Improved Performance State-Flow Based Photovoltaic Maximum Power Point Tracking Technique

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Abstract

The non-linearity of the Power-Voltage characteristics of a photovoltaic (PV) array that depends on the panel temperature and irradiance condition tends to inevitability of using Maximum Power Point Tracking (MPPT) technique for continuously tracking the maximum power at each ambient condition. PV MPPT can be considered as event driven problem. In addition to that, State-Flow is commonly used as a graphical design and development tool which can be utilized in logic problems' solving and complex control systems. This paper presents an enhanced performance PV MPPT technique based on State-Flow design. A detailed analysis along with simulation and experimental results confirm the feasibility of the proposed technique in comparison with conventional Perturb and Observe (P&O) MPPT technique.

1 Introduction

As people are much concerned with environmental problems caused by conventional power generation, renewable energy usage appears to be a good solution for reducing green house gas emission and fossil fuel consumption [1-2].

Despite the advantages of photovoltaic (PV) systems, it exhibits non-linear Power-Voltage characteristics, which mainly depend on the sun irradiation level and ambient temperature. Consequently, maximum power point tracking (MPPT) techniques are commonly adopted to deliver the maximum available power under varying environmental conditions [3-4].

Several algorithms have been developed for tracking maximum power point for PV system, which vary in complexity, effectiveness, number of sensors required and cost [5-6]. These algorithms include but are not limited to Fuzzy Logic [7-8], Incremental Conductance (IncCon) [9-10], Perturb & Observe (P&O) [11-14], Fractional Open-Circuit Voltage [9], and Neural Network [15]. Among those entire algorithms, P&O algorithm is most commonly used due to its simplicity despite of its known moderate power-oscillating performance.

State-Flow is a graphical design and development tool that can be used in logic problems and complex control. It can easily create varies scenarios, and then iterates until it models the desired behavior. In addition, it brings system specifications and design close together. State flow has different applications such as embedded systems, man machine interface and hybrid systems [16-17].

As PV MPPT can be considered as an event driven system, Stat-Flow is proposed as competitive MPPT technique featuring simplified implementation, more degree-of-freedom, and controllable event timing. Those features are expected to enhance State-Flow based MPPT tracking by minimizing the steady-state power oscillations and improve the transient performance.

State-Flow is widely utilized in renewable energy applications. The authors of [18] focuses on power balancing, with load shedding and PV constrained production, and takes into account the grid availability and grid vulnerability by smart grid messages. The system behavior modeling by Matlab/State-Flow enhance control strategy design, which concerns the power balancing and imposed power limits by the utility grid, while providing interface for energy management. While in [19], the application of Matlab/Simulink-State-Flow is developed for simulating, learning and analyzing of power electronic systems effectively. A coordinated control method that regulates the operation of power generation units according to the state of energy storage unit is presented in [20]. The hybrid simulation studies, which are based on Matlab/State-Flow, are carried out due to the coexistence of continuous and discrete system feature in independent wind-solar hybrid power system. As authors of [21] propose a methodology to design a fuzzy logic controller coupling with State-Flow to improve its performances, where State-Flow allows representing the system through state-transitions diagrams, the state is reserved for DG (output) to manage its sequence of on/off and the transition is reserved for three inputs: state of charge of battery, reference power of DG comes from fuzzy logic controller and difference power.

In this paper a State-Flow based PV MPPT technique is proposed. Simulations in addition to experimental verification are utilized to proof the proposed technique effectiveness by comparing the proposed technique with conventional P&O under various operating conditions.

The presented paper is organized in six sections, following the introduction in the first section, section two presents the PV module mathematical model and the associated DC/DC buck converter. The proposed State-Flow based MPPT approach is presented in section three. Simulation and experimental results comparing both techniques are investigated in sections four and five respectively. A conclusion is given in section six.

2 PV System under investigation

Stand-alone photovoltaic system is a combination of several elements such as PV array, DC/DC converter, load and most important a control algorithm to track the maximum power continuously as shown in figure 1 [22].

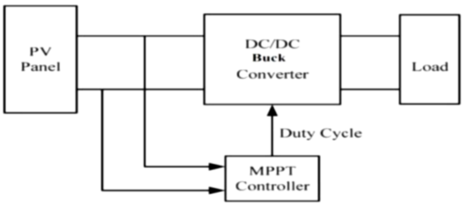

Figure 1: PV system

2.1 PV array model

The basic block of PV module is the solar cell which is simply described as a p-n semi-conductor junction that directly converts solar radiation into DC current using the photovoltaic effect. The electrical equivalent circuit of solar cell is shown in figure 2.

