A Platform for Analysing Advanced Photovoltaic Energy Controllers

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Abstract

Photovoltaic (PV) based power generation technology is being pushed to the forefront as a viable alternative source of renewable energy, particularly in small scale domestic applications. In addition, there is a growing interest in incorporating storage systems with small domestic generators that are connected to the grid. However, by incorporating storage with such systems there is a need to develop controllers that allow the owners to maximize the benefit of such a system.

Therefore this work introduces, and charts the development of, a virtual platform to test and analyze advanced controllers for small scale PV based power generation system. A Matlab/Simulink based model takes solar irradiation as an input and determines the power produced, taking into account all system inefficiencies including those of the buck-boost converter, AC inverter and battery charger. Moreover, the work demonstrates how the proposed platform can model any PV installation capacity using solar irradiation, temperature and power consumption data for the location of interest using a simple control strategy. It is suggested that the proposed model will significantly reduce time to develop advanced controllers for PV based power generation systems.

1. Introduction

The importance of using renewable energy system, including solar PV has attracted much attention these days, because electricity demand is growing rapidly worldwide (Bendib et al., 2014). Over the last decades, the international interest in the PV conversion of solar radiation has continuously grown. In this way, the use of PV systems is nowadays widespread to an extent that is considered to constitute the third greatest renewable energy source in terms of globally installed capacity, after hydro and wind power. Solar PV energy has been adopted in many countries as a complement for the external power grids in urban as well as remote areas (Shaahid and Elhadidy, 2008). However, the main disadvantage of PV generator is that, solar energy is subjected to daily and seasonal variations (Belfkira et al., 2011). Batteries are usually used for storing surplus solar energy (Sopian et al., 2008) in the case of sufficient sunshine, and supplying shortages in case of insufficient solar energy. Sometimes the daily demand for energy might be so large that it cannot be satisfied by solar energy and battery altogether. In such situations, the imbalance is required to be covered by national power grid or a diesel/gas generator (Koutroulis et al., 2006).

On the other hand, the prospects for PV systems further evolution get obstructed due to various technical and economic issues that have yet to be resolved. For this reason modern scientific and technological research focuses on the development of methodologies and equipment for the increase of energy efficiency of PV systems, the reduction of their production cost, the improvement of their market penetration, and the enhancement of their environmental performance (Branker et al., 2011). However, there is the potential to improve such systems through better control of the energy generated by them.

Several studies have been reported in the literature that investigate PV module (PVM) models to facilitate control system design. Petrone et al., (2007) developed a non-linear model of mismatched PV fields, while in Gow and Manning, (1999) a double exponential model is introduced. In Azab, (2009), the single diode PVM model and the diode equivalent circuit are discussed, and a piecewise linear model is proposed. Similarly, to develop control strategies, more simple models have been developed based on differential resistance (Femia et al., 2005), Norton (Gonzalez el Al., 2009) and Thevenin (Noroozian et al., 2009) circuital approximations.

Trejos et al., (2012) developed four models for step-up, double-stage, grid-connected photovoltaic power systems to be used as analytical tools for control design. The accuracy of the linear controllers were verified by simulation and experimental results using the proposed models. These models require further investigations to incorporate more complex DC/DC converters, like the SEPIC, CUK or ZETA to provide step-up/down operation, continuous input and output currents, or higher efficiency.

Given this need for better controllers to manage the energy generated by PV systems, the aim of this work is to undertake the computer-aided design and performance analysis of advanced controllers for both grid-connected and standalone PV systems using graphical programming environments like Simulink by Mathworks.

2. Methodology

Figure 1 shows a simplified representation of the setup of the test bench platform to be used to analyze advanced controllers for PV solar energy systems.

