Automatic Switching Algorithm for Photovoltaic Power Generation System

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***Abstract*— within remote area worldwide, solar panel is still considered as an alternative despite its low efficiency rate and complex system. Backup source and storage such as battery are substantially needed to keep Solar Panel working effectively. PI MPPT controller is equipped to remarkably improve the efficiency rate of the solar panel by maintaining it on its Maximum Power Point (MPP) reference. However, tackling the complexity of photovoltaic generator for remote area require another solution. This paper provide a simple yet applicable solution by presenting an algorithm to automatically control the photovoltaic generator system for remote area. The algorithm logic is determined by the key parameters from each system inside, which are solar panel, PI Boost Converter, Battery, and Load. The simulation proves that the algorithm is able to provide an appropriate result with all condition working properly. Thus, the algorithm is eligible to be applied and to be developed further.**

Keywords - Solar Panel; Switching Algorithm, MPPT; Boost converter; Power electronics; Simulations;

I. INTRODUCTION

Electric energy demand worldwide is gradually increasing following the development of technology. These days, renewable energy such as solar panel has been developing and being used. Not only sun provides an infinite amount of energy [1], it is also clean and safe to use. Remote area is an area with less population and development, thus resulting in less human resources whereas electricity is a necessity for development [2]. Therefore, solar panel as power source has started to become first choice for developing remote area because of its flexibility and unlimited resource.

Using solar panels as energy source is a complex system which require battery bank, switchboard, and controller to maximize its output [3]. Since the system is complex, the failure of solar panel pilot project sustainability is often occurred. Those problems are mainly caused by the inabilities to do maintenance and improvement when needed. When operating, problem may occur from its components, it may be an overcharge or short in battery bank, or the inabilities of the solar panels to generate sufficient amount of power, or maybe a malfunction within its transmission system [4]. If there are malfunctions as such, great cost and a number of technicians are needed just to repair, moreover to improve the work of solar panel. Since, researchers have been tackling problems one by one, for example MPPT for efficiency, BMS (Battery Management System) for safety, or Converter for adaptability, there are so little research focusing the complexity of the system. Therefore, an algorithm to make the whole system automatic is needed to secure and improve whole system.

MPPT is an algorithm to maximize the output of a solar panel by giving reference and allowing it to operate on its maximum power point. To improve its results, PI controller is added for whole controller [5]. Battery bank as a supporting source as well as a storage is connected parallel to the Load. This modelled system is connected by three main switches, which are *main switch* to separate solar panel system from the rest, *battery switch* to separate battery bank from the rest, and *load switch* to separate the whole controlled system from the load. Those three switches are automatically controlled by logic algorithm derived by key parameters provided in this paper. Combining the MPPT, Battery, and Solar Panel system, a model of solar panel system complexity can be derived. The algorithm is applied and simulated into the model using MATLAB Simulink S-Function under random irradiance, temperature, and load. This Paper is mainly focused on the algorithm that is tested by using basic and existing methods by other references to prove the eligibility of the switching algorithm.

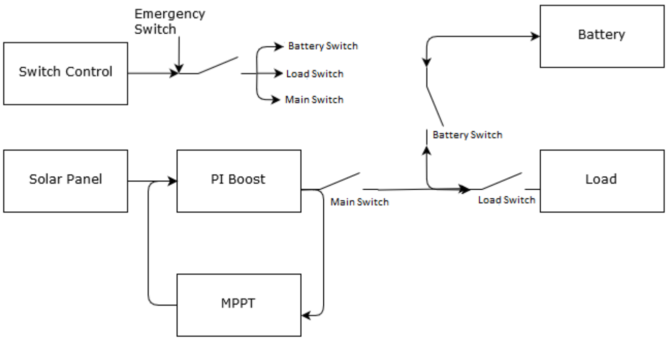


Figure 1 Whole System Design

II. STATE FLOW AND KEY PARAMETERS

Algorithm is used to control the switching mechanism between three switches, *main switch, battery switch,* and *load switch.* The purpose of these three switches is to optimize and secure the system from malfunctioning or overworking. To allow the algorithm to correctly gauge the change needed, there are key parameters obtained from the system used, which are:

1. V_{Boost} = Voltage measurement from *boost converter* as the Solar system Voltage output *(Volt)*
2. V_{Batt} = Voltage measurement from Battery as the Battery System Output *(Volt)*
3. *SoC* = Battery *State of Charge* derived from V_{Batt} using *Coulomb Counting Method*
4. I_{PV} = Current measurement from Solar Panel as the solar panel input from conversion between irradiance to current (Ampere)
5. Duty Cycle = Switching state to measure the working percentage of the controller
6. Emergency Switch = A manual switch to disable all the switches.

Resulting in a state flow such as:

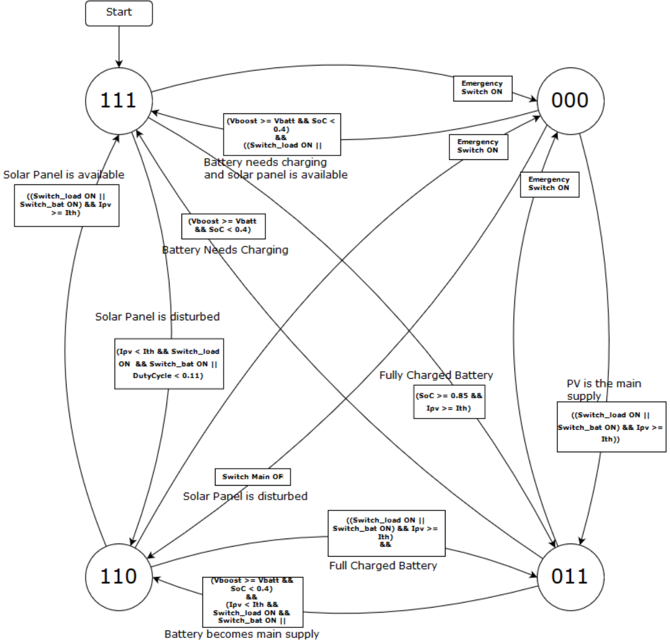


Figure 2 *State Flow*

With 1st, 2nd, and 3rd binary digits represent the condition of the *main switch, load switch,* and *battery switch* corresponding to chronological order.

The algorithm works in four main states interchanging one to another by logically comparing some key parameters to others.

For *battery switch (S3),* the logic goes as:

Battery is activated when:

- $V_{Boost} > V_{Batt}$ & SoC < standard

This condition stated that system is able to charge the battery and battery needs charging.

- S1 = 0

This condition stated that Solar panel system is unavailable so battery has to be used, even if the battery is already empty.

Battery is deactivated when:

- $V_{Boost} < V_{Batt}$ & SoC < 0.10

This condition stated that system is not able to charge the battery when the battery is empty, system then decide to fully support only the Load.

- SoC > 0.9 & $I_{PV} > I_{threshold}$

This condition stated that Solar panel system is able to supply the load by itself while the battery is full and does not need charging

For *Load switch (S2),* the logic goes as:

Load is activated when:

- S2 = 0

This condition stated that load is not connected previously, so system immediately reconnects it

For *Main switch (S1),* the logic goes as:

Solar Panel system is activated when:

- $I_{PV} > I_{threshold}$ & (S2 or S3 = 1)

This condition stated that system is able to become the main supply, whether to charge the battery or supply the Load

Solar Panel system is deactivated when:

- (S2 and S3 = 1) & $I_{PV} < I_{threshold}$

This condition stated that solar panel system is not able to be a supply but the battery is already connected, even if the battery is empty. System then decide to let the battery support the Load.

- Duty Cycle < 0.1

This condition stated that the controller is underwork (not operated as *boost*) so the system let the battery takes charge of being a supply.