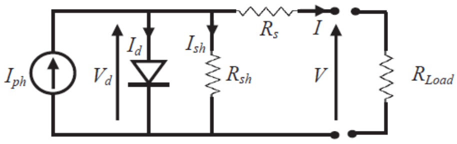

Figure 2: Single Diode Equivalent Circuit of PV Module

$$I = I_{ph} - I_{sat}.\left[\exp\left(\frac{q.(V + R_s.I)}{nkT}\right) - 1\right] - \frac{V + R_s.I}{R_{sh}} \quad (1)$$

where I and V denotes the output current (A) and voltage (V) of a solar array, I_{ph} is the generated light current (A) at certain insulation, I_{sat} denotes a diode reverse saturation current (A), q is the electronic charge $=1,6\text{x}10^{-19}$C, n refers to a dimensionless deviation factor from the ideal p–n junction diode, k is Boltzmann's constant $=1.3807\text{x}10^{-23}$ JK^{-1}, T denotes a solar cell temperature (K), R_s is the series resistance (Ω) that represents the internal losses, while R_{sh} is a shunt resistance (Ω) corresponds to the leakage current to ground.

The output characteristics of PV module are non-linear as it is dependent on the irradiance intensity and cell temperature as shown in figure 3. Hence it is necessary to continuously track the MPP in order to maximize the output power from the PV system. In the current design, a buck type DC/DC converter is used to match the load to the PV system in order to extract the maximum power.

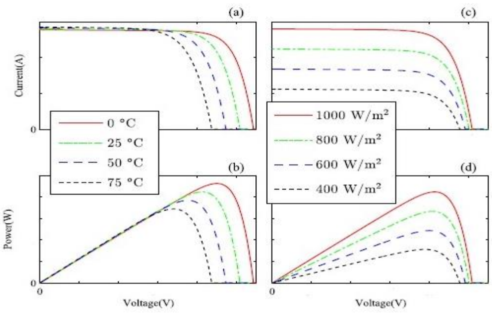

Figure 3: PV Characteristic (a) I−V and (b) P−V for varying temp, S = 1000 W/m^2. Characteristic (c) I−V and (d) P−V for varying irradiance, T = 25 °C

2.2 Buck type DC/DC converter

The buck converter is known to be a step-down converter where the ratio between its input voltage (v_i) and the output voltage (v_o) is controlled by the duty cycle (d) of the switch. The schematic of Buck DC/DC converter is shown in figure 4 [22].

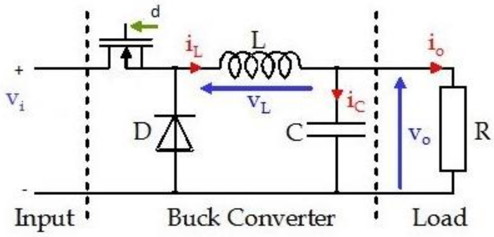

Figure 4: Buck DC/DC converter.

Under the assumption that the buck converter is working in continuous current mode, the converter input–output voltage relationship can be represented by the following (averaged) relation in equation 2.

$$d = \frac{v_o}{v_i} \quad (2)$$

The selection of capacitor and inductor size is a major part in designing a buck converter that is mainly affected by the selection of the switching frequency (f_s). At higher switching frequency, the value of inductor will be lower in order to produce continuous current and smaller capacitor size to limit output ripple].

The minimum inductor value (L_{min}) is determined as quoted in equation 3.

$$L_{min} = \frac{v_o(v_i - v_o)}{\Delta i_L \times f_s \times v_i} \quad (3)$$

Where Δi_L the inductor ripple current calculated as in equation 4 while i_o is the maximum output current.

$$\Delta i_L = 0.2 \times i_o \quad (4)$$

For the buck converter to operate at CCM, the inductance value has to be 25% greater than L_{min} [23] as in equation 5.

$$L = 1.25 \times L_{min} \quad (5)$$

The pulsating current produced by the switching action is smoothed by the capacitive filter at the input/output where the capacitance value is determined by equation 6, as v_r is the ripple voltage [24].

$$C = \frac{\Delta i_L}{8 \times f_s \times v_r} \quad (6)$$

3 Proposed State-Flow based MPPT

The chosen of appropriate converter with highly efficient design is important with proposing a MPP tracker, same as the applied algorithm that adjust the duty ratio automatically on the event of any atmospheric changes. In this paper, PV MPPT technique based on State-Flow is proposed.

