Design Impact of 6.08 kWp Grid-Connected Photovoltaic System at Malaysia Green Technology Corporation

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Abstract—**System design issues of a Grid-Connected Photovoltaic (GCPV) system installed in Malaysia Green Technology Corporation (MGTC), Malaysia based on field condition under Malaysia's climate is presented in this paper. Several important factors related with design procedure which affect the GCPV system performances are identified to be solar irradiance, temperature, de-rating factor and wind speed. System design's sizing and natural environmental analysis are two common issues and considered to be among the most crucial part of the study with the objective of enhancing the GCPV system performance in Malaysia's perspective. The power output is being determined by the sizing of the GCPV system. In addition, by connecting a none appropriate numbers of serial modules per string will give a non-optimum system design. Hence, the inverter performance is affected. The analysis fully utilizes the in-field data as a guide for sizing PV array and inverter, with the aim of guiding the designer during initial design stage for Malaysia's climate.**

Index Terms— **Amorphous Silicon (a-Si); Building integrated photovoltaic (BIPV); De-rating factor; Grid-connected inverter; Malaysian climate; Photovoltaic (PV); System design.**

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I. Introduction

INVERTER technology sparks the interest among researchers nowadays due to the installation of Grid-Connected Photovoltaic (GCPV) systems worldwide. Furthermore, current cost for PV modules and inverters are expensive. System designers and installers are continuously making an effort to cut off the cost. Next, in order to achieve the optimal inverter-to-PV array power sizing factor, proper inverter sizing is needed as it has a strong impact on PV array operating temperature. A few preliminary criteria is needed to be considered during initial design stage. Several criteria that can help to choose the inverter in order for its to perform well are as follows; (i) The selection on the wider input Maximum Power Point (MPP) voltage range of the inverter that can accept more or longer modules in serial per strings can be connected, (ii) The inverter's MPP-voltage range limits must be matching with the operating DC voltage of the PV array and, (iii) Suitable condition for operating ambient temperature range of inverter in actual field. Inverters nowadays have a built-in protection circuit to avoid damages which might occurr due to the unstable voltage originated from the PV array. As a prevention of overheated inverter, the temperature-controlled power reduction mode operates automatically whenever the ambient temperatures are extremely high or when the circulation of air around the inverter is disrupted. In some extreme cases, the inverter is switched off to allow it to cool down. Moreover, the inverter is also equipped with an over-voltage protection function such as a varistor [1-3]. Sizing criteria play an important role in order to establish the optimal power sizing factor of inverter-to-PV array in GCPV systems in order to maximize the yearly energy injected to the grid.

The current practice of under-sizing the inverter's nominal power with respect to the PV array power may not be the best choice for thin-film PV technologies in the tropical climate because of the different solar irradiation level and operating temperature based on geographical site. Earlier research for cold climate suggested that under-sizing of 10% to 40% of the inverter nominal power with respect to PV array power at STC is a best choice to maximize the energy injected into the grid [4-6].

However, the rule of thumb stated that approximately 10% to 40% under-sizing of inverter power is not suitable especially in the different geographical climate in terms of the site-dependent distribution solar irradiation levels, inverter operating temperature and operating ambient temperature conditions [7]. Earlier study by *R. Rüther et al.* , stated that this rationale contradicts to the rule of thumb, for cold climate the inverter nominal power can be considered lower than the PV array power or under-sizing inverter lower than PV array power at Standard Test Condition (STC), which might lead to energy losses, especially operating at warm and tropical climates such as in Brazil, where there is a high incidence of clear skies and the energy distribution of sunlight was shifted to higher irradiation levels [8] and influenced the PV cell technologies with small temperature coefficients of power like thin-film family. An amorphous Silicon (a-Si) typically present a negative value of $\gamma_{Pmp} \approx$ -0.23%/°C [9] and Cadmium Telluride (CdTe) about $\gamma_{Pmp} \approx$ -0.25%/°C [10]. Other than that, by over-sizing the inverter to be greater than the PV's array power benefits in terms of a cooler-running and long-lifespan of the inverter, but its lead to unnecessary maintenance costs [7]. However, by increase the inverter nominal power up to 80% of the installed PV peak power will contribute the overall system cost increases 2% by supplying extra energy yield increased about 2% according to the study were conducted by *S. Islam et al.* [11]. During optimal inverter-to-PV-array power sizing factor selection, some factors need to be taken into consideration such as distribution of solar irradiation level [7,8,11,12], PV module operating temperature [7,12], inverter maximum current limitation, mounting type [12], orientation of the PV array, and inclination angle of the PV array [11]. Besides that, the inverter-to-PV array power sizing factor represents the size of inverter nominal power with respect to the size of PV array power under STC. By having optimal power sizing factor, the energy yield produced from PV array will not be wasted, unnecessary maintenance costs and various potential failures related could be avoided, thus the reliability and durability of the BOS components will be longer.

