Sizing and Design of PV Array for Photovoltaic Power Plant Connected Grid Inverter

Ali Q. Al-Shetwi[1,2] and Muhamad Zahim Sujod[1]
[1]Faculty of Electrical and Electronics Engineering, University Malaysia Pahang (UMP)
Pekan, Pahang, Malaysia
[2]Department of Electronic Engineering and Automatic Control, University of Science and Technology, Sana'a, Yemen
alialshetwi@yahoo.com

Abstract— over the past few years, installation of photovoltaic power plants (PVPPs) are considered as one of the most promising technologies at many of countries around the world, in order to meet the growing demand of energy. The DC side (PV generators and MPPT) of a 1.5 MW PV power plant connected to the inverter is modeled and simulated using Matlab/Simulink. The sizing of the suggested PVPP is achieved, such as array sizing and enhanced perturb and observe maximum power point tracking (MPPT) technique, in order to overcome the disadvantages of conventional method such as oscillation and slowly tracking under sudden change of atmospheric conditions. The MATLAB/Simulink was run to simulate the PV array sizing and its characteristics depending on enhanced MPPT technique to improve the efficiency of the modules and getting maximum available power. The simulation result has been matched the sizing theoretical calculation results.

Keywords— PV array sizing; photovoltaic power plant; MPPT, PV modelling; Matlab/Simulink; PV inverter.

1. INTRODUCTION

In the recent period, there was a sharp increase in renewable energy (RE) development according to global scale. Based on last renewables global status report 2015 [1] the global RE capacity reached to 1712.7 GW in 2014 higher than total capacity in 2013 by around 8.38 %. The electricity consumption around the world generated as 78.3% by fossil fuels power plants and 19.1% from RE resources, whilst the nuclear power stations contributed by 2.6% from the global energy generation. The most dramatic growth of RE capacity occurred in the power sector led by wind energy, solar PV power, and hydropower. Excluding hydropower energy, the global RE capacity reached to 657 GW in 2014. In this regards, the top seven countries with respect to the installed capacity led by China then followed by USA, Germany, Italy, Spain, Japan, and India, as can be observed in Fig.1. Before the end of 2014, RE contribute by 27.7% of the world's power generation higher than 2013 by around 1.7% which was around 22.1% [1, 2].

Globally, there are thousands of photovoltaic power plant (PVPP) connected to the power grid in many regions and countries. Consequently, the PV industry has gained remarkable growth in the late years, which is often because of diminishing the cost of the solar PV per kilowatt. G.K. Singh in [3] gives an itemized on the researches as well as the development that has been done in the PV energy system from its commencement till now. The capacity of the PV system reaches to 139 GW in 2013 and 177 GW in 2014 with increasing by 39 and 38 GW, respectively [1, 4]. Most of the new solar PV capacity is in the form of PVPP integrated with electrical grid. The leading country in PV solar system installation that ranked in 2014 led by Germany and followed by China, Japan, Italy, USA, France, Spain, UK, Australia and then India, while the global PV market led by China followed by Japan and USA [1, 2].

The MPPT algorithm is very essential thing in grid-connected photovoltaic power plant to track the maximum power point (MPP) of the module for the purpose of increasing PV panels' efficiency. There are a lot of MPPT algorithms which utilized through the advancement of PV energy system. The issues of using MPPT to extract the maximum available power from the PV array has been studied and addressed using different algorithms in the literature. For instance, hill climbing (HC), incremental conductance (INC) method, perturb and observe (P&O) algorithm, look-up table method, constant voltage (CV) or constant current (CC). The aforementioned algorithms compared and reported in [5, 6].

