Sizing Software for Residential Grid-Connected Photovoltaic Systems

Nurul Afiqa Binti Abdul Rasid
Faculty of Electrical Engineering
Universiti Teknologi MARA
40450 Shah Alam, Selangor, Malaysia
nurulafiqa_abdulrasid@yahoo.com

Shahril Irwan Bin Sulaiman
Faculty of Electrical Engineering
Universiti Teknologi MARA
40450 Shah Alam, Selangor, Malaysia
shahril_irwan2004@yahoo.com

Abstract – **This paper presents software for sizing residential Grid-Connected Photovoltaic Systems developed by Microsoft Visual Basic. The software represents two design goals which are to meet specific output energy from the system and to maximize energy output from available roof space. The sizing process involves the selection of PV modules and inverter and computation of technical performance and expected income of the system. As existing sizing software for photovoltaic system such as PVSyst required manual selection of PV modules configuration and estimated PV array capacity (kWp), this sizing software perform automatic selection of PV modules and estimated PV array capacity.**

Keywords – GCPV; modules; energy; residential; photovoltaic; algorithm

I. Introduction

On 1839, Alexander Edmond Becquerel was the first person discovered about the photovoltaic effect. By using solar cell, energy being absorbed from the sun was converted as a flow of electrons. This situation was called as photovoltaic (PV) which the techniques for generating electric power. Then, the modern solar cells were established simultaneously with the investigation towards the properties of intrinsic silicon.

Nowadays, photovoltaic being used as an electric source that can power up the electrical equipment or to recharge a battery. Photovoltaic was widely used in grid connected power generation with the combination of the inverter modules. The Grid Connected Photovoltaic (GCPV) systems are used to supply the electric grid with the total energy produced by PV modules [1].

The usage of GCPV systems has become primarily significant in the urban areas, people that implement GCPV system can reduce the monthly electricity cost instead of using the imported electricity from the grid. In addition, although there is no power generated from the system, the user can still consume electricity from the grid. In spite of the strong potential, one of the most important issues in GCPV system is the sizing of the systems. If a GCPV system is not properly sized, the system might not be functioning as expected [2].

Besides that, the most difficult part in designing the GCPV system is to select the most suitable system components. This is because the sizing process involves many factors to consider such as the selection of PV module, inverter, and determination of other technical and economic parameters in the design. The design can be done either by manual computation or by using the software for sizing that operated automatically based on algorithm concept. Ironically, the application of sizing software are still limited due to the system designers are required to utilize the prescribed sizing algorithms readily embedded in the software indirectly.

In addition, existing software such as HOMER and PVsyst still cannot overcome the limitation. This limitation was explained in paper [3]; it states that HOMER is a micro grid optimization tools develop by National Renewable Energy Laboratory (NREL). Although HOMER can estimates output of typical PV installation based on the locations meteorological and the installation data, but it still has limitations. HOMER simulation also does not consider the area of the roof space for GCPV system. Due to this factor, it will produce inaccurate output and it is not suitable software for residential GCPV system application. Besides that, PVSyst software required manual selection of PV modules configuration and estimated PV array capacity which required high time consume.

In order to solve this limitation, this paper presents software for sizing residential Grid-Connected Photovoltaic systems with two design goals which are to meet specific output energy from the system and to maximize energy output from available roof space. The sizing software consider the availability of roof space and performed algorithm computation automatically to determine the PV modules configuration and the value of estimated PV array capacity in order to obtain the technical performance and expected income of the system.

II. Methodology

The sizing software represents two design goals which are to meet specific output energy from the system and to maximize energy output from available roof space. The first

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design goal, to meet specific output energy from the system is about design a GCPV system for a selected house such that the total annual electricity generation from the system is approximately equal to the annual electricity consumption. In addition, to maximize energy output from available roof space is about design a GCPV system for a selected house to maximize the electricity generation from an available roof space.

Apart from that, this sizing software was built by using a series of methods. Firstly, a database for PV modules and inverter was developed to display the specification that used in the sizing computation. Later, an automatic sizing algorithm calculation was developed based on algorithm equations to determine the system performance.