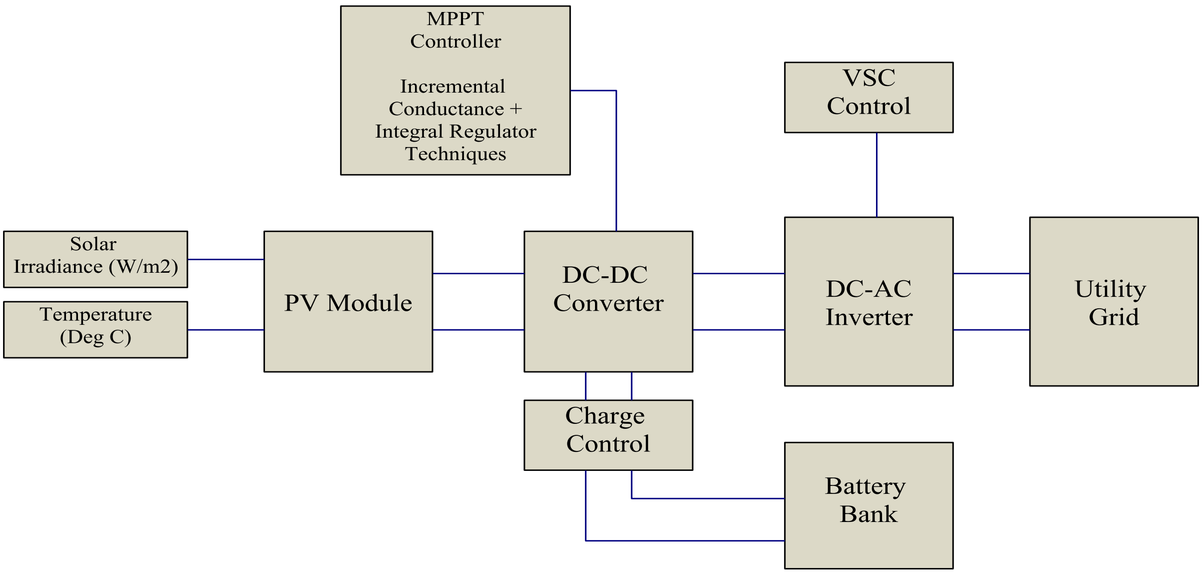

Figure 1. Photovoltaic system model producing power (kWh) proportional to global solar irradiance and temperature (˚C) data

2.1. PV Module

The PV module can be modelled by a five parameter model; using a current source I_L (light-generated current), diode (I_d), series resistance R_s, and shunt resistance R_{sh} to represent the irradiance and temperature dependent I-V characteristics of the module.