If *Emergency Switch* is activated, the whole system is forcefully deactivated until it is reset by reconnecting the emergency switch.

III. COMBINED SOLAR PANEL, PI MPPT, BOOST CONVERTER, AND BATTERY MODEL

The Solar Panel with PI MPPT, *Boost Converter,* Battery, and Switch Control are represented and modelled into single electrical circuit diagram to simulate the system and test the algorithm

A. *Solar Panel System*

Solar panel is a device that absorbs sunlight as its source and converts it into electricity. Solar panel uses MPPT to maximize its power output by using voltage reference to keep it working in its maximum power point. The Solar Panel using PI MPPT and *Boost Converter* can be represented as single electrical circuit which is shown by *fig 3*

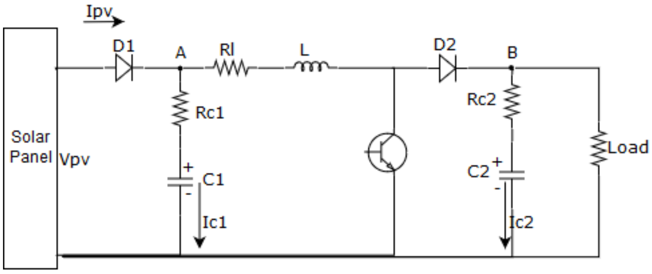


Figure 3 Boost-PI MPPT- PV System Equivalent Circuit

$C_{1,2}, and\ R_{C1,2}$ are the capacitance and internal resistance of capacitors, $L\ and\ R_L$ are the inductance and internal resistance of the inductor, $D_{1,2}$ are the diodes represent the working states of Boost Converter, and $V_{PV}, and\ I_{PV}$ are solar panel output, voltage and current.

As a current source, the current generated by solar panel is represented as:

$$I_{pv} = N_p I_{ph} - N_p I_s \left(\exp\left(\frac{q\left(\frac{V_{pv}}{N_S} + \frac{R_S I_{pv}}{N_P}\right)}{A\,K\,T_C} \right) - 1 \right) - \frac{\left(\frac{N_P V_{pv}}{N_S} + R_S I_{pv}\right)}{R_{sh}} \qquad (1)$$

I_{PH} is determined by the environment condition such as irradiance and temperature while I_S is the saturated current of the cell represented as (2) and (3)

$$I_{ph} = \left(I_{sc} + \alpha\left(T_C - T_{ref}\right)\right)\frac{\lambda}{\lambda_{ref}} \qquad (2)$$

$$I_S = \frac{I_{SC}}{\left(\exp\left(\frac{q\,V_{OC}}{A\,K\,T_C}\right) - 1\right)} \left(\frac{T_C}{T_{ref}}\right)^3 \exp\left(\frac{q\,E_G\left(\frac{1}{T_{ref}} - \frac{1}{T_C}\right)}{K\ A} \right) \qquad (3)$$

Since the *boost* IGBT is controlled by Duty Cycle, the voltage transformation increase proportional to the value of Duty Cycle. Summing the equation from ON state and OFF state of the IGBT, the system can be simplified as (4), thus resulting (5)

$$\frac{V_{PV} DT}{L} + \frac{(V_{PV} - V_{Boost})(1-D)T}{L} = 0 \qquad (4)$$

$$V_{Boost} = \frac{V_{PV}}{1-D} \qquad (5)$$

MPPT controller used in this system is an ICM (Incremental Conductance Method), a method that uses the shift in solar panel P-V curve to calculate error which then improved by PI (Proportional Integral) algorithm to reduce the settling time needed. Equation (6) shows the error calculation

$$\frac{d(V.I)}{dV} = \frac{V.dI + I.\ dV}{dV} = error \qquad (6)$$

B. Battery System

Battery is a device that can store electrical energy by storing electric charge in the form of chemical reaction. A battery can be modelled as a voltage source that gradually decreasing (discharge) or increasing (charging) with certain parameters. Figure 4 shows a battery system which is modelled as a Two Time Constant (TTC) Internal Resistance model, a simple representation of battery as a voltage source with internal resistance and dynamic state from two capacitors. The voltage value is a function of Battery State of Charge calculated with coulomb counting method. Equation (7), (8) and (9) show the calculation of I_{BATT}, V_{SOC} and dynamic state of the battery while (10) shows coulomb counting method to derive the momentary State of Charge (SoC).

