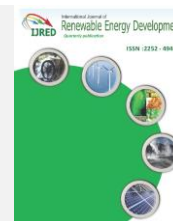




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The Effectiveness of New Solar Photovoltaic System with Supercapacitor for Rural Areas

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ABSTRACT. Countries like Malaysia have more than 70% of its population living in rural areas. The majority of these rural areas lie in regions where most villages do not have grid connected electricity. Renewable energy using photovoltaic (PV) panels offers an alternative and cost efficient solution that exploits the yearlong abundance of sunlight available in countries like Malaysia. The main problem with PV systems is the high maintenance costs in replacing batteries every few years which makes PV systems unattractive for rural areas. A full-scale PV system, developed in Semenyih Malaysia, aims to increase battery lifetime and reduce maintenance costs by incorporating supercapacitors. The system was developed in a life-sized cabin to mimic a rural home. A programmable load is used to test the system with the load profile of a typical rural household usage. Experimental and simulation results show that the supercapacitor bank is able to reduce the stress on the battery by absorbing peak current surges. Results also show that the system is able to maintain a high battery state of charge during the entire day. The experimental results show that the average battery current, using supercapacitors, is greatly reduced from 2.75A to 0.23A, average power reduces from 147.95 W to 12.1 W and the peak battery current reduces from 20.8 A to 16.4 A. All experimental results are comparatively similar with the simulation results.

Keywords: solar photovoltaic, supercapacitor, battery, hybrid, rural, effectiveness

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1. Introduction

About 81% of the global energy supply is reliant on fossil fuels such as oil, gas and coal (The International Energy Agency 2014). These non-renewable energy reserves are being depleted all across the world and it will finish soon. Hence, alternative energy sources need to be urgently developed in order to reduce the reliance on these resources. Furthermore, an extensive development, especially in the industrial and residential sectors, has rapidly increased the energy demand (Centre for Energy, Environment, and Technology; ECO logic Institute for International and European Environmental Policy). This increasing demand will not only deplete reserves faster but also increase the ever growing concern on the environmental impact of fossil fuels.

In 2014, the International Energy Outlook projected that the world's energy consumption will rise from 15.203137 quadrillion Btu in 2014 to 17.580429 quadrillion Btu in 2040 (U.S. Energy Information

Administration (EIA) 2014). Solar energy is a renewable energy (RE) source that is infinite and has the most potential in countries located near the equator. With proper management, it can fulfil a sufficient percentage of energy needs around the world with emission power from the sun approximately equivalent to 1.8 Mega Watt (MW) a year (Centre for Energy, Environment and Technology). According to Renewables 2014 Global Status Report, the total world energy consumption is 1,560 GW in 2013 (Renewable Energy Policy Network, Global Status Report 2014), and by 2050, it is projected to be about 30 TW (BP Statistical Review of World Energy 2013). These large figures show the need for extensive research to find innovative technologies to maximize usable energy available from the sun to fulfil future demands (Jennings Philip 2009). The total renewable energy power capacity in 2013 shown in Fig. 1 is approximately 139 GW which is a growth of 55% from 2007 (Renewable Energy Policy Network, Global Status Report 2014).

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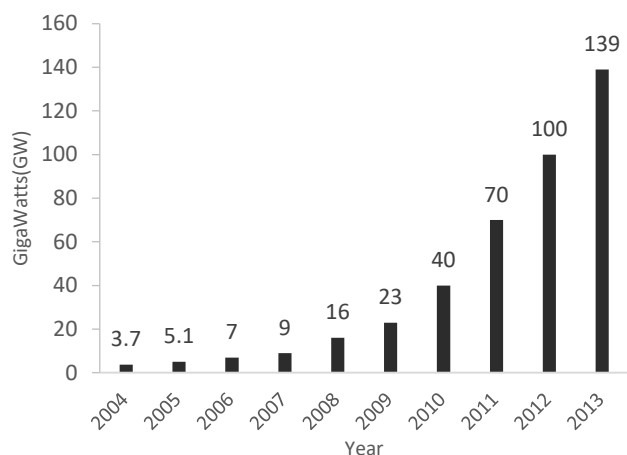


Fig. 1 Solar PV Total Global Capacity 2004-2013 (Global Status Report 2014)

Malaysia relies heavily on fossil sources such as natural gas, coal and crude oil for energy generation. In 2012, 97% of the total energy generation in the country was from fossil fuel sources (Energy Commission, Malaysia Energy Information Hub; Economic Planning Unit 2006).