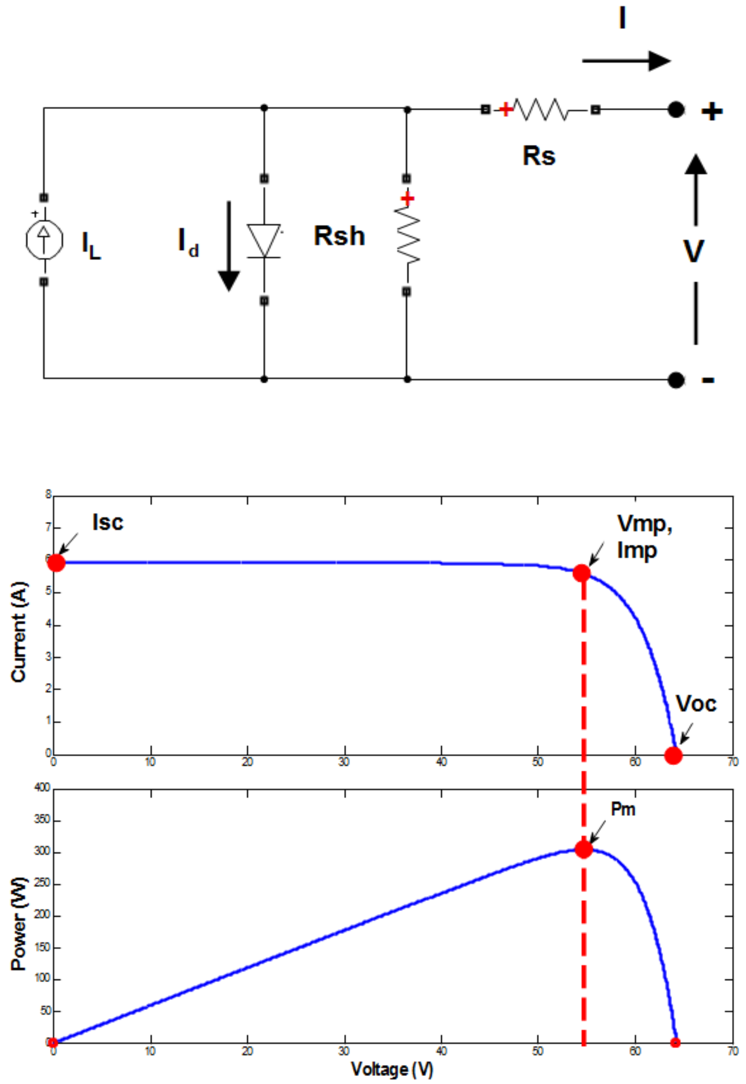

Figure 2. Single diode model of a solar cell, current and power characteristic curves

In doing this the diode I-V characteristics for a single module are defined by Equation 1 and 2

$$I_d = I_0\left[\exp\left(\frac{V_d}{V_T}\right) - 1\right] \qquad (1)$$

$$V_T = \frac{kT}{q} \times nI \times N_{cell} \qquad (2)$$

Where I_d is diode current, V_d is diode voltage, I_0 is diode saturation current, nI is diode identity factor, a number close to 1.0, k is Boltzman constant (1.3806e^{-23} J.K^{-1}), q is electron charge (1.6022e^{-19} C), T is cell temperature and N_{cell} is the number of cells connected in series in a module.

2.2. Maximum Power Point Tracking Control

In terms of maximum power point tracking, Moacyr et al., (2011) developed an Incremental Conductance (IC) technique which is based on the fact that the power slope of the PV is null at maximum power point (MPP) *(dP/dV = 0)*, positive in the left and negative in the right, as shown in Figure 3. Due to this condition, the MPP can be found in terms of the increment in the array conductance. Using Equation 3 it is possible to find the IC conditions presented by Equation 4.

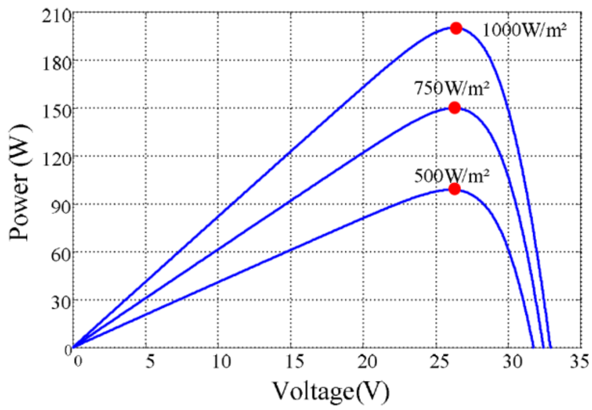

Figure 3. Power characteristic for different levels of irradiation

$$\frac{dp}{dv} = \frac{d(v.i)}{dv} = i + v\frac{di}{dv} = 0 \qquad (3)$$

$$\frac{\Delta i}{\Delta v} = -\frac{i}{v}(a), \frac{\Delta i}{\Delta v} > -\frac{i}{v}(b), \frac{\Delta i}{\Delta v} < -\frac{i}{v}(c) \qquad (4)$$

Where Equation 4a represents the condition at MPP. Equation 4b represents the condition on the left and Equation 4c on the right of MPP. The flowchart of the IC algorithm is presented in Figure 4.