A. Flow Chart

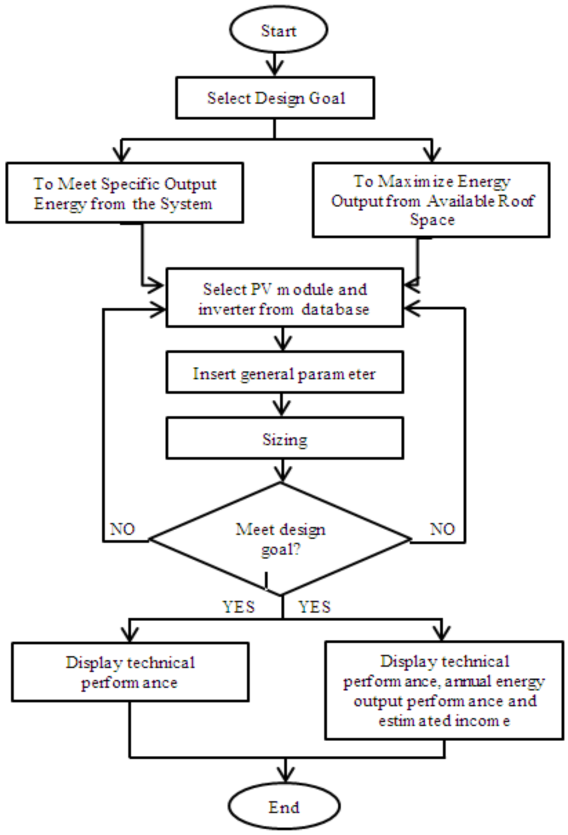

Figure 1: Flow chart sizing of software for residential Grid-Connected Photovoltaic Systems

B. Software Design

To determine the technical and economic performance of the sizing software, a house at Bandar Melaka, facing South-East (Azimuth angle -45 deg) and the tilt angle is 30 deg was selected to become the experimental location. The following steps show the relationship between the equation and the sizing process for the first design goal:

Step1: Determine the annual energy output requirement from the system as specified by the user, E_{sys_req} in kWh. The total annual energy output was obtained from the house electricity bill for a year and the value was 1900 kWh/ year.

Step 2: PV module and inverter was selected from the database. All the required electrical parameters for PV module are rated at standard test conditions (STC). The STC specifies that the respective module ratings are obtained at irradiance of 1000Wm^{-2}, air mass (AM) of 1.5 and cell temperature of 25°C [4]. The required parameter rating of PV module and inverter was shown in Table I and Table II respectively.

TABLE I
PV MODULE SPECIFICATION

Parameters	Value	Unit
Brand of PV module	Mitsubishi PV-TJ235GA6	
Type of solar cell	Polycrystalline	
Maximum power, P_{mp_stc}	235	Wp
Voltage at maximum power, V_{mp_stc}	30.5	V
Open circuit voltage, V_{oc_stc}	36.8	V
Short circuit current, I_{sc_stc}	8.49	A
Temperature coefficient for maximum power, γ_{Pmp}	-0.41	% per °C
Temperature coefficient for voltage at maximum power, γ_{Vmp}	-0.41	% per °C
Temperature coefficient for open circuit voltage, γ_{Voc}	-0.32	% per °C
Reduction factor for array output due to manufacturer's tolerance, , f_{mm}	0.97	
Maximum allowable system voltage, V_{sys_max}	1000	V
Length of PV module, L_{mod}	1.658	m
Width of PV module, W_{mod}	0.994	m

TABLE II
INVERTER SPECIFICATION

Parameters	Related results	Units
Brand of inverter	Fronius IG15	
Nominal power of inverter, P_{inv}	1500	W
Maximum input voltage of inverter, V_{max_inv}	500	V
Maximum input voltage limit to the MPPT, $V_{max\_win\_inv}$	400	V
Maximum input voltage limit to the MPPT, $V_{min\_win\_inv}$	150	V
Maximum input current, $I_{dc\_max\_inv}$	10.75	A
Nominal efficiency, η_{inv}.	94.2	%

Step 3: After that, the maximum number of PV modules that could be install on the available roof space in different mounting arrangement was computed. There are two types of mounting arrangement of PV modules which are lengthwise across (LA) and lengthwise up (LU). Besides that, a gap between each PV module, l_g need to consider. The maximum number of PV modules that can be installing on the available roof space using LA and LU, $N_{roof\_max\_LA}$ and $N_{roof\_max\_LU}$ was computed using

$$N_{roof\_max\_LA} = [W_{roof} / (W_{mod} + l_g)] \text{ x } [L_{roof} / (L_{mod} + l_g)] \quad (1)$$

$$N_{roof\_max\_LU} = [W_{roof} / (L_{mod} + l_g)] \text{ x } [L_{roof} / (W_{mod} + l_g)] \quad (2)$$

where W_{roof} and L_{roof} is the width and the length of the roof in m respectively. In addition, both of LA and LU value must be rounded down towards the nearest integer. LA arrangement is better than LU arrangement because LA could reduce the effect of dirt or dust accumulation on the PV modules since only one string is potentially affected by the dirt [5]. On the other hand, LU has higher possibility affected by the dust accumulation since all of the PV modules were arranged in parallel strings.