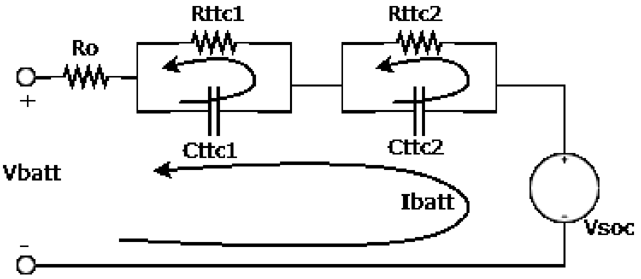


Figure 4 TTC Battery System Equivalent Circuit

$$V_{TTC1,2} = -\frac{V_{TTC1,2}}{R_{TTC1,2} C_{TTC1,2}} + \frac{Ibatt}{C_{TTC1,2}} \qquad (7)$$

$$Ibatt = \frac{V_{SOC} - V_{TTC1} - V_{TTC2}}{R_O} \qquad (8)$$

$$V_{SOC} = Ns * (V_{OC} + k_{SOC}\ln(SOC) - k_{LC}\ln(LC)) \qquad (9)$$

$$\Delta SOC = SOC(t) - SOC(t_0) = \frac{1}{C_{rated}} \int_{t_0}^{t} i(\tau) d\tau \qquad (10)$$

K_{SOC} and K_{LC} represent the relationship between State of Charge and Life Cycle to battery open circuit voltage. These constants are obtained from battery testing and may differ for each type of battery.

C. Combined System

Whole system of combined solar panel with PI MPPT – Boost Converter and battery bank is represented by circuit diagram shown by Figure 5 with two diodes D1 and D2 (where D2 is a diodes contrary to the state of IGBT) and three switches. Thus, there will be 2^5 or 32 states represented shown by Table 1, although there are some states that will due to its possibility. The system works by giving calculation for momentary states happening that time and constantly changing. Active condition is shown as 1 while inactive is shown as 0.

TABLE 1. SWITCHING CONDITIONS

State	Diodes		Switches		
	D1	*IGBT' (D2)*	*Main*	*Load*	*Battery*
0	0	0	0	0	0
1	1	0	0	0	0
2	0	1	0	0	0
3	1	1	0	0	0
4	0	0	1	0	0
5	1	0	1	0	0
6	0	1	1	0	0
7	1	1	1	0	0
8	0	0	0	1	0
9	1	0	0	1	0
10	0	1	0	1	0
11	1	1	0	1	0
12	0	0	1	1	0
13	1	0	1	1	0
14	0	1	1	1	0
15	1	1	1	1	0
16	0	0	0	0	1
17	1	0	0	0	1
18	0	1	0	0	1
19	1	1	0	0	1
20	0	0	1	0	1

21	1	0	1	0	1
22	0	1	1	0	1
23	1	1	1	0	1
24	0	0	0	1	1
25	1	0	0	1	1
26	0	1	0	1	1
27	1	1	0	1	1
28	0	0	1	1	1
29	1	0	1	1	1
30	0	1	1	1	1
31	1	1	1	1	1