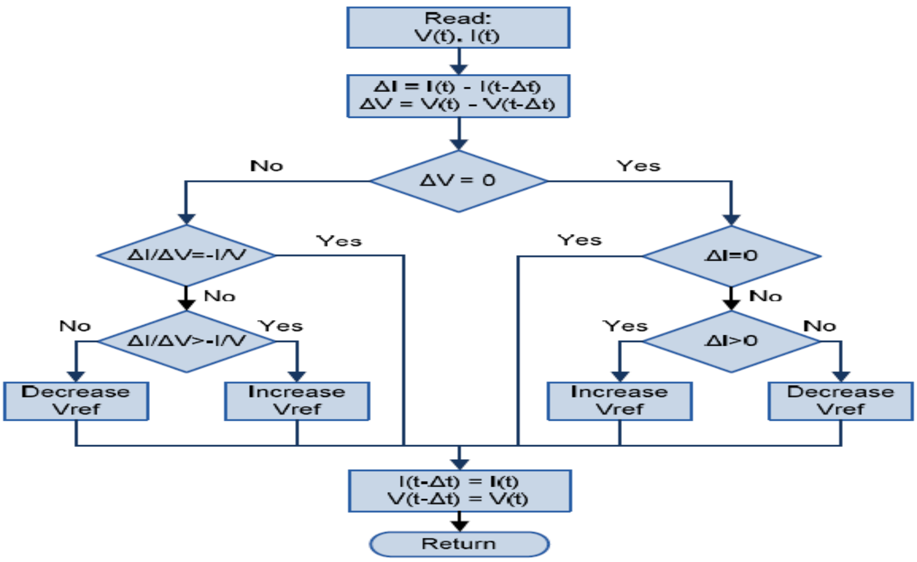

Figure 4. Flowchart of the IC Algorithm

2.3. DC-DC Converter

In handling the voltage from the PV an Insulated gate bipolar transistor (IGBT) type DC-DC boost converter is switched on and off at a specified frequency to transfer energy from the DC source to the load. The average output voltage (V_o) is a function of the duty cycle (D) of the IGBT switch as shown in Equation 5.

$$V_o = \frac{1}{1-D} V_{dc} \qquad (5)$$

And duty ratio D is given by Equation 6

$$D = 1 - \frac{V_{dc}}{V_o} \qquad (6)$$

inductor L1 in Figure 5 is given by Equation 7

$$L = \frac{V_{dc} D}{\Delta I_L f} \qquad (7)$$

Where ΔI_L the variation in inductor current and f is the switching frequency.

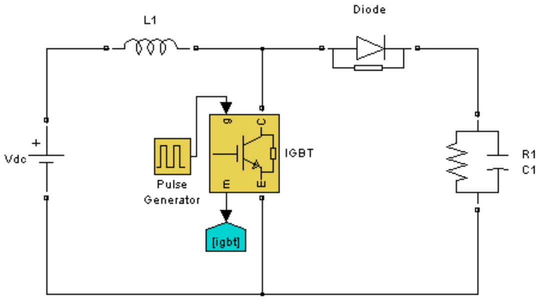

Figure 5. DC-DC boost converter with MPPT control

The DC-DC boost converter increases the voltage from the PVs natural voltage to the desired maximum DC voltage. In turn the switching duty cycle is optimized by the maximum power point tracking (MPPT) controller that uses the 'Incremental Conductance and Integral Regulator' technique. This MPPT system automatically varies the duty cycle in order to generate the required voltage to extract maximum power.

2.4. DC-AC Inverter

Inverters transfer power from a DC source to an AC load, as such the inverter in Figure 6 is built with an IGBT/diode block (in Simulink) which is the basic building block for voltage source converter (VSC). The aim of the inverter is to convert the DC link voltage to the desired AC voltage and keep the power factor near unity.