Step 4: The estimated PV array capacity, $P_{array\_stc\_req}$ in Wp was computed using

$$P_{array\_stc\_req} = E_{sys\_req} / (H_{tilt} \text{ x } f_{mm} \text{ x } f_{temp} \text{ x } f_{dirt} \text{ x } \eta_{inv} \text{ x } \eta_{pv\ inv}) \quad (3)$$

where H_{tilt} is the expected annual peak sun hours (PSH) for the specific tilt angle of the PV array and the value was obtained from solar irradiation table at tilt angle 30 deg which is 1565.1 kWh/ m^2 [6]. f_{dirt} was determined based on the severity of the dirt accumulation on PV modules with typical values ranging from 0.95 to 1. η_{pv_inv} is the estimated cabling efficiency from the PV array and inverter and was denoted as 0.95. The reduction factor due to temperature effect, f_{temp} was computed using

$$f_{temp} = 1 + [(\gamma_{Pmp}/100) \text{ x } (T_{cell\_avg} - T_{stc})] \quad (4)$$

where T_{stc} was selected to be 25°C. Since, it was difficult to physically measure the cell temperature when the system has not been installed, the average cell temperature in °C, T_{cell_avg} was estimated using

$$T_{cell\_avg} = T_{amb\_day} + T_{stc} \quad (5)$$

where T_{amb_day} was selected to be 32°C.

Step 5: The estimated total number of PV modules for the PV array, N_{tot_est} was determined using

$$N_{tot\_est} = P_{array\_stc\_req} / P_{mp\_stc} \quad (6)$$

where the value of N_{tot_est} must be rounded up towards the nearest integer.

Step 6: Next, the input voltage limits to the MPPT of inverter was revised to ensure that the output voltage from the PV array would always be within the input voltage range of the inverter. The revised voltage limits were the revised maximum input voltage of inverter in V, $V_{max\_inv\_rev}$, revised maximum input voltage limit to the MPPT of inverter in V, $V_{max\_win\_inv\_rev}$, and revised minimum input voltage limit to the MPPT of inverter in V, $V_{min\_win\_inv\_rev}$ [7].

$$V_{max\_inv\_rev} = [(100/100) - (\lambda_{upper}/100)] \text{ x } V_{max\_inv} \quad (7)$$

$$V_{max\_win\_inv\_rev} = [(100/100) - (\lambda_{upper}/100)] \text{ x } V_{max\_win\_inv} \quad (8)$$

$$V_{min\_win\_inv\_rev} = [(100/100) + (\lambda_{lower}/100)] \text{ x } V_{min\_win\_inv} \quad (9)$$

where λ_{upper} and λ_{lower} are the safety margin of the upper limit and lower limit of the input voltage to the inverter respectively, described in %. The λ_{upper} and λ_{lower} were chosen to be 5% and 10% respectively [8] after considering the lowest and highest module temperature recorded in Malaysia.

Step 7: The extreme output voltages from the expected PV module was determined by calculating the maximum open circuit voltage of the PV module in V, V_{max_oc}, the maximum voltage at maximum power of the PV module in V, V_{max_mp}, the minimum voltage at maximum power of the PV module in V, V_{min_mp} and the minimum voltage at maximum power of the PV module after considering voltage drop in V, $V_{min\_mp\_vd}$ also was calculated using

$$V_{max\_oc} = V_{oc\_stc} \text{ x } \{1+[(\gamma_{Voc} / 100) \text{ x } (T_{cell\_min} - T_{stc})]\} \quad (10)$$

$$V_{max\_mp} = V_{mp\_stc} \text{ x } \{1+[(\gamma_{Vmp} / 100) \text{ x } (T_{cell\_min} - T_{stc})]\} \quad (11)$$

$$V_{min\_mp} = V_{mp\_stc} \text{ x } \{1+[(\gamma_{Vmp} / 100) \text{ x } (T_{cell\_max} - T_{stc})]\} \quad (12)$$

$$V_{\min\_mp\_vd} = 0.95 \times V_{\min\_mp} \quad (13)$$

where T_{cell_min} and T_{cell_max} are the expected minimum and maximum cell temperature in °C respectively. T_{cell_min} and T_{cell_max} were selected to be 20°C and 75°C respectively.