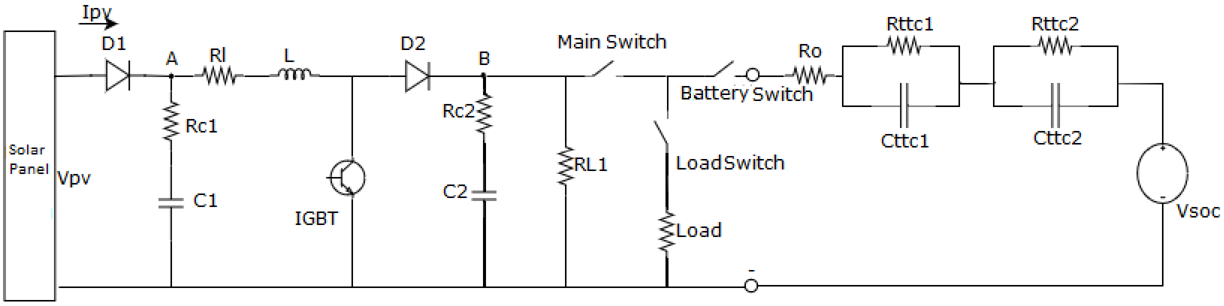


Figure 5 Full System Equivalent Circuit

For state number 27, where D1 is 1 (PV is actively generating power), D2 is 1 (IGBT is open), main load and battery switch is 1 (connected) while main switch is not (state value 0), the system can be derived by analyzing the circuit and put into matrices as follows:

State Matrix:

$$\begin{bmatrix} \frac{dV_{C1}}{dt} \\ \frac{dV_{C2}}{dt} \\ \frac{dI_L}{dt} \\ \frac{dV_{TTC1}}{dt} \\ \frac{dV_{TTC2}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{C_1} & 0 & 0 \\ 0 & a_{22} & a_{23} & 0 & 0 \\ \frac{1}{L} & a_{32} & a_{33} & 0 & 0 \\ 0 & 0 & 0 & a_{44} & a_{45} \\ 0 & 0 & 0 & a_{54} & a_{55}) \end{bmatrix} \begin{bmatrix} V_{C1} \\ V_{C2} \\ i_L \\ V_{TTC1} \\ V_{TTC2} \end{bmatrix} +$$

$$\begin{bmatrix} 0 \\ 0 \\ -\frac{1}{L} \\ 0 \\ 0 \end{bmatrix} V_{D2} + \begin{bmatrix} 0 \\ 0 \\ \frac{R_{C1}}{L} \\ 0 \\ 0 \end{bmatrix} I_{PV} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{C_{TTC1}(R_O+Load)} \\ \frac{1}{C_{TTC2}(R_O+Load)} \end{bmatrix} V_{SOC} \quad (11)$$

Output Matrix:

$$\begin{bmatrix} V_{PV} \\ V_{Load} \\ I_{Batt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{(R_O+Load)} & -\frac{1}{(R_O+Load)} \end{bmatrix} \begin{bmatrix} V_{C1} \\ V_{C2} \\ i_L \\ V_{TTC1} \\ V_{TTC2} \end{bmatrix} +$$

$$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} V_{D1} + \begin{bmatrix} R_{C1} \\ 0 \\ 0 \end{bmatrix} I_{PV} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{(R_O+Load)} \end{bmatrix} V_{SOC} \quad (12)$$

Where

$$a_{22} = \frac{-1}{C_2(R_{C2}+RL1)} \quad (13)$$

$$a_{23} = \frac{1}{C_2} - \frac{R_{C2}}{C_2(R_{C2}+RL1)} \quad (14)$$

$$a_{32} = \frac{R_{C2}}{L(R_{C2}+RL1)} - \frac{1}{L} \quad (15)$$

$$a_{33} = \frac{R_{C2}^2}{L(R_{C2}+RL1)} - \frac{(R_{C1}+R_L+R_{C2})}{L} \quad (16)$$

$$a_{44} = -\left(\frac{1}{R_{TTC1}C_{TTC1}} + \frac{1}{C_{TTC1}(R_O+Load)}\right) \quad (17)$$

$$a_{45} = -\frac{1}{C_{TTC1}(R_O+Load)} \quad (18)$$

$$a_{54} = -\frac{1}{C_{TTC2}(R_O+Load)} \quad (19)$$

$$a_{55} = -\left(\frac{1}{R_{TTC2}C_{TTC2}} + \frac{1}{C_{TTC2}(R_O+Load)}\right) \quad (20)$$