1.1 Solar energy in Malaysia

Renewable energy is becoming an attractive choice in many countries including Malaysia due to the richness of natural sources (MBIPV Project 2010; Sustainable Energy Development Authority of Malaysia (SEDA); Ministry of Energy, Green Technology and Water 2013; Chua SC *et al.* 2012). Policies on renewable energy have been developed to lay out the strategy to manage and protect the resources in Malaysia. In 1981, the Four-Fuel Diversification Strategy was introduced to diversify the fuel mix used in generating electricity (Ali *et al.* 2012). In 2002, the Five-Fuel Diversification Strategy was introduced to integrate new renewable energy sources with oil, gas, coal and hydro (Devon Association for Renewable Energy 2010; Borhanazad *et al.* 2013). The implementation of this policy resulted in a steady decrease in the use of fuel sources such as coal and gas to generate electricity.

Malaysia has a strategic geographical location with sustained solar irradiation with more than 10 sun hours per day (Amin *et al.* 2009) and averaging approximately 1643 kWh/m² per year (Ahmad *et al.* 2011, Haris *et al.* 2008). It is thus important to tap into this potential for Malaysia's benefit. Therefore in Malaysia, with a maximum solar radiation of about 5.51kWh/m² per day, the potential for applying solar energy for electrification is very high (APEC Energy Overview 2012).

A grid extension to rural areas through difficult terrains and thick jungles is not feasible and economically viable (Haris 2006). More than 800 schools currently in Malaysia are not supplied with 24-hour electricity as these schools are mostly located in the rural areas of Sabah and Sarawak (Sreeraj *et al.*, 2008; Muhammad-Sukki *et al.* 2012; Mahmud 2010). The off-

grid electricity which can be generated by solar, wind or hydro because of a low maintenance cost, reliability and environmentally friendly. The current system of generating energy is mainly by using solar photovoltaic (PV) with a diesel generator as the backup power supply. There are many problems for a rural area to maintain power generation by depending on diesel generator including long distances from the petrol station to buy diesel, higher maintenance costs and environmental pollution (Ministry of Rural and Regional Development 2012; Foster *et al.* 2009; Anyi *et al.* 2010).

1.2 Standalone Solar Systems

The best solution for most of the rural countries like Malaysia is the use of standalone solar PV systems. The challenge is to bring the setup and maintenance costs down so that the system can be affordable in rural areas. The most important component in a PV system is the batteries which are used as the primary energy storage in order to increase the reliability of the system. The most popular and commonly used energy storage device for a PV system is the lead acid battery. This type of battery is widely available and relatively low cost compared to other types of battery. The direct charging of a battery not ideal because of the output from a solar PV panel needed to fully rely on weather conditions thus making the charging of a battery not ideal (Vazquez *et al.* 2010; Ng *et al.* 2010). It is difficult for batteries to undergo frequent and quick power fluctuations without a dramatic loss of value in their lifetime. In basic principle, the charge/discharge rate of battery is restricted because of its low power density (Rajagopal 2013).

A promising energy buffer device, the supercapacitor, has begun increasingly used recently because of its higher power density, longer cycle period and higher charging-discharging efficiency compared with that of the traditional battery. The main disadvantage of supercapacitors is the low energy density (Ma *et al.* 2014). Supercapacitors are able to charge and discharge at a higher faster rate compared to batteries and have significantly larger charge capacity compared to conventional capacitors. Conventional batteries have a disadvantage of only capable of a few thousand charge cycles while supercapacitors have a few hundred thousand charge cycles (Glavin *et al.* 2007).

In power generation, lead acid batteries balance the average energy demand while supercapacitors are applied to meet the fast changing power demand (Glavin *et al.* 2008). When lead-acid batteries are used for households, frequent replacement costs will be incurred as the battery lifetime will be reduced due to fast and high power fluctuations. The reliability and cost of energy have improved in this simultaneous units due to availability of multiple sources of energy (Bernal-Agustín & Dufo-López 2009).

In order to achieve higher impact on the lifetime of the battery, the size supercapacitor that needs to be applied to the system must be sufficiently large (van Voorden *et al.* 2007). There has been a few research work done to combine solar hybrid with a supercapacitor. M.E Glavin’s work on hybrid systems combines solar PV, supercapacitor, and battery in one system (Glavin *et al.* 2012).

The objective of this paper is to prove that the combination of this hybrid energy storage between supercapacitor and battery is better than battery only standalone energy storage. Additionally this paper also demonstrates that simulation and experimental results are significant and comparable. Simulation in this paper was done by using Matlab Simulink and all the experiments was done in a solar cabin at University of Nottingham Malaysia Campus (UNMC).

2. System Design

A system was developed in Solar Research Centre (SRC) in UNMC to simulate a common rural non-grid main power household using solar power as the main energy source to meet the energy demands of a typical rural household (Fahmi *et al.* 2014). A standard grid-connected photovoltaic (PV) power system consists mainly of a PV panel connected to a utility grid. Other subsystems are solar charge controller, grid charger, power condition units, batteries, inverters and grid connection equipment. The solar power condition units will monitor the charging/discharging battery voltage, solar power output and the load.