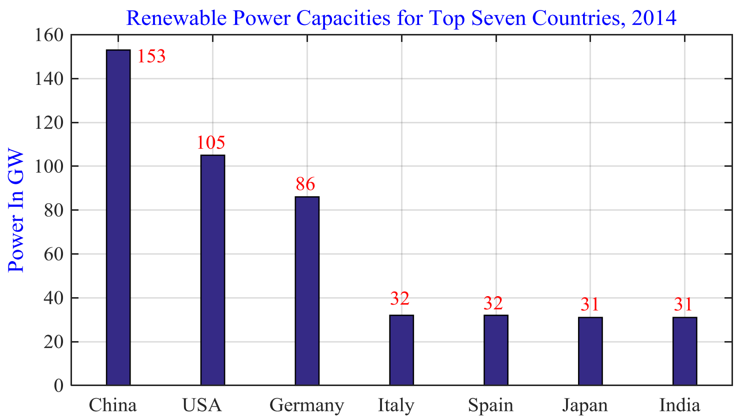

Figure 1: The global RE capacity in 2014

Power electronic inverter Play an important role in grid-interconnection PV system. This importance comes since the inverters needed to realize the power conversion and control optimization [7]. In general, grid connected pulse width modulation (PWM) voltage source inverters are commonly used in PV system, which have two capacities at minimum, since of the special components of PV modules. Firstly, the dc bus voltage of the inverter should be balanced out to a particular value because of the output voltage of the PV panels fluctuates with weather condition in addition to the impact of MPPT. Secondly, the energy should be fed from the PV panels into the utility network by modifying the dc current into a sinusoidal waveform synchronized with utility grid [8].

The content of this paper arranged as follows: background review is provided in the introduction, followed by designing and sizing of the PV array, in section 2. The proposal enhancement of perturb and observe (P&O) MPPT algorithm is presented in section 3. The validation of the theoretical calculations sizing of the DC part of PVPP are presented in section 4. Conclusion and remarks are given in section 5.

2. The PV Array Sizing

A. Mathematical model

Fig.2 shows an equivalent circuit of the PV module which consist of several PV cells. It includes a current source generates photo current that depends on the irradiation, a big diode which equivalent to the p-n transition area of the solar cell, the voltage losses represented by series resistance and parallel resistance describing the leakage current. The output current and voltage relationship of PV module can be expressed by the following equation:

$$I_{\mathrm{L}} = [I_{\mathrm{sc}} + \alpha_i (T - 25)] \frac{G}{G_{\mathrm{ref}}} - I_{\mathrm{sat}} \left(e^{\left(qV_{\mathrm{D}}/mN_{\mathrm{S}}KT \right)} - 1 \right) - \frac{I_{\mathrm{L}} R_{\mathrm{S}} + V_{\mathrm{L}}}{R_{\mathrm{P}}} \tag{1}$$

where I_{Ph} , I_D , I_P and I_{sat} are the photo current at nominal PV standard tests condition (STC) (normally 25°C and 1000W/m^2) for temperature and irradiation, where I_{Ph} is highly affected by these two factors [9], the diode current of the PV cell, shunt current and the reverse saturation current of the solar panel, respectively. Ns is the number of cells connected in series, V_T is the thermal voltage that equal to 25.7V at 25°C (298K) and m is the ideally factor of the diode (1-5(V_T)). K is the Boltzmann constant (1.381×10^{-23} J/K) and q is the charge of the electron (1.6021×10^{-19}C). R_S and R_P are the equivalent series and parallel resistance of the solar module, respectively.

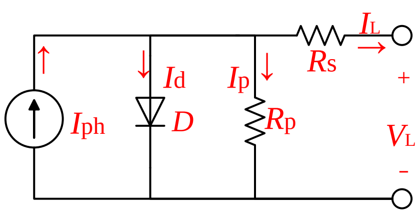

Figure 2: Equivalent circuit of a solar cell.

The I_{sc} is the nominal short circuit current of the module. G and G_{ref} are the amount of actual and nominal irradiation, respectively. T is the temperature degree in kelvin (K) and α_i is the current temperature coefficient [10]. The $I_{sc,ref}$ and $V_{oc,ref}$ are the short circuit current and open circuit voltage of the module at STC, whereas, α_v is the open circuit voltage temperature coefficient, normally these values evaluated by the manufacturer [11, 12].