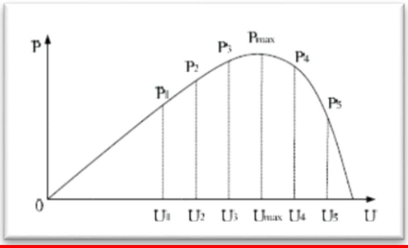

Figure 5: Tracking diagram of the P&O MPPT technique

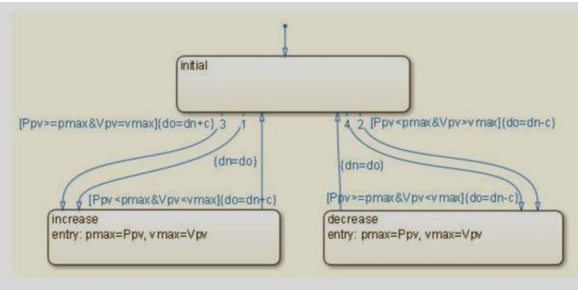

Figure 6: Proposed State-Flow based PV MPPT technique

In searching for the MPP and tracking this point in order to minimize the spread between the operating power and the optimal power in the event of change of the weather conditions, the control circuit of the buck converter intelligently perturbs periodically the operating point of the PV module [25-26]. Conventional P&O method, also known as Hill Climbing, has been widely used because its simple feedback structure and fewer required measured parameters It operates by applying a small active voltage perturbation in the array terminal voltage and comparing with the observed power output, under the condition of output power increasing the perturbation will continue in the same direction; otherwise the direction of perturbation will be reversed. Figure 5 represents Conventional P&O method diagram [26].

This method has two major drawbacks:

- Repeating the perturbation process periodically causes the system to oscillate around its MPP in steady state.
- Under rapidly changing atmospheric condition the algorithm may moves the operating point far from the MPP.

Stat-Flow is proposed as competitive MPPT technique featuring simplified implementation as shown in figure 6, more degree-of-freedom, and controllable event timing. Those features are expected to enhance MPPT tracking by minimizing the steady-state power oscillations and improve the transient performance. The MPPT implementation in State-Flow diagram incorporates four conditions, states, and two actions as shown in figure 6. The proposed algorithm has been simulated using Matlab/Simulink and validated experimentally.

4 Simulation Results

The PV model with its controlled DC/DC buck converter are simulated using MATLAB/Simulink software as shown in figure 7 to demonstrate the features of the proposed MPPT algorithm based State-Flow in comparison with the Conventional P&O MPPT method. Two scenarios were denoted; the first shows the start-up and steady state performance at irradiance of 800W/m^2 and temperature of 25°C as shown in figures 8 and 9 while the second scenario represents the system transient response to step-change in insulation level. Figures 10 and 11 present the result of changing in insulation from 800W/m^2 to 400W/m^2 at t= 0.3s and back to 800W/m^2 at t=0.6s and constant temperature of 25°C.