Step 8: Then, the minimum and maximum number of PV modules in series (per string) was calculated as well as the maximum number of parallel strings to satisfy the inverter voltage and current limits using

$$Ns_{min} = V_{min\_win\_inv\_rev} / V_{min\_mp\_vd} \quad (14)$$

$$Ns_{max\_oc} = V_{max\_inv\_rev} / V_{max\_oc} \quad (15)$$

$$Ns_{max\_mp} = V_{max\_win\_inv\_rev} / V_{max\_mp} \quad (16)$$

$$Np_{max} = I_{dc\_max\_inv} / [(1 + \omega) \text{ x } I_{sc\_stc}] \quad (17)$$

where Ns_{max_oc} and Ns_{max_mp} are the maximum number of PV modules per string based on the open circuit voltage of the PV module and the maximum number of PV modules per string based on the voltage at maximum power of the PV module. Both value was rounded down towards the nearest integer and the lower value between Ns_{max_oc} and Ns_{max_mp} was selected as the maximum allowable number of PV modules per string, $Ns_{,max}$. The minimum allowable number of PV modules per string, $Ns_{,min}$ was rounded up towards the nearest integer such that the expected output voltage from the PV array did not fall below $V_{min\_win\_inv\_rev}$. Besides that, the maximum allowable number of parallel strings, $Np_{,max}$ was rounded down towards the nearest integer to ensure the array current did not exceed $I_{dc\_max\_inv}$ [9]. In addition, safety margin for the input current to the inverter, ω was set to be 25% after considering the occasionally high irradiance cases with more than 1000 Wm^{-2} recorded in Malaysia [10].

Step 9: Then, all possible array configuration based on Ns_{min}, Ns_{max} and Np_{max} was derived with the corresponding towards total possible number of PV modules, N_t. If more than one array configurations were left, the N_t for each array configuration was compared with $N_{roof\_max\_LA}$ and $N_{roof\_max\_LU}$ [2]. If N_t was smaller than $N_{roof\_max\_LA}$ *and* $N_{roof\_max\_LU}$, then LA was choosed as the optimal mounting array (MA). But, if N_t was larger than $N_{roof\_max\_LU}$ and lower than $N_{roof\_max\_LA}$, so the optimal MA was LA. Other than that, if the N_t was larger than than $N_{roof\_max\_LA}$ and lower than than $N_{roof\_max\_LU}$, so the optimal MA was LU.

Step 10: The step followed by determine the inverter to PV array sizing ratio, k where the range of k is between 0.75 to 0.80.

$$k = P_{inv} / P_{array\_stc\_new} = P_{inv} / (N_t \text{ x } P_{mp\_stc}) \quad (18)$$

Step 11: The new annual energy output from the inverter in Wh, E_{sys_new} was calculated using

$$E_{sys\_exp\_new} = P_{array\_stc\_new} \text{ x } H_{tilt} \text{ x } f_{mm} \text{ x } f_{temp} \text{ x } f_{dirt} \text{ x } \eta_{pv\ inv} \text{ x } \eta_{inv} \quad (19)$$

Step 12: The Excess Factor, *EF* of the energy supplied from the system was calculated using

$$EF = E_{sys\_exp\_new} / E_{sys\_exp} \quad (20)$$

Step 13: The Specific (Final) Yield in kWh per kWp, *SF* of the system was obtained using

$$SY = E_{sys\_new} / P_{array\_stc\_new} = E_{sys\_new} / (N_t \text{ x } P_{mp\_stc}) \quad (21)$$

where *SF* show the amount of energy can be extract from the system per kWp.

Step 14: Determine the performance ratio in decimal or in percentage (%), PR using

$$PR = E_{sys\_exp\_new} / E_{ideal} \quad (22)$$

where

$$E_{ideal} = P_{array\_stc\_new} \text{ x } H_{tilt} \quad (23)$$

or *PR* also can be written as

$$PR = f_{mm} \text{ x } f_{temp} \text{ x } f_{dirt} \text{ x } \eta_{pv\ inv} \text{ x } \eta_{inv} \quad (24)$$

The following steps show the procedure that was implemented for the second design goal:

Step 1: Repeat Step 2 from the first design goal.