B. Array Sizing of the PV Farm

In this paper, PV Monocrystalline module (SunPower SPR-415E-WHT-D manufactured by SunPower Company) selected to use in this design due to its specification. It is consist of 128 cells with maximum power (P_{max}) of 415W, open circuit voltage (V_{oc}) is 85.3 V, short circuit current (I_{sc}) is 6.09A, while the maximum power point voltage (V_{mp}) and current (I_{mpp}) are 72.9 V and 5.69 A, respectively. In order to accomplish the proposed PV plant which is designed to generate a peak power of 1500 kW, the needed numbers of modules can be obtained by the following equation [13]:

$$N_{pv} = \frac{\text{The needed power}}{\text{Maximum power of the panel}} \Rightarrow N_{pv} = \frac{1.5\times10^6}{415} = 3618 \text{ modules} \quad (2)$$

In this design, the system DC-link rated at 650 VDC to reduce the output current ripple and regulate the voltage at the dc side of the inverter, therefore the number of necessary PV modules in series (N_{pvs}) is obtained as:

$$N_{pv_s} = \frac{\text{DC nominal voltage}}{\text{Maximum power point voltage}} \Rightarrow N_{pv_s} = \frac{650}{72.9} = 9 \text{ modules} \quad (3)$$

The number of strings of the photovoltaic array can be obtained according to the following relation [13]:

$$N_{pv_{st}} = \frac{\text{Number of array modules}}{\text{Number of PV series modules}} \Rightarrow N_{pv_{st}} = \frac{3618}{9} = 402 \text{ strings} \quad (4)$$

As a result, to generate 1.5 MW of power at STC, a 3618 module with maximum power of 415W has been used and distributed as nine series modules and 402 parallel strings, as can be observed in Fig. 3.

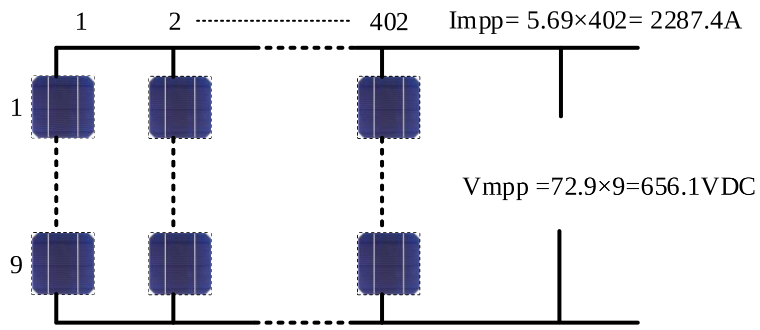

Figure 3: The System array configuration.

The actual maximum voltage (V_{mpv}) and the actual maximum current (I_{mpv}) of the PV array can be obtained by (5) and (6), respectively:

$$V_{mpv} = \text{Number of series modules} \times \text{Maximum power point voltage} = 9\times72.9 = 656.1 \text{ VD} \quad (5)$$

$$I_{mpv} = \text{Number of parallel strings} \times \text{Maximum power point current} = 5.69\times402 = 2287.4 \text{ A} \quad (6)$$

On the other hand, the actual maximum output power of the PV power plant can be calculated according to (7):

$$P_{dc} = V_{mpv} \times I_{mpv} = 656.1\times 2287.4 = 1500763 \text{ w} \quad (7)$$

The array maximum open circuit voltage (V_{oc}) can be calculated based on (8), while the maximum short circuit current (I_{sh}) of the array will be obtained by (9).

$$V_{oc} = \text{Number of series modules} \times \text{Open circuit voltage} = 9\times 85.3 = 767.7 \text{ VDC} \quad (8)$$

$$Ish = \text{Number of parallel strings} \times \text{Short circuit current} = 402 \times 60.9 = 2448.2 \text{ A} \quad (9)$$

3. ENHANCED P&O MPPT ALGORITHM

The most common MPPT algorithm is P&O because of its simplicity and less number of sensors utilized. By periodically increasing or decreasing PV array voltage, the conventional P&O technique changes the operating voltage towards maximum power point. The process is carried out by comparing the amount of power observed between present and past cycle. If the power during this cycle exceeds the past cycle, the perturbation is proceeded in the same direction at the following perturb cycle. Otherwise, the perturbation direction is reversed to the opposite direction [14-16].