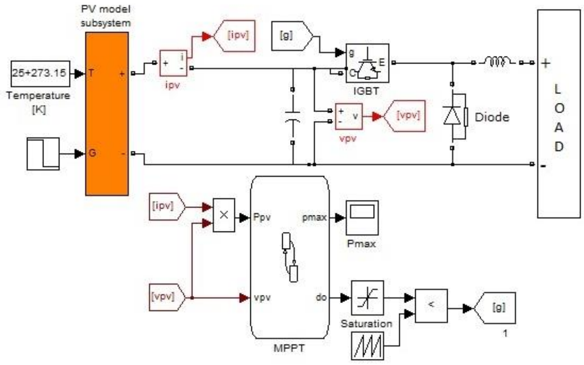

Figure 7: Simulation Diagram

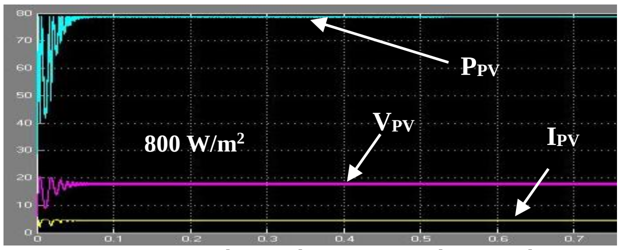

Figure 8: Proposed State-Flow MPPT simulation results

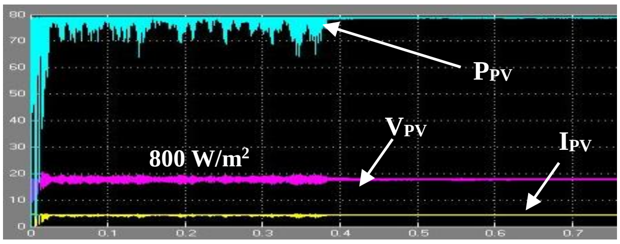

Figure 9: Conventional P&O simulation results

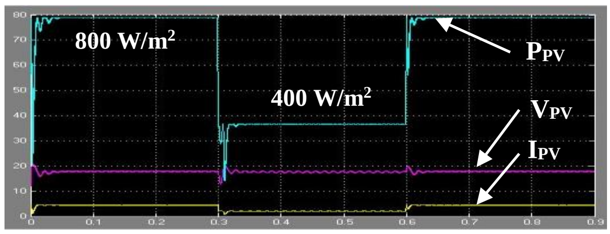

Figure 10: Proposed State-Flow MPPT transient simulation results

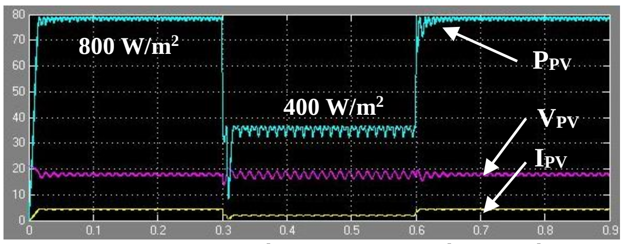

Figure 11: Conventional P&O transient simulation results

The proposed technique shows reduced steady-state power oscillation in addition to better transient performance when compared to conventional P&O MPPT technique.

5 Experimental Results

A prototype of the PV system under investigation is developed as shown in figure 12. The system configuration and control strategy were kept same for both simulation and experimental setup for accurate validation of the proposed algorithm.

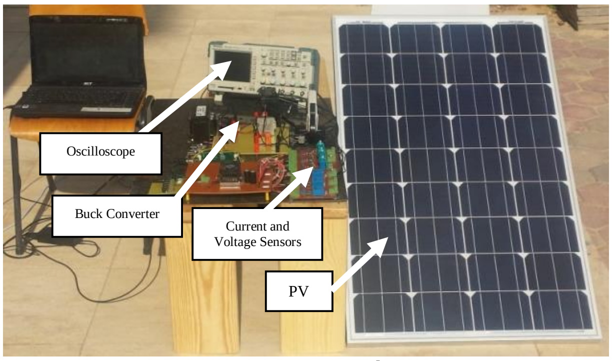

Figure 12: Experimental set-up

The prototype of the system features Solara 130W PV panel and a DC/DC buck converter.

Table 1: PV array specifications

Electrical Characteristics	
Open- circuit voltage (V_{OC})	
Short-circuit current (I_{SC})	
Voltage at maximum power	
Current at maximum power	
Maximum power	
Temperature coefficient of I_{SC}	
Temperature coefficient of V_{OC}	

Table 2: Parameters of DC/DC Buck Converter

Switching Frequency	3 kHz
Capacitor (C)	1000 µF
Inductor (L)	2.5 mH
Inductor resistance	0.022 Ω
IGBT	STGP35HF60W
Fast recovery diode	

The proposed control strategy is discretized and coded into Digital Signal Processor TMS320F28335 32-bit controller. PV sensed voltages and currents are acquired using Hall-Effect voltage sensors (LV-25), current sensors (LA-55P). Signal conditioning circuits for scaling and filtering purposes are developed. Experimental results are obtained for various operating conditions to confirm the effectiveness of the proposed algorithm. Figures 13 and 14 compare the system steady-state operation under two different algorithms at 800 W/m^2. Figures 15 and 16 illustrate the transient operation at two different irradiance levels between 400 and 800 W/m^2 using emulation.

The experimental results, whether steady-state or transient, show the superiority of the proposed State-Flow based MPPT in reducing the PV power oscillations in various operating conditions.