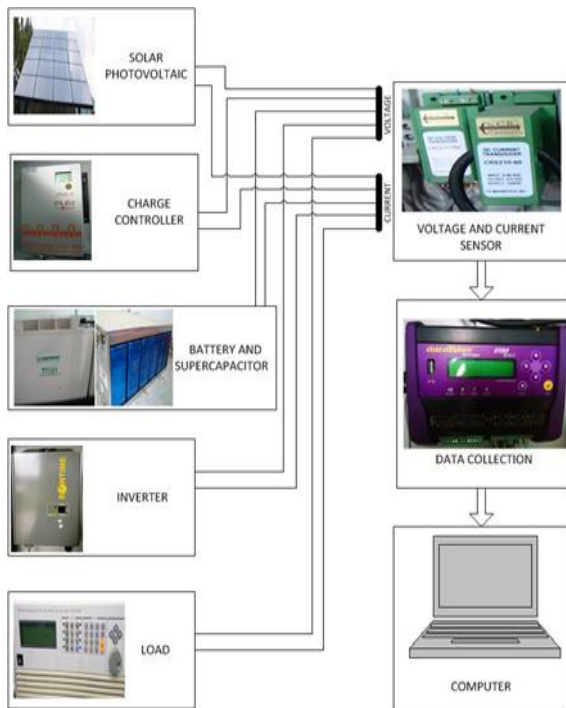


Fig. 2 Solar System block diagram

Fig. 2 shows the block diagram of the system which is powered by 2kiloWatt (kW) solar panels. The batteries used in this project have a capacity of 150Ah. The inverter is used invert the system voltage from 48VDC to mains electricity supply rated 230VAC. Fig. 3 shows the schematic of the supercapacitor bank as an extra feature to this system to support the battery and make the system more efficient. All these equipment and system modelings in this project have been reviewed in depth in previous works (Fahmi *et al.* 2014).

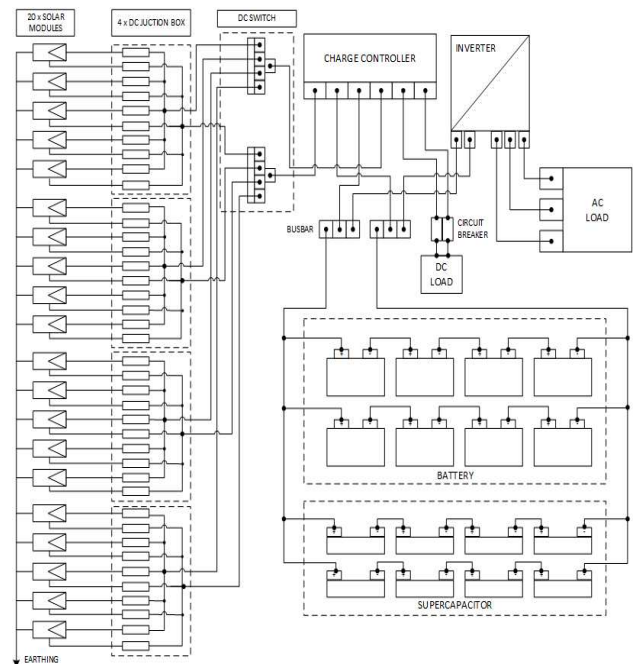


Fig. 3 Solar PV system with supercapacitor

The estimation of energy usage in rural areas is based on a study which shows that only certain important items are used in a typical rural household such as television, water pump, ceiling fan, light and socket outlet (Fahmi *et al.* 2014). The total estimated energy usage is 4916W and this is expected to grow by 20% in 5 years. Based on this data, the experiment was setup with the battery and supercapacitor to ascertain whether the proposed solar system design is able to fully meet the estimated energy usage in a typical rural household.

A simulation model of the exact system has also been performed in Matlab Simulink in order to verify the experimental results. This simulation model consists of solar irradiation profile, PV array, battery, supercapacitor and load. This simulation model is shown in Fig. 4. The battery and supercapacitor block diagram is from Matlab (Mathworks 2016).

The battery block implements a broad dynamic model parameterized to characterize most favorite types of rechargeable batteries. The type of battery used in Solar Cabin is Lead Acid. The corresponding circuit of the battery is shown in Fig. 5.