The MPPT algorithm objective's is to track the maximum current (I_{max}) and maximum voltage (V_{max}) of the photovoltaic array, in which the maximum available output power (P_{max}) is obtained. This paper proposes an enhancement to the P&O method to overcome the limitation of the conventional method such as failure under sudden changing in weather condition and oscillations at steady state condition, as mentioned in previously. In order to guarantee that MPPs are followed under sudden change of sun irradiance, the new proposed enhancement point of the P&O algorithm is to use variable perturbation depending on power change instead of fixed perturbation step size in conventional P&O and some of adaptive methods [5, 17] as well. It means that, the perturbation step size varies and adjusts consistently under changing weather condition. This proposed method can reduce the primary disadvantage usually related to P&O algorithm such as tracking efficiency and convergence speed. The variable perturbation step size that relies on power change can be obtained by the following equation and flowchart.

$$\Delta V_i = \Delta V_o \times \frac{dP_i}{dV_i} \tag{10}$$

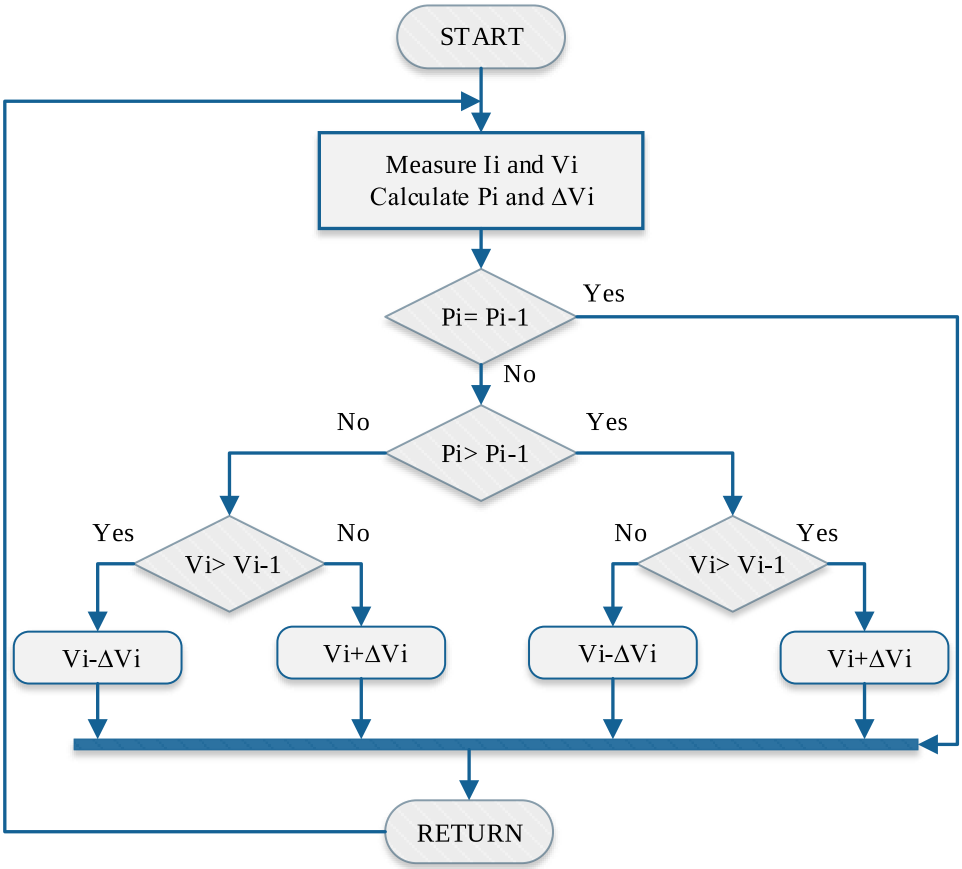

Figure 4: Flowchart diagram of enhanced P&O MPPT method.

