency, %	90	Pouch cell specific heat, $JKg^{-1}K^{-1}$	1200
Average panel output, W	220	Pouch cell internal resistance R, Ω	0.0034

2.5. Numerical procedures

The solar power system model is developed using Matlab Simulink 2017b. The design of the solar power system is based on the basic electric appliances requirement for a household in the rural area. The solar power system must be able to supply electricity for two days period when the PV cells do not operate due to the local weather conditions. From the calculation, about four PV cells are required to be connected in parallel to charge up the 3 kWh battery pack in 8 hours. Overall PV system efficiency is taken as 50% and discharge efficiency is taken as 90%.

3. Results and Discussions

In order to validate the solar power system model, the simulation results are compared with the experimental data recorded on 31st October 2016 on the rooftop of KB block, UTAR Sungai Long. Fig. 1 illustrate the comparison between simulation and experimental data on 31st October 2016 at UTAR Sungai Long Campus from 1:41 pm to 4:58 pm (197 minutes). Total power generated by the PV cell is about 26,290.2 W while the simulation result from the model is about 25,943.58 W. Relative error of the simulation results and experimental data is about 1.31%.

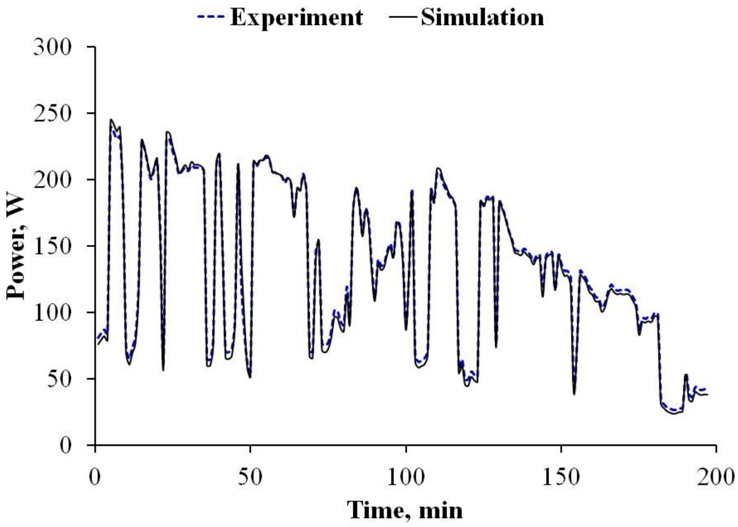

Fig 1. Comparison of simulation and experimental data of the PV cell.

The discharging characteristic of the battery estimated through the battery model and measurement of the battery current for 1C to 3C-rates are illustrated in Fig. 2. As shown in Fig. 2, the battery model predicted the experimental result well with the average relative error of 3.57%, 6.87% and 7.69% for 1C, 2C and 3C-rate, respectively.

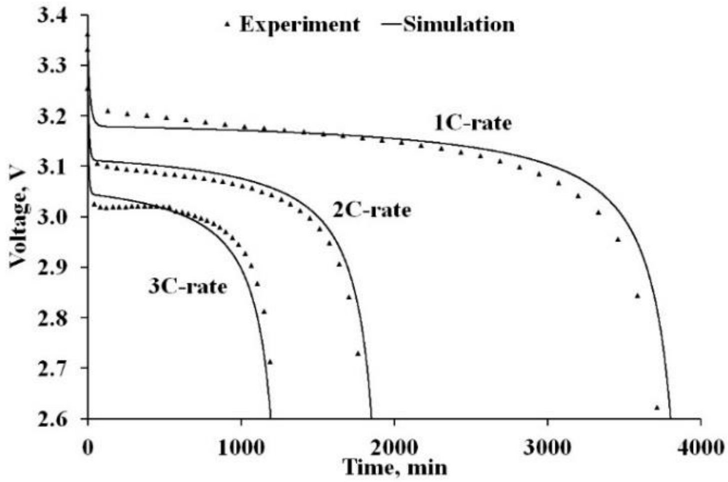

Fig. 2. Validation of the battery model for 1C, 2C and 3C-rate of discharge.

In order to examine the electrical characteristic of the battery pack under real world condition, solar data as shown in Fig. 1 is used to charge the battery pack. Fig. 3 illustrate the charging characteristic of the battery pack predicted by the battery model.

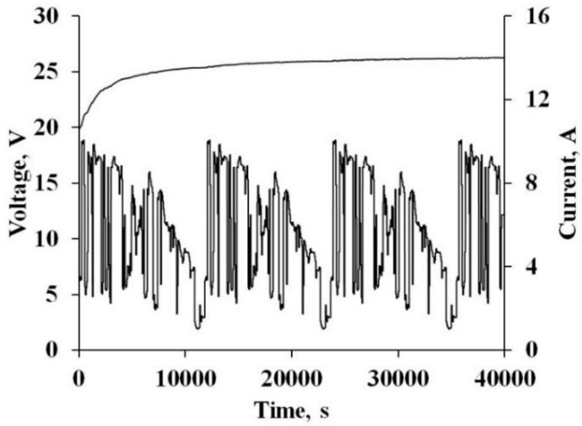

Fig. 3. Charging characteristic of the battery pack predicted by battery model.

4. Conclusions

In this study, numerical modelling through Simulink is used to predict the performance of the solar power system. Calibrated PV model and battery model are integrated to investigate the performance of the solar power system under real world conditions. The numerical model predicted the experimental data well with relative error less than 10% for all cases. It is suggested that, the solar power system is preferable to have large number of battery arrange in parallel to improve its reliability and reduce maintenance in the rural area. Future research work can be conducted by constructing a prototype of the solar power system to validate the numerical model under weather conditions.

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