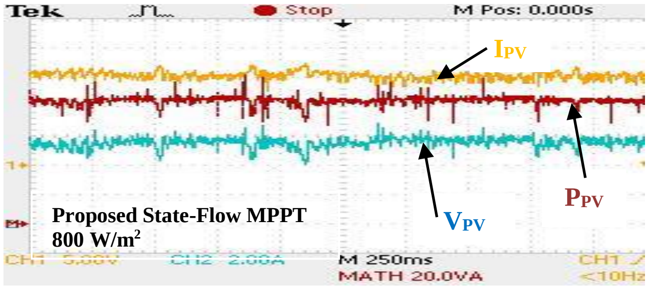

Figure 13: Proposed State-Flow MPPT practical results

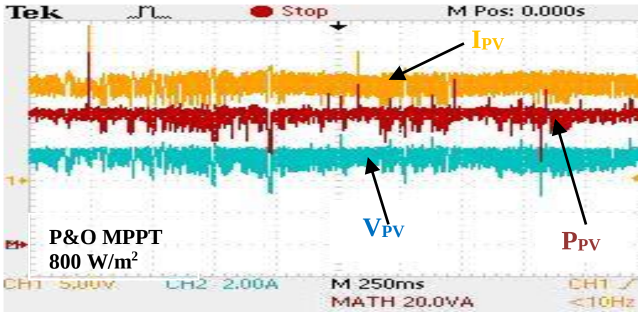

Figure 14: Conventional P&O practical results

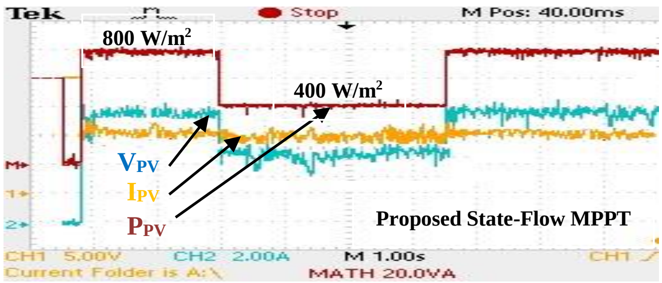

Figure 15: Proposed State-Flow MPPT Transient practical results

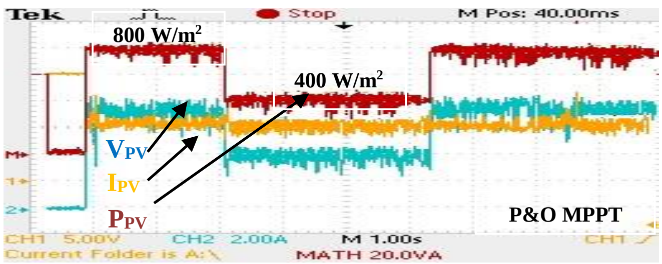

Figure 16: Conventional P&O Transient practical results

6 Conclusion

An enhanced performance State-Flow based PV MPPT technique is proposed. A comparative study between Conventional P&O MPPT and the proposed technique has been presented in this paper. The PV system under investigation was simulated under various conditions. In addition, the system performance has been verified experimentally showing the effectiveness of the proposed algorithm under varying conditions. The presented technique offers minimized steady-state power oscillations, enhanced transient performance, and faster start-up operation when compared to conventional P&O.

Acknowledgements

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References

[1] Online: 'A plan for a Sustainable Future', Available at www.ScientificAmerican.com, November 2009.

[2] Online: International Energy Agency "Energy Technology Perspectives 2012" (2012).

[3] Mohammadmehdi Seyedmahmoudian, Saad Mekhilef, Rasoul Rahmani, Rubiyah Yusof and Ehsan Taslimi Renani, "Analytical Modeling of Partially Shaded Photovoltaic Systems" www.mdpi.com/journal/energies, Energies, 6, 128-144; 2013.

[4] J. Salazar, F. Tadeo, C. Prada, L. Palacin, "Simulation and Control of a PV System connected to a Low Voltage Network" JORNADAS DE AUTOMÁTICA, September 08-10, 2010, JAÉN, Spain.

[5] A Safari, S. Mekhilef, "Implementation of Incremental Conductance Method with Direct Control" TENCON 2011 - 2011 IEEE Region 10 Conference

[6] Esram T, Chapman P.L. Comparison of photovoltaic array maximum power point tracking techniques. *IEEE Trans. Energy Conversion*, 2007; **22**: 439–449.

[7] B. N. Alajmi, K. H. Ahmed, S. J. Finney, and B. W. Williams, "Fuzzy-Logic-Control Approach of a Modified Hill-Climbing Method for Maximum Power Point in Microgrid Standalone Photovoltaic System," *IEEE Transactions on Power Electronics*, vol. 26, pp. 1022-1030, 2011.