4. MATLAB/SIMULINK PV ARRAY SIZING RESULT

As mentioned in Section 2-B, the sizing calculation results has been done. In this section, the testing of array sizing by using Simulink was implemented based on the enhanced MPPT technique which utilized to ensure that the solar energy is captured and converted as much as possible. The results illustrated that, the PV array delivering a maximum power of 1500 kW at STC, as can be shown in Fig.5. According to the configuration in Fig.3, this design requires 3618 PV modules distributed as nine series panels and 402 parallel strings, in order to provide the required power. Furthermore, the PV array has actual maximum PV array voltage V_{mpv} = 656 VDC to comply with DC-link. The DC-link designed with 650V to reduce the output current ripple and regulate the voltage at dc side of the inverter. This link voltage consist of capacitors C_1 and C_2 which split into ± 325 V, actual maximum PV array current I_{mpv} = 2287.4A and P_{mpp} equal to around 1.5 MW. Fig.5 shows that by using a Simulink model, the sizing calculation results has been matched to the simulation results.

Fig.6 below explains *I-V* and *P-V* characteristics of the system array which were used in this design that consist of 9 series module and 402 parallel strings at a different level of radiation. The result of the calculation sizing demonstrated that the actual maximum open circuit voltage was V_{oc} = 767.7*VDC* and the actual maximum current short circuit current I_{sh} was 2448.2A.

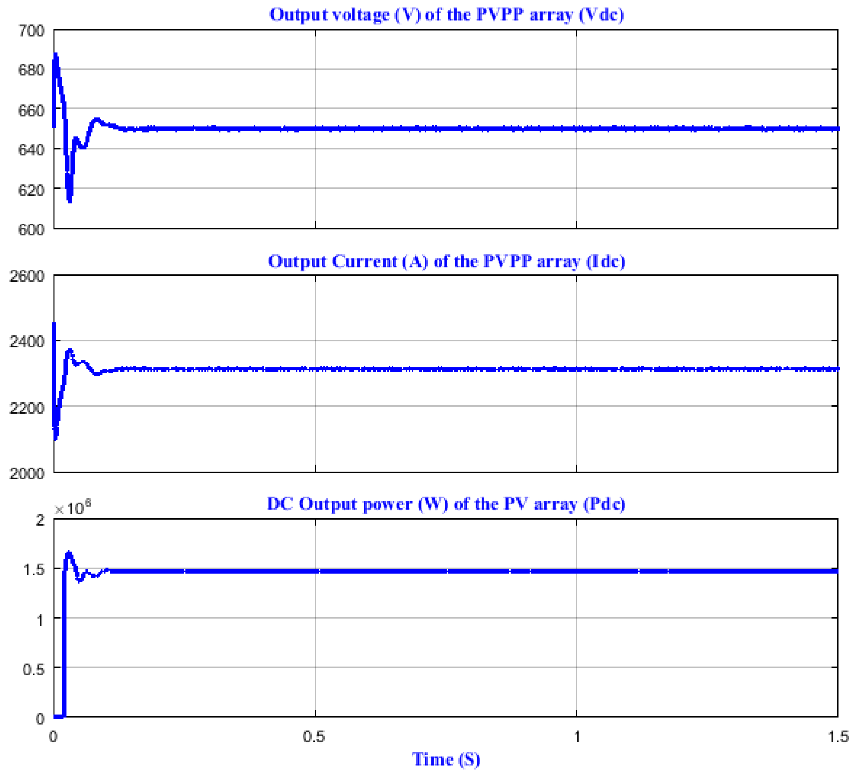

Figure 5: Maximum voltage, current, and power of the PVPP array at STC.