The goal of this paper is set to be on the study of impact system design issues and the influence environmental aspects toward the inverter performance. A detailed in-field analysis measurements for the year 2010 on the quarter hour basis was performed. In this paper, the performance analysis on the effect in the outdoor field will be studied and discussed as a case study for reference on accurate sizing procedure in order to know clearly about inverter performances, especially in Malaysia's climate.

II. SYSTEM DESCRIPTION

A. Malaysia Green Technology Corporation

Different capacity of PV array power with three different type of PV cell technologies are separated into six pack system with different location at Malaysia Green Technology Corporation (MGTC) is presented in Table I. All PV system monitored is a building integrated PV (BIPV) type, in which the PV array forms the roof of the building as described in Fig. 1 [13]. This Governmental Office-MGTC Pack B system was launched and operated since 28 June 2007 [14]. A total of 95 units of working modules plus 17 units functioning as dummies for aesthetic reasons were installed for Governmental Office-MGTC Pack B as shown in Fig. 2. The structure of PV modules is mounted to an inclination angle of 5 degrees. The electrical system installation of this GCPV system was conducted by a certified electrician based on the Malaysian Standard: MS 1837:2005 [13].The detail specifications of Governmental Office-MGTC Pack B as a case study is tabulated in Table II below.

TABLE I
GOVERNMENTAL OFFICE -MGTC BUILDING GCPV SYSTEM INFORMATION [13]

System	PV cell technology	Array nominal power (kWp)	Location
Pack A1 Pack A2	Polycrystalline (mc-Si)	47.28	Main roof
Pack B	Amorphous Silicon (a-Si)	6.08	Second main roof
Pack C1 Pack C2	Monocrystalline glass-glass / semi-thru	11.64	Building atrium
Pack D	Monocrystalline (sc-Si)	27.0	Car park roof

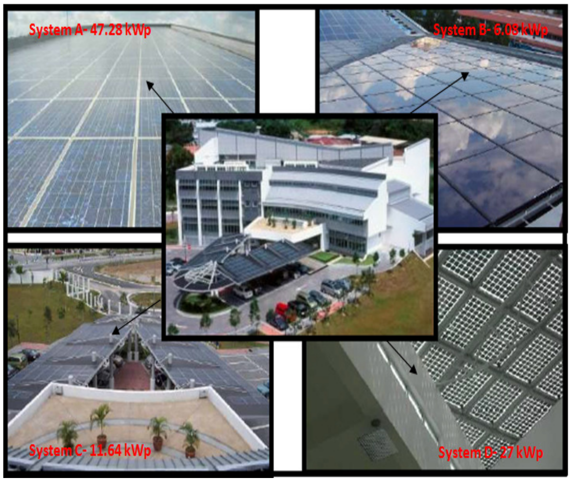

Fig. 1. Governmental Office- MGTC Building, Bandar Baru Bangi, Malaysia.

Fig. 2. Governmental Office- MGTC-Pack B, Bandar Baru Bangi, Malaysia.

TABLE II
GOVERNMENTAL OFFICE- MGTC-PACK B , BANDAR BARU BANGI, MALAYSIA SPECIFICATIONS.

Subject	Specification
PV technology type	Amorphous Silicon (Thin Film)
PV module type	Kaneka GPA 064 (64W)
Array nominal power	6.08 kWp
Inverter type	Fronius IG 60
Inverter nominal power	4600 W_{AC}
Array configuration	19 parallel x 5 series
Pnom_inv/Parray_stc	4600/6080 = 0.76
Vmax_win/Vmp_stc	400/340 = 1.18
Vmin_win/Vmp_stc	150/340 = 0.44
Commissioning date	28 June 2007

III. METHODOLOGY

The monitoring system complies to meet the requirements of IEC 61724 international standard [15] and within the International Energy Agency Photovoltaic Power System (IEA-PVPS) Program Task 2 framework [16]. A silicon irradiation sensor and two PT1000 for temperature sensors were used to obtain the meteorological parameters for the purpose of performance monitoring. These sensors were connected to Fronius IG SensorBox and then the data was transmitted to the integrated datalogger which was embedded in the Fronius inverter. All parameters measured will be displayed on the FRONIUS IG Public Display. For general data acquisition, Fronius datalogger measurement is presented in Table III. The parameters being monitored at MGTC are shown below;

TABLE III
PARAMETERS OF THE MGTC MONITORING SYSTEM.