[8] R. Arulmurugan, Dr. N. Suthanthira Vanitha, "Intelligent Fuzzy MPPT Controller using Analysis of DC to DC Novel Buck Converter for Photovoltaic Energy System Applications" Proceedings of the 2013 International Conference on Pattern Recognition, Informatics and Mobile Engineering.

[9] T.Esram and P. L. Chapman, "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques," *IEEE Transactions on Energy Conversion*, vol. 22, pp. 439-449, 2007.

[10] M. A. G. de Brito, L. Galotto, L. P. Sampaio, G. de Azevedo e Melo, and C. A. Canesin, "Evaluation of the Main MPPT Techniques for Photovoltaic Applications," *IEEE Transactions on Industrial Electronics*, vol. 60, pp. 1156-1167, 2013.

[11] A. K. Abdelsalam, A. M. Massoud, S. Ahmed, and P. N. Enjeti, "High-Performance Adaptive Perturb and Observe MPPT Technique for Photovoltaic-Based Microgrids," *IEEE Transactions on Power Electronics*, vol. 26, pp. 1010-1021, 2011.

[12] P. E. Kakosimos, A. G. Kladas, and S. N. Manias, "Fast Photovoltaic-System Voltage- or Current-Oriented MPPT Employing a Predictive Digital Current-Controlled Converter," *IEEE Transactions on Industrial Electronics*, vol. 60, pp. 5673-5685, 2013.

[13] O. Lopez-Lapena, M. T. Penella, and M. Gasulla, "A Closed-Loop Maximum Power Point Tracker for Subwatt Photovoltaic Panels," *IEEE Transactions on Industrial Electronics*, vol. 59, pp. 1588-1596, 2012.

[14] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "Optimization of perturb and observe maximum power point tracking method," *IEEE Transactions on Power Electronics*, vol. 20, pp. 963-973, 2005.

[15] L. Whei-Min, H. Chih-Ming, and C. Chiung-Hsing, "Neural-Network-Based MPPT Control of a Stand-Alone Hybrid Power Generation System," *IEEE Transactions on Power Electronics*, vol. 26, pp. 3571-3581, 2011.

[16] Harel, David, "Statecharts: A Visual Formalism for Complex Systems," Science of Computer Programming 8, 1987, pages 231-274.

[17] Rana Ahmed, A. Namaane and N. K. M'Sirdi, "Improvement in Perturb and Observe Method Using State Flow Approach" Energy Procedia Volume 42, 2013, Pages 614–623, Mediterranean Green Energy Forum 2013: Proceedings of an International Conference MGEF-13

[18] Baochao Wang; Sechilariu, M. ; Locment, F., "Intelligent DC Microgrid With Smart Grid Communications: Control Strategy Consideration and Design" *IEEE Transactions on Smart Grids*, Vol. 3, Issue: 4, Dec. 2012.

[19] Bisht, H. ; Singh, R.K., "A Novel Simulation Method Using State-Flow for DC-DC converters" Power, Control and Embedded Systems (ICPCES), 2012 2nd International Conference

[20] Qi Zhiyuan, "Coordinated Control for Independent Wind SolarHybrid Power System ", Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific.

[21]fffBerrazouane,S. ; Mohammedi,K.,"Hybrid system energy man agement and supervisionbased on fuzzy logic approach for ele ctricity production in remote areas" Renewable Energies and Vehicular Technology (REVET), 2012 First International Conference.

[22] In-Hwan Oh,"A soft switching synchronous buck converter for zero voltage switching (ZVS) in Light and Full load conditions", IEEE xplore, 978-1-4244-1874-9/08, pp.1460-1464, 2008.

[23] N. J. A. B. Mohd, "Photovoltaic Charge Controller," Bachelor Degree Electrical & Electronics Engineering, Universiti Malaysia Pahang 2009.

[24] N.H. Abdul Rahman, A.M. Omar, E.H. Mat Saat, "A Modification of Variable Step Size INC MPPT in PV System" IEEE 7th International Power Engineering and Optimization Conference (PEOCO2013), Langkawi, Malaysia. June 2013.

[25] H. Afghoul, D. Chikouche, F. Krim and A. Beddar, "A novel implementation of MPPT sliding mode controller for PV generation systems" EuroCon 2013, July 2013, Zagreb, Croatia.

[26] Lijun Qin,Xiao Lu, "Matlab/Simulink-Based Research on Maximum Power Point Tracking of Photovoltaic Generation" International Conference on Applied Physics and Industrial Engineering, Physics Procedia 24 (2012).