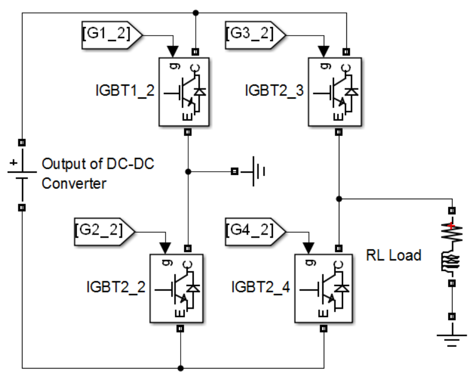

Figure 6. Single phase full-bridge inverter

The VSC control system uses two control loops, an external control loop that regulates the DC link voltage and an internal control loop that regulates I_d and I_q grid currents (active and reactive current components). The I_d current reference is the output of the DC voltage external controller, while I_q, the current reference, is set to zero in order to maintain a unity power factor. V_d and V_q are the voltage outputs of the current controller and are converted to two modulating signals U_{ab_ref} used by the PWM Generator. The control system uses a sample time of 100 microseconds for voltage and current controllers as well as for the phase locked loop (PLL) synchronization unit. Pulse generators of Boost and VSC converters use a fast sample time of 1 microsecond in order to get an appropriate resolution of PWM waveforms. As such the current waveforms of the inverter are given by Equation 8.

$$i_o(t) = \begin{Bmatrix} \frac{V_{dc}}{R} + \left(I_{min} - \frac{V_{dc}}{R}\right) e^{-t/\tau} & for\ 0 < t < \frac{T}{2} \\ \frac{-V_{dc}}{R} + \left(I_{max} + \frac{V_{dc}}{R}\right) -e^{(t-T/2)/\tau} & for\ 0 < \frac{T}{2} < T \end{Bmatrix} \qquad (8)$$

Where V_{dc} is the DC voltage at the inverter input, R is the resistance of the load, t is the switching time and $\tau = L/R$. The power of the inverter is determine from Equation 9 assuming ideal switches.

$$P_{dc} = V_{dc} I_s \qquad (9)$$

Subsequently the quality of the AC output voltage or current can be determined by using total harmonic distortion (THD) given by Equation 10, assuming no DC component in the output.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty}(V_{n,rms})^2}}{V_{1,rms}} = \frac{\sqrt{V_{rms}^2 - V_{1,rms}^2}}{V_{1,rms}} \qquad (10)$$

Where the *THD* of current is determined by substituting current for voltage in Equation 10.

2.5. Battery storage

PV systems generate power intermittently and the output power varies significantly. Furthermore the PV installations are located close to the loads so require the storage of energy at appropriate times and to minimize the imbalance between generation and consumption (Tremblay and Dessaint, 2009). The charging and discharging model equations for the proposed lead-acid battery is given by equations 11 and 12.

Charge model

$$V_{batt} = E_0 - R \times i - K\frac{Q}{it - 0.1Q}\ i^* - K\frac{Q}{Q - it} it + Exp(t) \qquad (11)$$

Discharge model

$$V_{batt} = E_0 - R \times i - K\frac{Q}{Q - it}(it + i^*) + Exp(t) \qquad (12)$$

where E_0 is battery constant voltage (V), *Exp(t)* is exponential zone dynamics (V), *K* is polarization constant (Ah^{-1}), i^* is low frequency current dynamics (A), *i* is battery current (A), *it* is extracted capacity (Ah) and *Q* is maximum battery capacity (Ah).

The State-Of-Charge of the battery is calculated using equation 13.

$$SOC = 100(1 - \frac{1}{Q}\int_0^t i(t)dt) \qquad (13)$$

The Exp(s) transfer function represents the hysteresis phenomenon for the Lead-Acid battery during charge and discharge cycles. The exponential voltage increases when battery is charging, no matter the SOC of the battery. When the battery is discharging, the exponential voltage decreases immediately.