This simulation result supports the theoretical sizing study since it gets an equivalent values. This figure also showed the PVPP array with different sun radiation to provide the system operator with a background by the amount of the power and current of the system which could be generated in case of increasing or decreasing the radiation levels.

By using an enhanced P&O MPPT algorithm with variable step size relying on power changes at different weather condition in Simulink, Fig.7 illustrates that the PV array delivering a maximum power around 1500 kW at 1000W/m^2 sun irradiance, if the sun irradiation decreased to 500W/m^2 the maximum obtained power is about 750 kW.

The purpose of the enhanced MPPT method is to overcome the limitation of the conventional method such as improving the response speed in order to extract maximum available power of the array. According to the array's current and voltage behavior under different sun irradiance shown in Fig. 8, in addition to above discussions, the speed response shows the effectiveness of the enhanced strategy, But, on the other side the oscillation problem still exists.

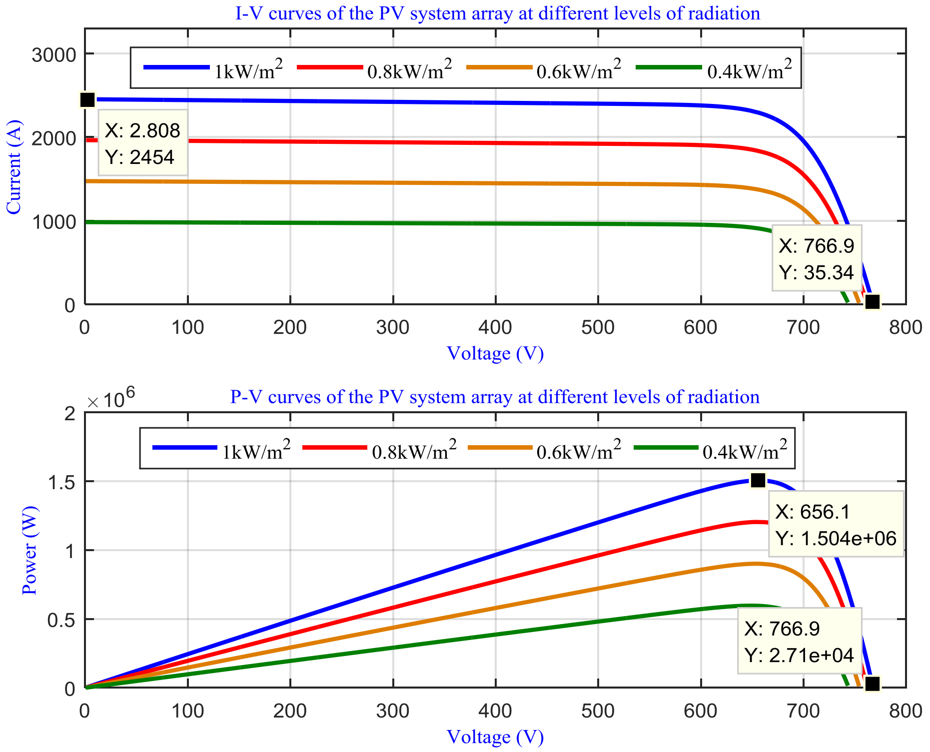

Figure 6: I-V and P-V curvesfor PV system array consist of 9 series modules and 402 parallel strings.