Electrical Parameter	Meteorological Parameter
DC current, AC current (A)	Total solar irradiance, G (W/m^2)
DC voltage, AC voltage (V)	Ambient temperature, T_{am} (°C)
AC power, P_{AC} (W)	Module temperature, T_m (°C)
Array output energy, E_A (kWh)	

For the given peak power rating of PV array at STC, peak sun hour (PSH) for specific tilt angle and de-rating factors, the predicted energy yield, E_{sys} (kWh) of the system can be obtained by following equation;

$$E_{sys} = P_{array\_stc} \times f_{de\_rating} \times PSH_{pa} \quad (1)$$

The de-rating factor value of inverter-to-PV array power, k depends on the type of PV cell technologies. It is an important parameter that is needed for the sizing purposes. The inverter nominal power, P_{nom_inv} (W) can be obtained by calculating the peak power of PV array at STC, P_{array_stc} (W) multiplying with the value of *k*. The ratio between these two powers is known as "Inverter-to-PV array power sizing factor" and is defined as (2);

$$P_{nom\_inv} = k \times P_{array\_stc} \quad (2)$$

Where the de-rating factor value of *k* is described as the ratio of the inverter nominal power to the PV array power rating at STC, it is very important to determine the appropriate de-rating value for inverter-to-PV array power sizing factor to avoid any power losses in the PV system. An optimal inverter-to-PV array power sizing factor can help to give the best inverter design in terms of averting energy wastage and maintain minimal cost of inverter from over-sizing or under-sizing when comparing with the PV array power [17].

Approximately 25676 continuous data were taken from MGTC- Pack B system with a sampling rate of 15 seconds per sample and to be averaged out in every 15 minutes by utilizing the Fronius datalogger. All data set was collected and analysed for a one year period from January 2010 until December 2010.

IV. Result And Discussion

A. *Solar Irradiance and Temperature Analysis*

The available power generated by PV array output (P_{DC}) depends on the solar irradiance and temperature of the PV site installation. If a higher temperature is detected, the inverter will reduce its output to prevent overheating. During temperature de-rating, the inverter reduces its power output to protect components from overheating. This temperature de-rating only occurs when the cooling is no longer sufficient and can happen for various reasons, e.g. when the PV array and inverter are not well synchronized or when installation conditions interfere with the inverter's heat dissipation [1]. So, it is very important to know the geographical distribution of the solar irradiation level and the operating temperature condition at the specific site before PV installation is implemented. Fig. 3 shows the distribution of in-plane solar irradiance throughout the period monitored.

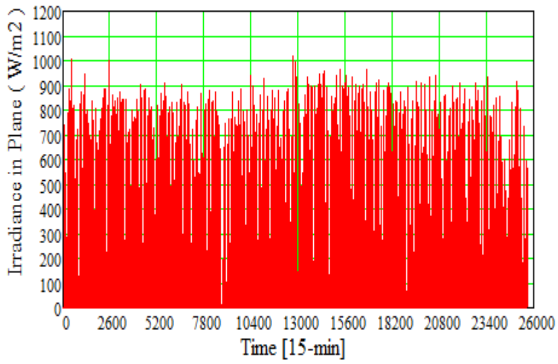

Fig. 3. Distribution of in-plane solar irradiance levels in January until December 2010.

A scatter plot below indicates a linear relationship between the in-plane solar irradiance with the operating PV module temperature. Within one year period's data was observed, it is concluded that the highest solar irradiance was approximately 1018 W/m^2 occurred during the month of August 2010 with the maximum operating PV module temperature recorded 79°C throughout the periods as described in Fig. 4 below.

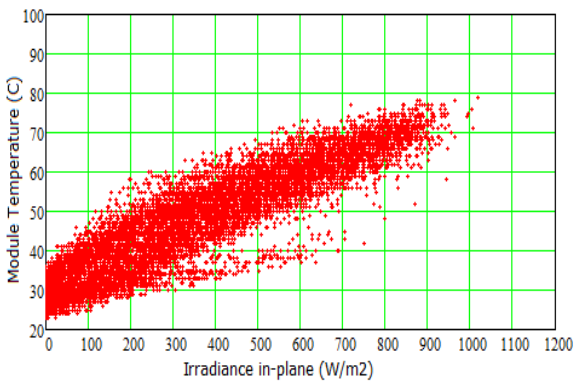

Fig. 4. The relationship between operating PV module temperature and in- plane solar irradiance in 2010.