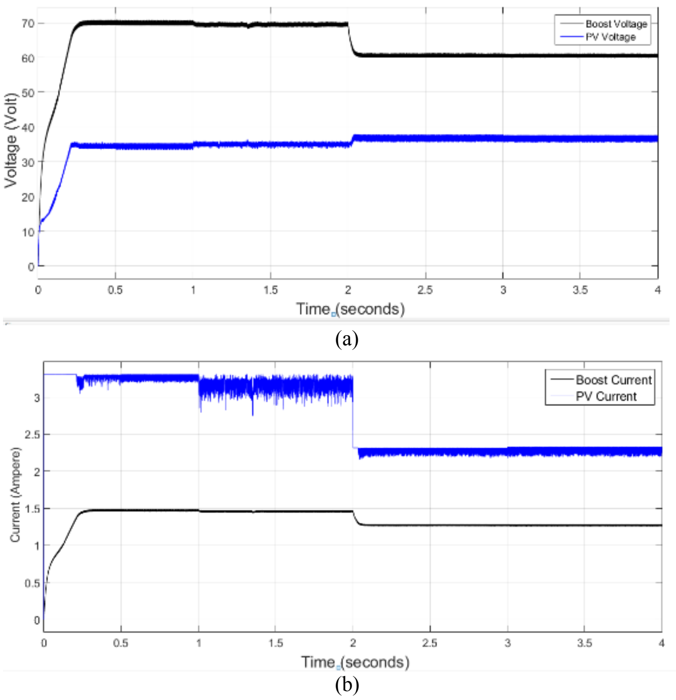
IV. SIMULATION RESULTS

The proposed algorithm in this paper is tested using a combined model of three systems working altogether, PI MPPT, Battery, and Boosted PV. These three systems is modeled as an electrical circuit equivalent to the complex combined system. The algorithm is simulated using MATLAB S-Function Block. The test is done within 2 segments, which are the specific condition testing and random condition testing. For the 1st segment, system is tested by manually state the input of the switch according to the state flow from Figure 2. This test is run for showing the key results of each condition before combining. If the test is proven to be working optimally, then the 2nd test is conducted to see whether it is possible to combine all the condition and make them interchange if a certain condition occur. The 2nd segment is tested with random irradiance changing each second for 15s, random temperature changing every 2.5s and a load of 50Ω

A. *Condition Testing*

Figure 6, 7, and 8 shows the output of testing where the whole system works on each condition shown by state flow. The test is using varied irradiances of 1000W/m^2 to represent the standard irradiance that change to 700W/m^2 in the 2nd second and varied temperature of 298 kelvin that change to 315 kelvin in the 3rd second.

- 011 condition (PV with Load)

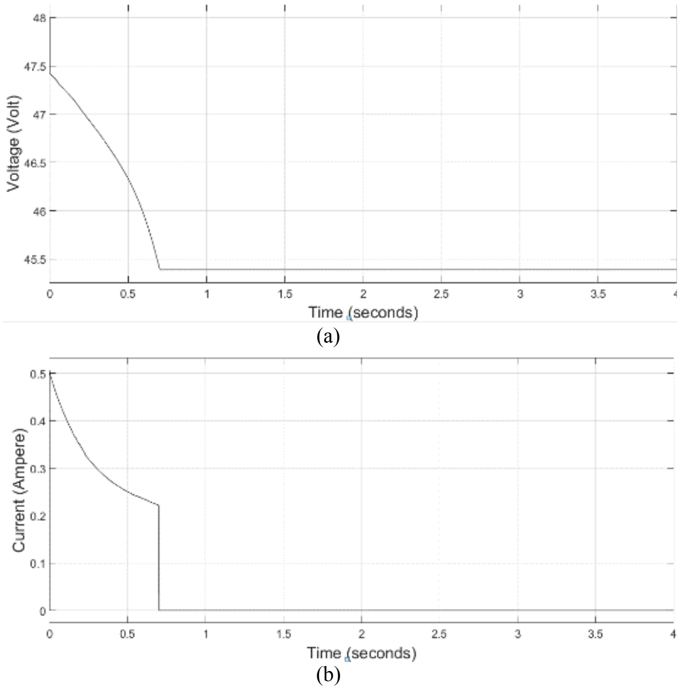


(a)