Step 2: Determined number of LA and LU by using equation (1) and (2) from Step 3 above.

Step 3: Equation (7), (8) and (9) was performed todetermine the revised voltage limits, $V_{max\_inv\_rev}$, $V_{max\_win\_inv\_rev}$ and $V_{min\_win\_inv\_rev}$.

Step 4: The extreme output voltages from the expected PV module was computed using equation (10) until (13) to obtain the value of V_{min_mp}, V_{max_oc}, V_{max_mp} and $V_{min\_mp\_vd}$.

Step 5: The value of $Ns_{,min}$, Ns_{max_oc} and Ns_{max_mp} and $Np_{,max}$ was determined using equation (14) until (17) to obtain the PV array configuration.

Step 6: Step 9 from the first design goal was repeated to obtain the value of N_t by following the similar condition.

Step 7: The inverter to PV array sizing ratio, k was determined by performed equation (18).

Step 8: The expected annual energy output from the inverter in Wh, E_{sys_exp} was computed using equation (19).

Step 9: The performance ratio, *PR* was calculated using equation (22) or equation (24).

Step 10: The value of Specific (Final) Yield in kWh per kWp, *SY* was determined using equation (21).

Step 11: The processes followed by determine the Roof Utilization Factor, *RUF* using

$$RUF = A_{pv,array} / A_{roof} \quad (25)$$

$$A_{pv,array} = A_{pv,mod} \text{ x } N_t \quad (26)$$

$$A_{pv,mod} = [L_{mod} + l_g\ (2)] \text{ x } [W_{mod} + l_g\ (2)] \quad (27)$$

$$A_{roof} = W_{roof} \text{ x } L_{roof} \quad (28)$$

Step 12: Lastly, estimated income, $Income_{exp}$ in RM was calculated using

$$Income_{exp} = FiT\ Rates \text{ x } E_{sys\_exp\_new} \quad (29)$$

III. Results And Discussions

TABLE III
TECHNICAL PERFORMANCE FOR BOTH DESIGN GOAL

Parameters	Design goal 1	Design goal 2	Unit
PV module	Mitsubishi PV-TJ235GA6	Mitsubishi PV-TJ235GA6	
Inverter	Fronius IG15	Fronius IG15	
Required annual energy output, E_{sys_exp}	1900	-	kWh/ year
Required rated power of PV array, $P_{array\_stc\_req}$	1658	-	Wp
Number of estimated PV modules, N_{tot_est}	8	-	mod
Number of parallel string, N_p	1	1	string
Number of PV modules in series, N_s	8	8	mod
Total number of PV modules, N_t	8	8	mod
New annual energy output, E_{sys_new}	2155	2155	kWh/ year
New rated power of PV array, $P_{array\_stc\_new}$	1880	1880	Wp
Excess factor, EF	1.13	-	
Specific yield, SY	1.15	1.15	kWh/ kWp
Performance ratio, PR	73.2	73.2	%
Roof utilization factor, RUF	-	0.43	

Table III showed the technical performance for both of the design goal. The sizing process of design goal 1 determined the total annual electricity generation from the system to ensure it is approximately equal to the annual electricity consumption of the selected house. For design goal 2, the sizing involves the process of maximize the electricity generation from an available roof space. Both of the sizing process was performed automatically by the software.

Based on the data in Table III, the sizing manages to design the new annual energy approximately equal to the annual electricity consumption and the number of PV modules also was the same. This situation was similar with the design goal 2 technical performance. Both of the design goals had the same specific yield and performance ratio. Design goal 1 did not perform RUF computation but it performed the excess factor computation compare to design goal 2.