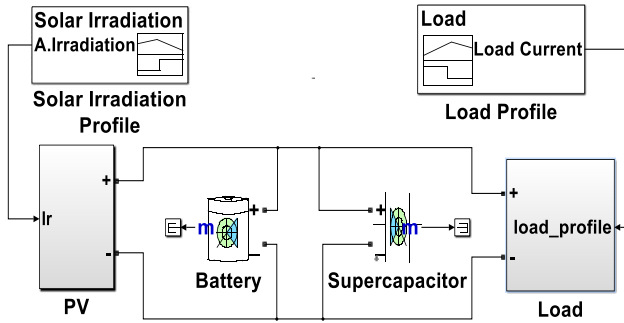


Fig. 4 Solar System simulation model in Matlab Simulink

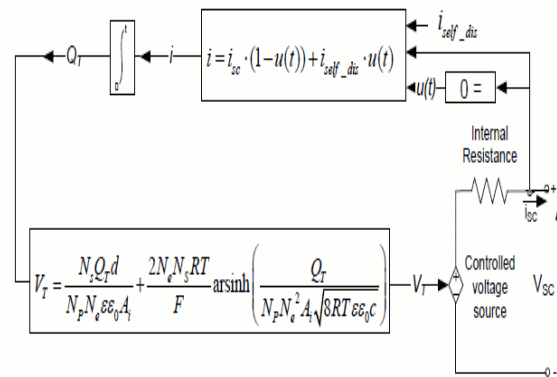


Fig. 6 Equivalent Circuit of the Supercapacitor

$$V_{sc} = \frac{N_s Q_T d}{N_p N_e \epsilon \epsilon_0 A_i} + \frac{2 N_e N_s R T}{F} \sinh^{-1} \left(\frac{Q_T}{N_p N_e^2 A_i \sqrt{8 R T \epsilon \epsilon_0 c}} \right) - R_{sc} \cdot i_{sc}$$

where,

- A_i Interfacial area between electrodes and electrolyte (m^2)
- c Molar concentration (mol/m^3) equal to $c = 1/(8N_A r^3)$
- F Faraday constant
- i_{sc} Supercapacitor current (A)
- V_{sc} Supercapacitor voltage (V)
- R_{sc} Total resistance (ohms)
- N_e Number of layers of electrodes
- N_p Number of parallel supercapacitors
- N_s Number of series supercapacitors
- Q_T Electric charge (C)
- R Ideal gas constant
- d Molecular radius
- T Operating temperature (K)
- ϵ Permittivity of material
- ϵ_0 Permittivity of free space

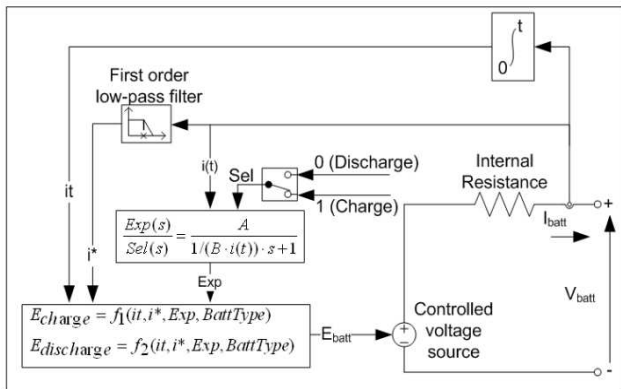


Fig. 5 Equivalent Circuit of the Battery

Discharge model ($i^* > 0$)

$$f_1(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot 0 \right)$$

Charge Model ($i^* < 0$)

$$f_2(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{it + 0.1 \cdot Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s} \right)$$

where,

- E_0 Constant voltage (V)
- $Exp(s)$ Exponential zone dynamics (V)
- $Sel(s)$ Represents the battery mode. $Sel(s) = 0$ during battery discharge, $Sel(s) = 1$ during battery charging.
- K Polarization constant (Ah-1) or Polarization resistance (Ohms)
- i^* Low-frequency current dynamics (A)
- i Battery current (A)
- it Extracted capacity (Ah)
- Q Maximum battery capacity (Ah)

The Supercapacitor block implements a generic model parameterized to explain most popular types of supercapacitors. The Fig. 6 shows the equivalent circuit of the supercapacitor.

3. Results and Discussions

All simulation and experimental results will be discussed in this section. Four experiments were conducted in the proposed solar system and simulation results are used to verify the experimental results. All data are collected using the Delogger software. All four experiments are designed to show the system performance difference with and without supercapacitors added to the system. The ultimate aim of this paper is to prove the suitability this system for rural households by protecting the battery from peak current discharge that will reduce the lifetime of the battery and increase the overall maintenance costs in frequently replacing batteries. The load current profile is created using the Chroma 63800 Series programmable load that allows the current profile to be set differently for every hour.

3.1. Solar and Load Data

Fig. 7 shows the average solar irradiance data collected per month for 20 months in the solar cabin. The

maximum average solar irradiance is 10,429 w/m² and minimum irradiance was 3411 w/m² in December 2014.