(b)

Figure 6 Voltage (a) and Current (b) between PI-MPPT and Boost

- 110 condition (Battery with Load)

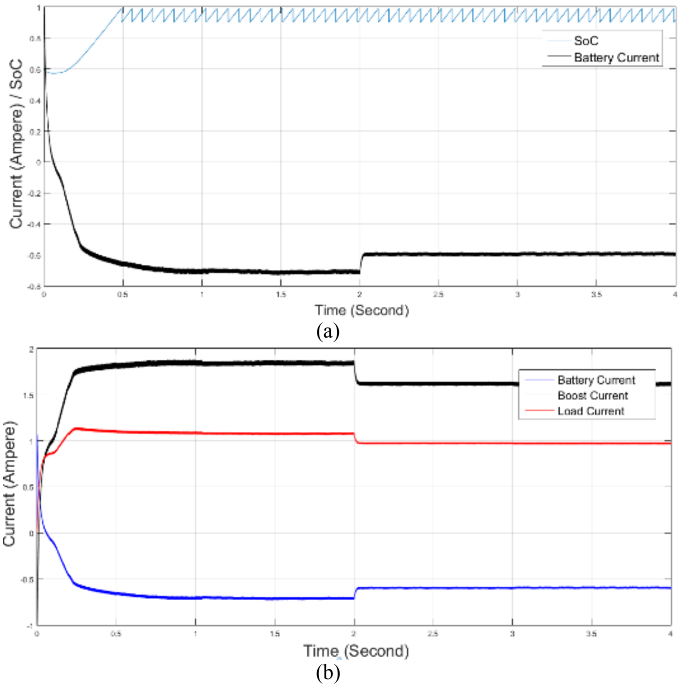


(a)

(b)

Figure 7 Voltage (a) and Current (b) of Battery Output

- 111 condition (Full System Working)



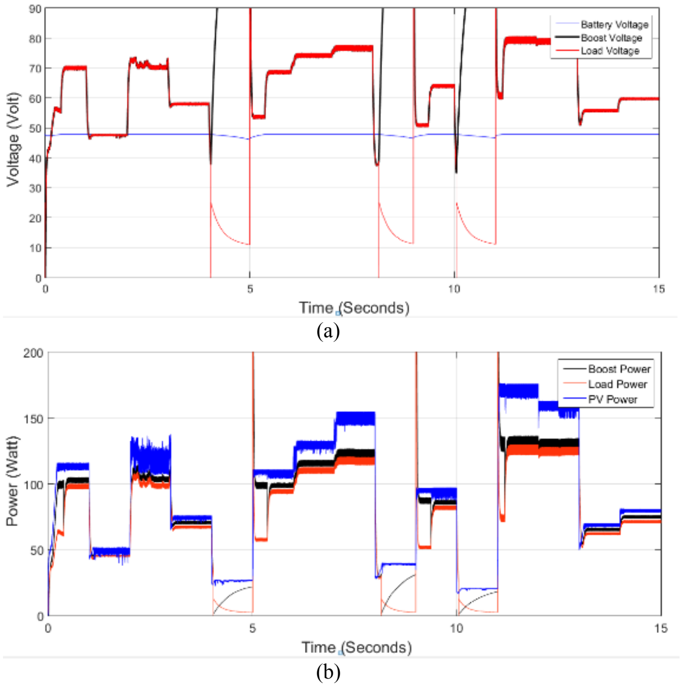
(a)

(b)

Figure 8 Current and SoC of the battery (a) and Load-PV-Battery current (b) from the system

B. *System Testing*

Figure 9 shows the testing output where the switching algorithm is applied to the system. The test used varied irradiances of [1000 400 1300 600 200 950 1200 1500 300 800 150 2000 1700 550 650] W/m^2 that changed each second and varied temperature of [298 320 250 280 400 270] kelvin that changed once every 2.5 second.