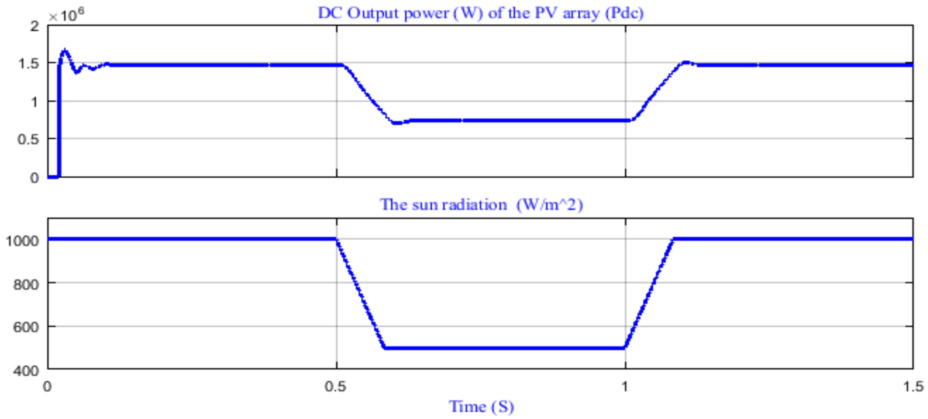

Figure 7: Output power of the PV generators (DC part).

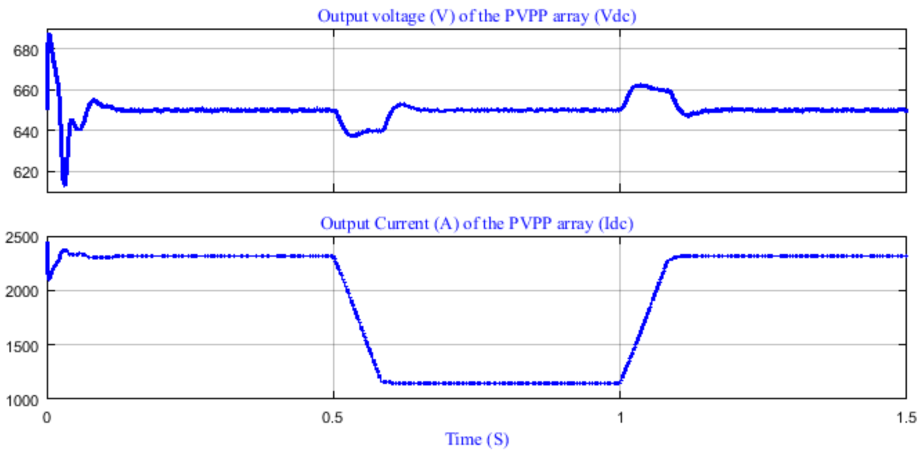

Figure 8: Maximum voltage and current of the PV array at two different levels of radiations

5. Conclusion

In this paper, a Matlab/Simulink model of PVPP array sizing and configuration design was developed and presented. The DC side (PV array & MPPT) of a 1.5 MV PV farm with MPPT technique which used to enhance the panels efficiency has been carried out. For the purpose of generating this amount of power needed at around 3618 PV panel or module, the panel configuration arranged as 9 series module and 402 parallel strings. The amount of DC output voltage of the proposed array's structure is 656 V to comply with DC-link voltage in the purpose of connection to solar inverter. The theoretical sizing calculation results of the system were proved by using Simulink software. MPPT techniques are utilized to extract the maximum available power from the solar PV array. The conventional P&O MPPT algorithm with fixed perturb size is not effective during oscillation and cannot track sudden change of atmospheric conditions. Therefore, in order to overcome these drawbacks of the conventional method, an enhanced method applied using variable step size that depend on power changes. As conclusion, the results show the effectiveness of the proposed MPPT technique in case of weather condition change, but the oscillation problem still exist. In addition, the DC part sizing and designing results have been matched the modeling results.

Acknowledgment

This research was funded by Fundamental Research Grant Scheme (Project RDU 150125) led by the second author. Also, the authors are grateful for University Malaysia Pahang (UMP)'s support to the first author.