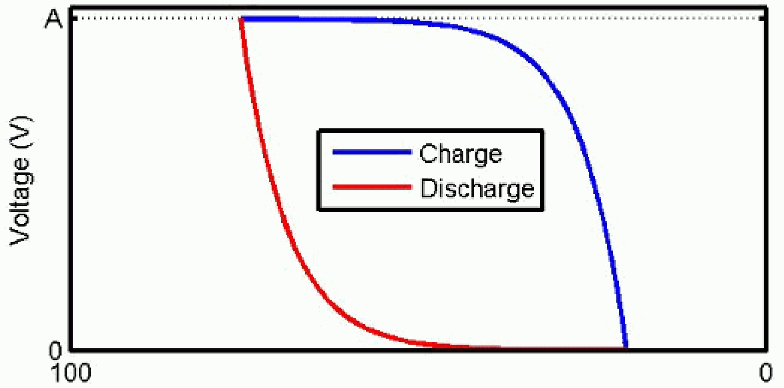

Figure 7. Exponential zone for Lead_Acid battery, State of charge (%)

2.6. Platform Overview

Having outlined the basis of the test platform, a complete plant model is shown in Figure 7. This platform uses hourly or half hourly global solar irradiation and temperature data as inputs and produces proportional power in kWh as the output taking into account the inefficiencies of the DC-DC converter, the DC-AC inverter as well as PV performance degradation due to temperature rises. Further, power consumption data (kWh) from any load can be used to calculate how much power is needed to satisfy the load requirement or surplus to charge battery or export to utility grid. The controller block in Figure 8 can be replaced with any controller of choice in Matlab/Simulink for the plant control. This platform can be used as a test bench for testing advanced controllers, such as model predictive controllers (MPC) or fuzzy logic controllers, to check and improve the performance of the PV solar energy system.

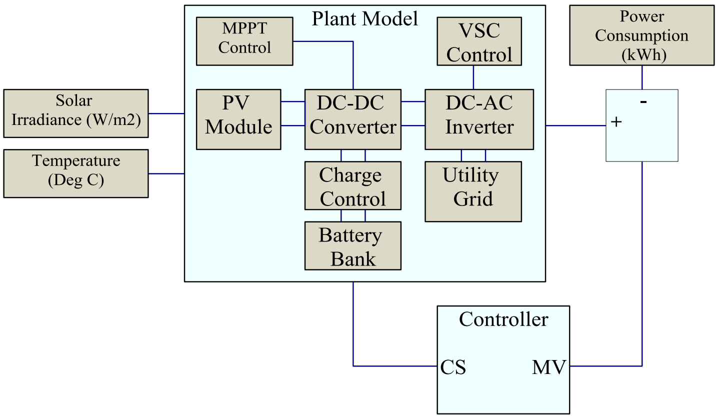

Figure 8. Plant model with controller

3. Results and discussion

In this section the proposed plant model is simulated and results are compared with installed 3kW PV system in New Plymouth (Latitude: -39.05, Longitude: 174.07). The complete model in Figure 7 was simulated with a PID controller, 12V lead acid battery and using power consumption data for a residential house with 2 adults and 2 children to validate the proposed PV plant model as shown in Figure 9.