(a)

(b)

Figure 9 Voltage (a) and Power (c) comparison between PV-Boost, Battery and Load and Switch

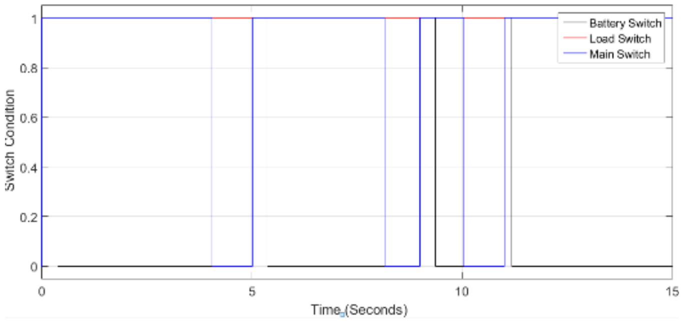


Figure 10 Automatic Switching Algorithm Pattern

Figure 10 shows that the system is working properly and performed good results by working optimally according to irradiance and temperature condition. The MPPT maximizes the output, the battery can either be a storage or a source, and therefore, switch is able to interchange between each condition whenever needed. However, model is generated with parameters from combined sources with little adjustment.

V. CONCLUSION

This paper proposed a switching algorithm to control a Photovoltaic Power Generation System automatically. System is modelled using MATLAB and being tested on random condition of irradiance and temperature. The simulation for either condition testing and system testing give good results where it is working properly as PV-MPPT-Boost, Battery source, or fully functional system. When the algorithm is applied to the system and simulation is run, algorithm is able to keep the system working properly and interchange the state whenever needed with an acceptable error. Therefore, with great result, it is eligible to say that the algorithm is working and applicable, although it needs further improvement.

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GLOSSARY OF SYMBOLS

V_{PV} = Solar Panel Voltage (V)
V_{Boost} = Boosted Voltage (V)
V_{OC} = Open Circuit Voltage (V)
$R_{C1,2}$ = Capacitor Internal Resistance (Ω)
$D_{1,2}$ = Diode Voltage (V)
R_L = Inductor Internal Resistance (Ω)
L = Inductor (H)
$C_{1,2}$ = Capacitor (F)
$I_{C1,2}$ = Capacitor Discharge/Charge Current (A)
I_{PV} = Solar Panel Current (A)
I_{PH} = Solar Panel Conversion Current (A)
I_S = Saturated Current (A)
I_{SC} = Short Circuit Current (A)
Q = Electron Charge (Coulomb)
Eg = Energy Gap (eV)
A = Correction Factor
λ = Irradiance captured (lambda)
λ_{Ref} = Sun Irradiance (lambda)
K = Boltzmann Constant
R_S = Solar Panel Internal Resistance (Ω)
R_{SH} = Solar Panel Shunt Resistance (Ω)
N_P = Number of Cells Connected Parallel
N_S = Number of Cells Connected Series
T_C = Current Temperature (Kelvin)
T_{ref} = Environment Temperature (Kelvin)
D = Dutycycle percentage (%)
$V_{TTC1,2}$ = Time Constraint Voltage (V)
$R_{TTC1,2}$ = Time Constraint Resistance(Ω)
$I_{TTC1,2}$ = Time Constraint Current (A)
$C_{TTC1,2}$ = Time Constraint Capacitance (C)
I_{BATT} = Battery Current (A)
V_{BATT} = Battery Voltage (V)

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