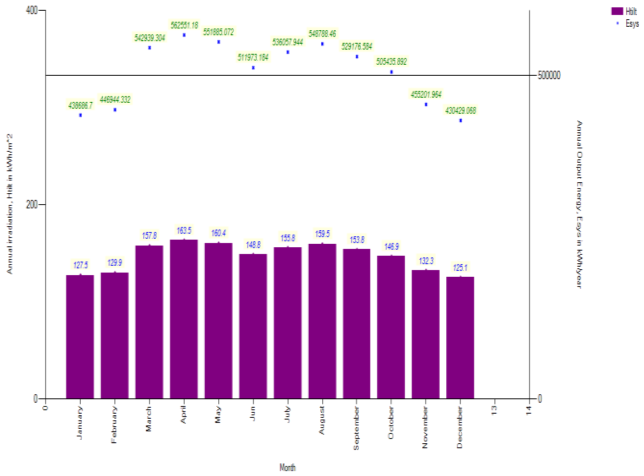

Figure 2: Performance of annual energy output based on total PSH for every month

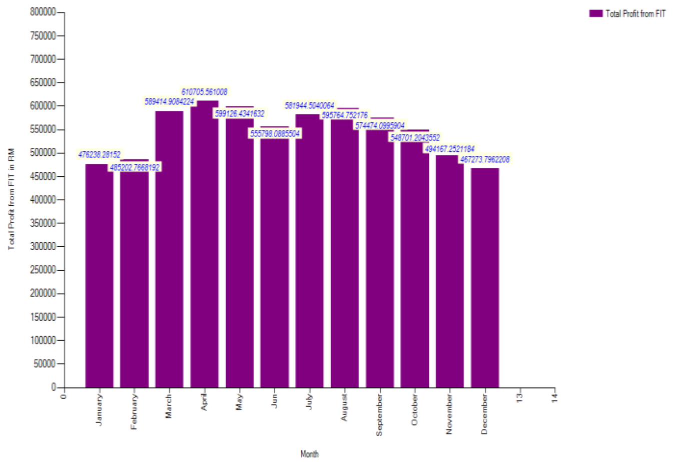

Figure 3: Economic performance of expected income based on annual energy output and FiT Rates

The technical performance of annual energy output based on the total PSH was represent in a graph form as shown in Figure 2. Then, the economic performance for the sizing was shown in Figure 3 which is the computation of expected income based on annual energy output.

IV. Conclusion

As a conclusion, the software for sizing residential Grid-Connected Photovoltaic systems was able to develop which performed technical performance and expected income of the system. The total annual energy electricity generation was managed to design in order to create approximately equal total annual electricity consumption for a selected house and the highest electricity generation from an available roof space. By using this software, all important parameter was took into an account instead of existing software which did not consider a few important parameters in designing the GCPV systems. A part from that, the sizing able to identify the maximum energy output from the system.

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REFERENCES

[1] A. Kornelakis, Y. Marinakis, “Contribution for optimal sizing of grid-connected PV-systems using PSO,” *Renewable Energy*, vol. 35, pp. 1333-1341, June 2010.

[2] S. I. Sulaiman, T. K. A Rahman, I. Musirin, S. Shaari, K. Sopian, “An intelligent method for sizing optimization in grid-connected photovoltaic system,” *Solar energy*, vol. 86, pp. 2067-2082, July 2012.

[3] P. Gilman “A comparison of three free compute models for evaluating PV and hybrid system designs: Homer, Hybrid2, and Retscreen”[Online]. Available e-mail: poulgilman@earthlink.net

[4] E. Skoplaki, J. A. Palyvos, “On the temperature dependence of photovoltaic module electrical performance: A review of efficiency or power correlations,” *Solar Energy,* vol. 83, pp. 614–624, 2009.

[5] S. Shaari, A. M. Omar, A. H. Haris, S. I. Sulaiman, 2010. Solar Photovoltaic Power: Designing Grid-connected Systems. Kementerian Tenaga, Teknologi Hijau dan Air, Putrajaya.

[6] S.I. Sulaiman, S. Shaari, A. M. Omar, *Solar Irradiation Data for Malaysia,* Sustainable Energy Development Authority (SEDA) Malaysia, vol.1, pp.13, February 2012.

[7] S. I. Sulaiman, T. K. A. Rahman, I. Musirin, “Design of Grid-connected Photovoltaic System using Evolutionary Programming,” in *IEEE Int. Conf. on Power and Energy (PECon2010)*, Kuala Lumpur, 2010, pp. 947-952.

[8] Installation of grid-connected photovoltaic (PV) system, 2010. Malaysian Standard MS 1837:2010.

[9] S. I. Sulaiman, Z. Othman, T. K. A. Rahman, "Dimensioning of photovoltaic array using Genetic Algorithm, "*IEEE Symposium on Computer Applications and Industrial Electronics (ISCAIE2012)*, pp. 89-93, Dec. 2012.

[10] S. I. Sulaiman, T. K. A. Rahman, I. Musirin, S. Shaari, "Sizing grid-connected photovoltaic system using genetic algorithm, "*IEEE Symposium on Industrial Electronics and Applications (ISIEA2011),* pp. 505-509, Sept. 2011.