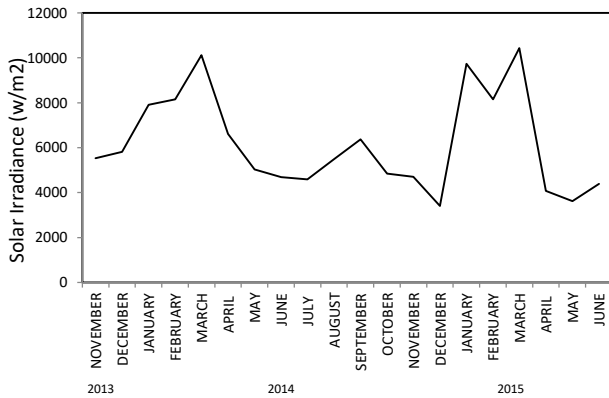


Fig. 7 Average Solar Irradiance per Month for 20 Months

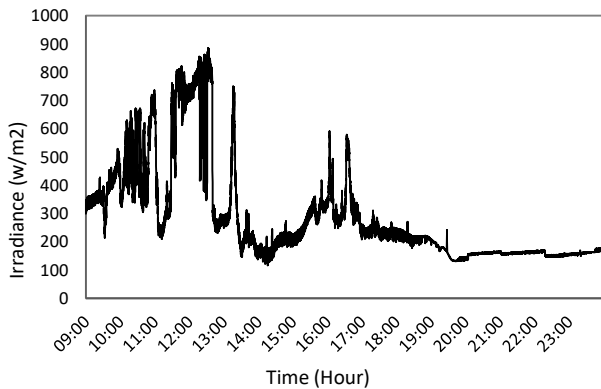


Fig. 8 Solar Profile for experiment without Supercapacitor

Each experiment is conducted for an entire day from 9 am to 12 midnight. The solar irradiation will differ from day to day so it is not possible to have a common solar profile. Fig. 8 and Fig. 9 is the solar profile for the experiment days that was conducted with and without supercapacitor respectively. The same actual solar profile will also be used for the corresponding simulation study.

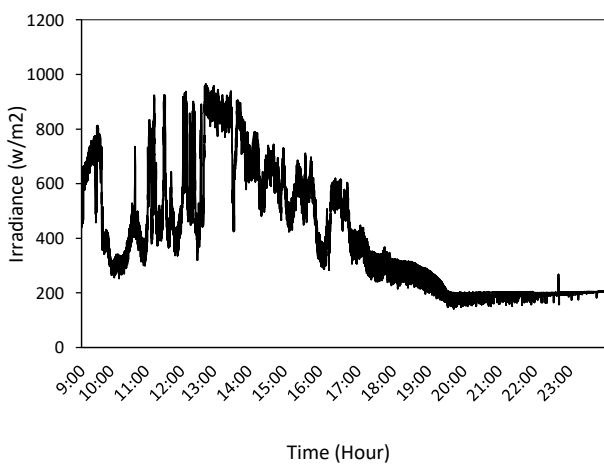


Fig. 9 Solar Profile for experiment with Supercapacitor

3.2. Real Usage for Rural Area

Based on estimated energy usage data, the load current profile has been set up by using previous load current profile (Fahmi *et al.* 2014). The experiment was conducted to mimic the hourly average usage of power in a typical rural household.

Fig. 10 shows the battery voltage results for the simulation and experiment with the load profile applied. When the load current increases, the battery voltage is decreased. Furthermore, the battery is able to support the high load demand, especially at night. There was no effect on the battery voltage during the day as the battery was constantly charged by the solar power but at night, the simulation shows a high value compare to the experiment. The simulation and experiment results are slightly different due to the configuration of the battery model used in simulation making it different from an actual battery. The battery is configured to be 52V nominal which is different to the 48V nominal in the actual battery. The battery voltage from the experiment fall instantly due to the lack of solar energy in the evening but in simulation, the voltage drops slowly.

Fig. 11 shows the State of Charge (SOC) of the battery. The lowest voltage of the battery while supplying power was still above 100% for the entire day. This means that the system was able to supply power to the load continuously. Besides that, the battery in the simulation is not overcharged and operating below SOC of 100%.