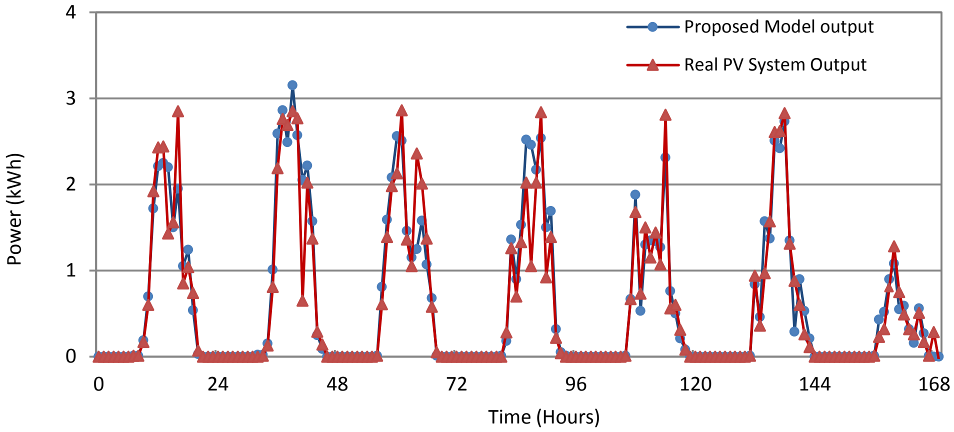

Figure 9. Output power of proposed model vs real 3KW system installed in New Plymouth

Following on from this, Figure 10 shows the PV production and power consumption for the real system in operation. As such, Figure 11 and 12 shows the PID control switch states for when PV production is more than or less than power demand respectively and Figure 13 shows battery state of charge for one week. The battery is charged only when there is excess energy available from the PV system. Figure 13 shows charging behavior during the day time but shows continuous decrees in SOC for the one week period which shows that consumption is more than production. From this it can be seen that the battery is charging when PV production is more than demand during day time and discharging during periods of low or no solar irradiance, as would be expected.

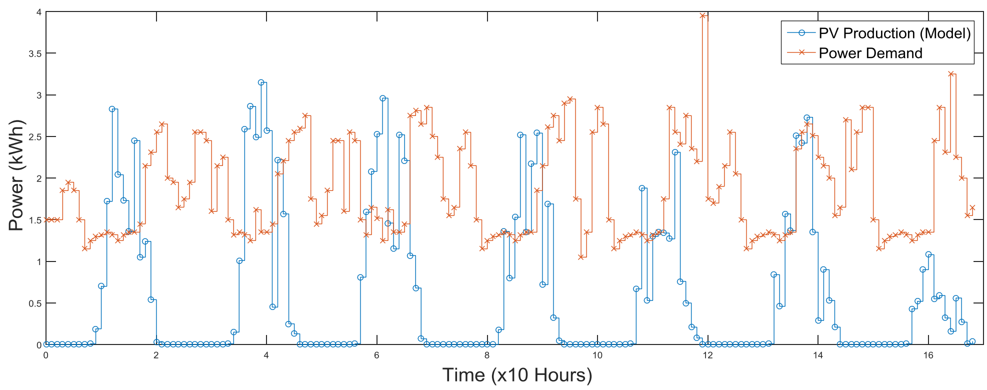

Figure 10. Modelled output power and real load for 3KW system installed in New Plymouth