References

[1] Global Status Report, "Renewables 2015 Global Status Report,". Available: http://www.ren21.net/wp-content/uploads/2015/06/GSR2015_KeyFindings_lowres.pdf. (accessed: 23 January 2016)

[2] A. Raturi, A. Singh, and R. D. Prasad, "Grid-connected PV systems in the Pacific Island Countries, " Renewable and Sustainable Energy Reviews, vol. 58, pp. 419-428, 2016.

[3] G. Singh, "Solar power generation by PV (photovoltaic) technology: a review, " Energy, vol. 53, pp. 1-13, 2013.

[4] A. Q. Al-Shetwi, M. Z. Sujod, and N. L. Ramli, "A Review of the Fault Ride Through Requirements in Different Grid Codes Concerning Penetration of PV System to the Electric Power Network, " ARPN Journal of Engineering and Applied Sciences, vol. 10, No. 21, pp. 9906-9912, 2015.

[5] B. Subudhi and R. Pradhan, "A comparative study on maximum power point tracking techniques for photovoltaic power systems," Sustainable Energy, IEEE transactions on, vol. 4, pp. 89-98, 2013.

[6] H. P. Desai and H. Patel, "Maximum power point algorithm in PV generation: an overview," in Power Electronics and Drive Systems, 2007. PEDS'07. 7th International Conference. pp. 624-630. 2007.

[7] H. M. Kojabadi, B. Yu, I. A. Gadoura, L. Chang, and M. Ghribi, "A novel DSP-based current-controlled PWM strategy for single phase grid connected inverters, " Power Electronics, IEEE Transactions on, vol. 21, pp. 985-993, 2006.

[8] B. Yang, W. Li, Y. Zhao, and X. He, "Design and analysis of a grid-connected photovoltaic power system," Power Electronics, IEEE Transactions on, vol. 25, pp. 992-1000, 2010.

[9] T. Salmi, M. Bouzguenda, A. Gastli, and A. Masmoudi, "Matlab/simulink based modeling of photovoltaic cell," International Journal of Renewable Energy Research (IJRER), vol. 2, pp. 213-218, 2012.

[10] M. G. Villalva and J. R. Gazoli, "Comprehensive approach to modeling and simulation of photovoltaic arrays,"Power Electronics, IEEE Transactions on, vol. 24, pp. 1198-1208, 2009.

[11] H. Bellia, R. Youcef, and M. Fatima, "A detailed modeling of photovoltaic module using MATLAB," NRIAG Journal of Astronomy and Geophysics, vol. 3, pp. 53-61, 2014.

[12] A. Bouraiou, M. Hamouda, A. Chaker, M. Sadok, M. Mostefaoui, and S. Lachtar, "Modeling and Simulation of Photovoltaic Module and Array Based on One and Two Diode Model Using Matlab/Simulink," Energy Procedia, vol. 74, pp. 864-877, 2015.

[13] A. Q. Al-Shetwi, "Design and Economic Evaluation of Electrification of Small Villages in Rural Area in Yemen Using Stand-Alone PV System," International Journal of Renewable Energy Research (IJRER), vol. 6, pp. 1442-1451, 2016.

[14] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "Optimizing duty-cycle perturbation of P&O MPPT technique," in Power Electronics Specialists Conference, PESC 04. 2004 IEEE 35th Annual, 2004, pp. 1939-1944, 2004.

[15] C. Kalpana, C. S. Babu, and J. S. Kumari, "Design and Implementation of different MPPT Algorithms for PV System," International Journal of Science, Engineering and Technology Research (IJSETR) Volume, vol. 2, 2013.

[16] S. K. Kollimalla and M. K. Mishra, "A novel adaptive P&O MPPT algorithm considering sudden changes in the irradiance," Energy Conversion, IEEE Transactions on, vol. 29, pp. 602-610, 2014.

[17] S. K. Kollimalla and M. K. Mishra, "Variable perturbation size adaptive P&O MPPT algorithm for sudden changes in irradiance," Sustainable Energy, IEEE Transactions on, vol. 5, pp. 718-728, 2014.