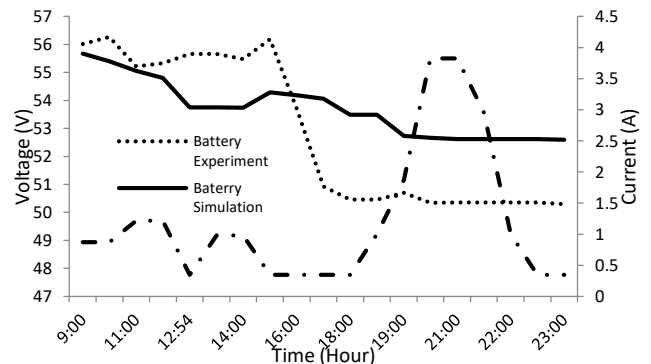


Fig. 10 Battery Voltage Experiment and Simulation with Current Load Profile

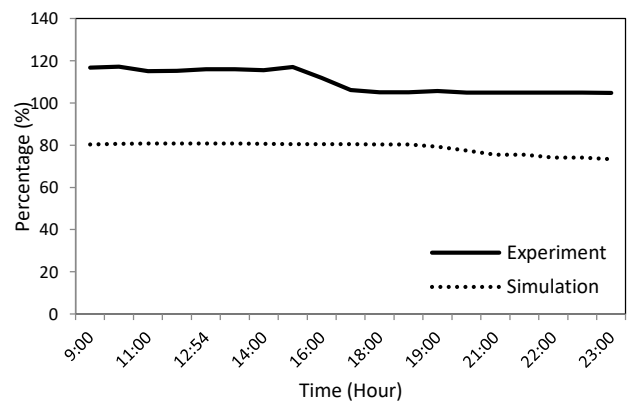


Fig. 11 State of Charge Experiment and Simulation vs Time

Fig. 12 and Fig. 13 shows the battery, load and solar current results from simulation and experiment. The results look almost identical which verifies that the experimental results are accurate.

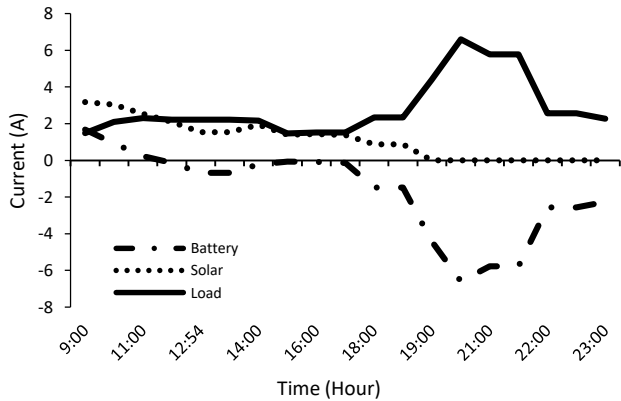


Fig. 12 Battery, Load and Solar Current from Simulation

The battery current was negative during the night as the battery was supplying the load due to the lack of solar power. During the day the battery current was mostly positive as the majority of the power was supplied by the incoming solar energy. The load current profile is the opposite of the battery current; it decreases when battery current increases and vice versa.

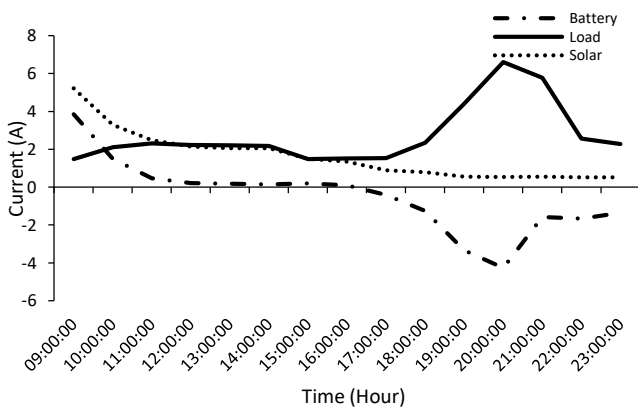


Fig. 13 Battery, Load and Solar Current from Experiment

3.2. Real Usage for Rural Area

The simulation and experiment studies were repeated with the addition of the supercapacitor bank to the system using the same solar profile shown in Fig.7. The supercapacitor bank is initially charged externally to avoid charging directly from the battery with high current (>60A) which will damage the battery. With a continuous supply current of 2 Amps, the supercapacitor bank will be fully charged (15V) in 2 hours for each module. The total numbers of modules of

supercapacitors used in this system are 8 and are all connected in parallel with the battery.

Fig. 14 and Fig. 15 shows the battery voltage normal operation and compared with adding supercapacitors during a normal day cycle for the simulation and experimental studies.

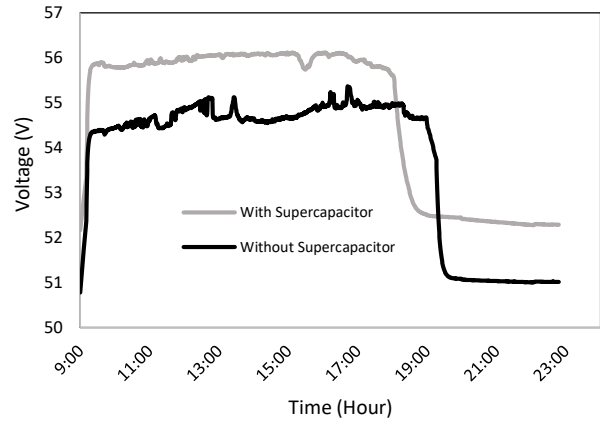


Fig. 14 Battery Voltage vs Time from Simulation

The result clearly shows that supercapacitors cause the battery voltage to be maintained at a higher level compared to without supercapacitors. At night, the battery voltage dropped because the battery charges the supercapacitor but this was not seen in the simulation result. The experimental results are more volatile because of the resistance in the system and other effects making it charge and discharge faster compared to the simulation results which shows a smooth graph due to the idealistic conditions.