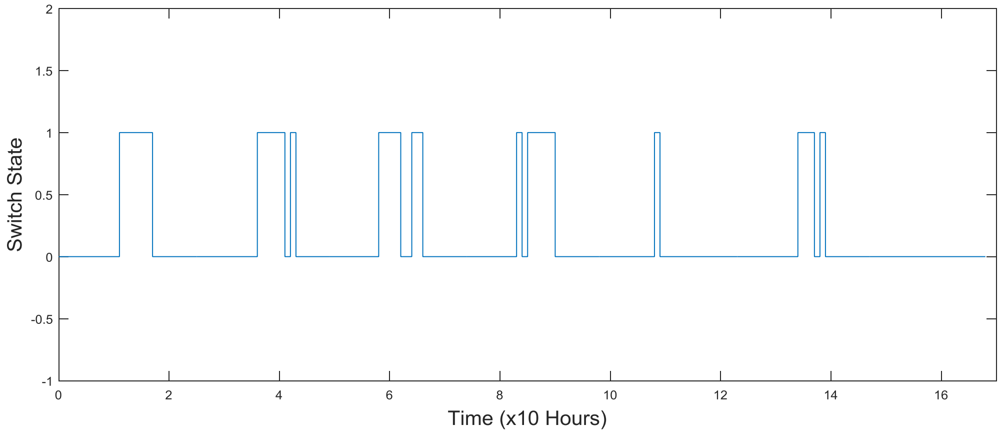

Figure 11. Control switch states for PV production more than demand

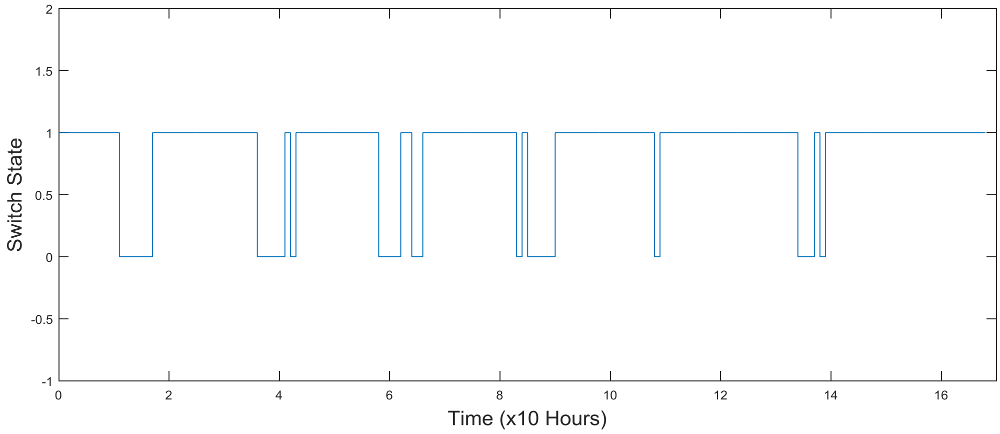

Figure 12. Control switch states for demand more than PV production

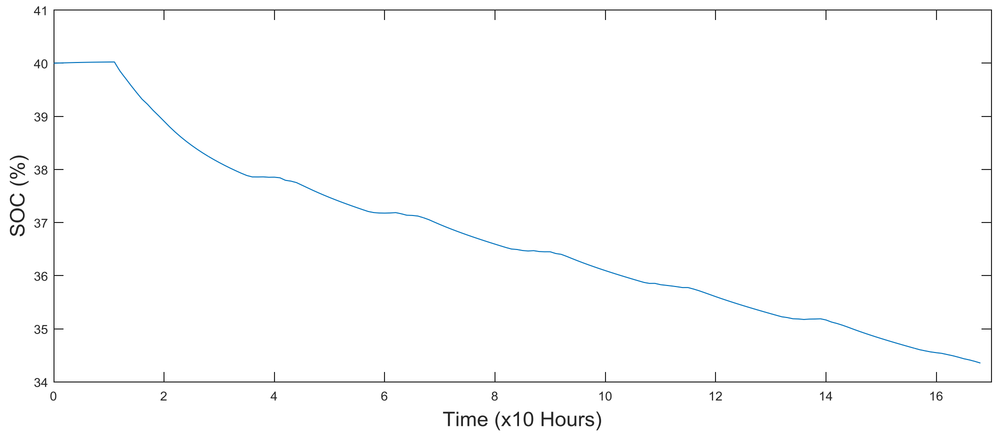

Figure 13. Lead acid battery SOC showing charging and discharging behaviour

4. Conclusion

In this study a virtual testing platform was developed in Matlab/Simulink to analyse and improve the performance of the PV solar energy systems, and in particular, the controllers to manage the energy generated by these systems. The plant model is capable of accurately showing the generated power in kWh proportional to the global solar irradiance and temperature data taking into consideration the inefficiencies of the PV cells, DC-DC converter, DC-AC inverter and thermal effects of the Lead-Acid battery storage. The model can also provide input for the power consumption data to examine more advanced control strategies (than the simple PID system demonstrated) that can utilize excess power from the PV system to charge the batteries, which can be utilized during periods of low or no solar irradiance. Finally, it is suggested that further study is needed to investigate the effect of system aging and to incorporate it in the plant model.

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