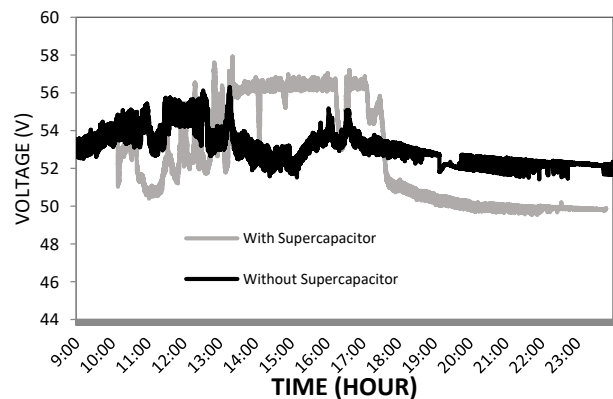


Fig. 15 Battery Voltage from Experiment

As shown in Fig. 16 and Fig. 17, the battery current without supercapacitor fluctuates greatly but with a supercapacitor, the fluctuations are significantly reduced. The current at night is negative due to lack of solar power and battery supplies the current to the load. Both simulation and experiment results show that the battery without supercapacitor has higher peak current than with supercapacitor.

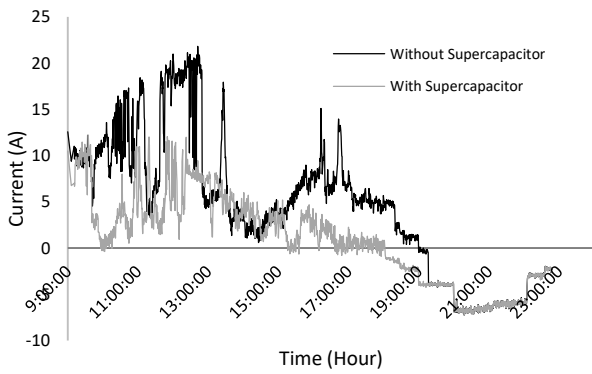


Fig. 16 Battery Current vs Time Simulation

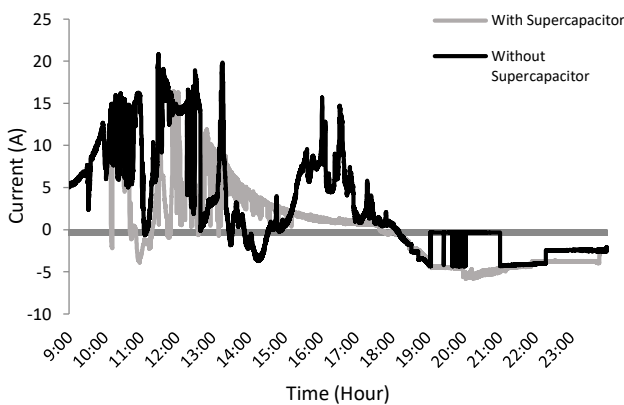


Fig. 17 Battery Current vs Time in Experiment

Fig. 18 shows the supercapacitor current for simulation and experiment. As can be seen, the supercapacitor supplies maximum peak current of 7A in the experiment when high load demand while supercapacitor current in the simulation is stable and lower around 1A.

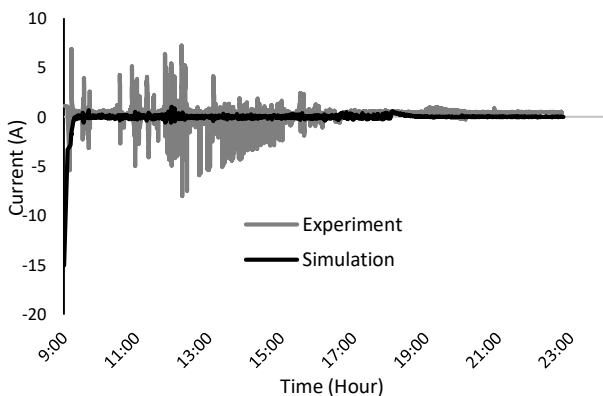


Fig. 18 Supercapacitor Current Results from Simulation and Experiment

Fig. 19 and Fig. 20 show the state of charge (SOC) of the battery for simulation and experimental results. The

graph in the simulation is a stable line while the experimental graph line shows significant fluctuations. The SOC is more than 100% in the simulation results for the battery without supercapacitor and 70% for battery with a supercapacitor.

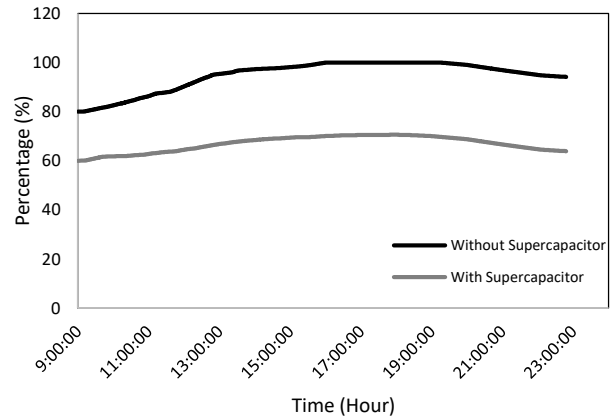


Fig. 19 State of Charge (SOC) Simulation

The simulation environment is idealistic so the energy is shared between battery and supercapacitor causing the drop in SOC of the battery. The experimental result shows that the SOC at night drops by around 10% with supercapacitor while without supercapacitor it drops by 3%. This is due to the battery charging the supercapacitor at night when the supercapacitor voltage drops.

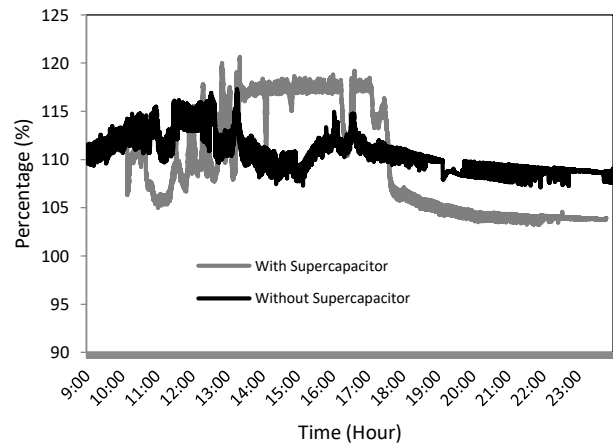


Fig. 20 State of Charge (SOC) Experiment

4. Conclusion

This paper presented the simulation and experimental results of a life-sized solar cabin powered by solar panels, batteries and supercapacitors. The system with battery and supercapacitor combined shows significant enhancements compared with battery alone. The voltage of the batteries is maintained at a high level because the supercapacitors are providing the high current during the day. Another advantage is that the fluctuations of the battery current are significantly

decreased as the supercapacitors supply the peak current demands of the load. Furthermore, the average battery power and battery current are also reduced with the addition of supercapacitors. Simulation and experimental results are comparable and within 5% which clearly justifies the validity of the solar cabin system. Simulation results also prove that the system can protect the battery from peak current demands and thereby increase the battery lifetime.

Further modifications will be needed to counter battery charges supercapacitor during a night because of the SOC of the battery at night is important. All the simulation and experimental results are summarized in Table 1 showing keys parameters. All data have been analyzed and this table only shows the average and peak of the data. For example, the battery voltage that shown in Fig. 14 and Fig. 15 is tabulated as the average and peak values in Table 1.

Table 1
Average and peak results for Solar PV System Simulation and Experiment

	Simulation		Experiment	
	With Supercapacitor	Without Supercapacitor	With Supercapacitor	Without Supercapacitor
Average Battery Voltage (V)	54.75	53.52	52.59	53.08
Average Battery Current (A)	0.88	3.83	0.23	2.75
Average Battery Power (W)	54.67	247.08	12.1	147.95
Average Supercapacitor Voltage (V)	54.75	-	52.34	-
Average Supercapacitor Current (A)	0.0051	-	0.29	-
Peak Battery Voltage (V)	56.11	55.36	57.92	56.28
Peak Battery Current (A)	12.21	21.82	16.41	20.84
Peak Supercapacitor Voltage (V)	56.11	-	57.56	-
Peak Supercapacitor Current (A)	1.01	-	7.24	-
Average Solar Irradiation (W/m ²)	405.72	289.24	405.72	289.24
Peak Solar Irradiation (W/m ²)	964.60	885.51	964.60	885.51

The experimental results show that the average battery current, using supercapacitors, is greatly reduced from 2.75A to 0.23A, average power reduces 147.95 W to 12.1 W and the peak battery current from 20.8 A cut down to 16.4 A. All experimental results are comparatively similar with the simulation results.

The results presented in this paper shows that the proposed solar system is suitable to be used for rural areas in countries like Malaysia. The overall performance of the battery with the addition of the supercapacitor clearly shows that the battery will last significantly longer thereby reducing the maintenance costs for rural homes.

Based on real-time energy demand, the system was able to supply sufficient power to a typical house as the demand was less than the system capacity and its backup battery storage. Support from the backup battery can supply enough power during the night even if the system was not charged during the day. In fact, without charging, the system can supply enough energy to meet demands for almost 2 days. The system still needs to be developed further including the integration of a smart control algorithm and bidirectional DC to DC converter to control the energy flow of the supercapacitors. The addition of more components adds to the cost of the system so more experiments will be planned to show that these costs are justified by system performance and long-term cost savings.

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