The process in determining on how many quantity of PV modules in series connection, the operating voltage range of the PV array is identified by checking the highest array voltage using the coldest expected PV module temperature. The lowest operating array voltage is checked by using highest expected PV module temperature to verify that the array voltage limits complies with the inverter operating MPP-voltage range. Referring to Fig. 4 above, the average maximum operating PV module around 71.9°C, while the maximum monthly was measured at 79°C and the minimum about 23°C. The minimum PV module temperature was measured when the inverter wakes up in the morning shows the PV module temperature had not reached less than 20°C throughout the one-year period. So, it is recommended PV module temperature for T_{cell_min} changed from 20°C to 22°C. However, T_{cell_max} = 75°C is maintained because the PV module temperature is higher than 75°C is very uncommon. In current practice in Malaysia's climate, it is recommended that the highest cell operating temperature be set at 75°C. At the lowest cell operating temperature it is recommended to be set at 20°C [17-18], which is widely used in the mornings to ensure the inverter will operate properly and safely at its maximum efficiency and without damaging the inverter in Malaysia's climate condition.

Ambient temperature is one of an important factor in determining the appropriateness of the Grid-connected inverter, chosen in terms of the suitability in ambient operating temperature. In warm and tropical climate, the distribution of the average, maximum and minimum ambient temperature on the selected site location during daylight time is taken consideration especially when the system is supposed to run. Based on Malaysian Meteorological Department (MMD), average daytime for operating ambient temperature in between 24 – 32°C with a lower temperature at night time ranges from 21- 24°C under Malaysia's climate [19]. As illustrated in Fig. 5 below, it can be seen that the maximum ambient temperature at MGTC Building was reached to 44°C and the minimum was 25°C, whereas the average daily operating ambient temperature recorded about 34.8°C, from this site location. Other than that, the average maximum operating ambient around 37.08°C over the period of one- year data were analysed.

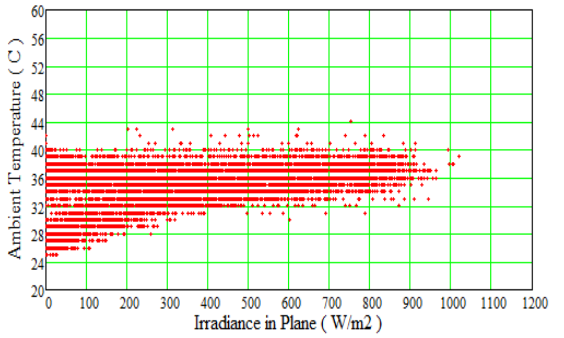

Fig. 5. The operating ambient temperature and in-plane solar irradiance level at MGTC Building in 2010.

B. *Performance of The Operating DC Voltage*

Since the operating voltage range of PV array might be directly applied to grid-connected inverters, the PV array voltage output should be limited below the maximum input DC voltage of the inverter to prevent damage to the inverter [18]. A safety margin of 5% should be calculated for the maximum allowed input window voltage of the inverter to avoid the maximum open circuit voltage, thus no damages to the inverter components [19]. This limitation will cause power losses, since the direct effect of input temperature and solar irradiance will lead the maximum power point (MPP) voltage of the PV array out of the inverter's MPP-voltage range during daytime operation. The input MPP-voltage range of the inverter Fronius IG60 is between 150V – 400V for MGTC- Pack B while the maximum input DC voltage, $V_{max\_inv\_input}$ is about 500V [2]. Since solar irradiance and PV module temperature are fluctuate throughout the day, the current and voltage is injected by PV array also moves significantly, greatly affecting output from the inverter.

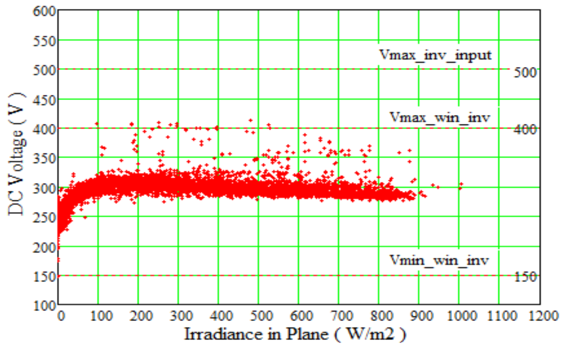

Fig. 6. Measured operating DC voltage and in-plane solar irradiance for MGTC-Pack B.

As can be seen from Fig. 6 represents the operating DC voltage and in-plane solar irradiance in Fronius's MPP-voltage range for the one-year period. Based on the analysis above, what we have seen that some of the data points for actual DC voltage of MGTC- Pack B is not safely operating within the allowable window range of the input MPP-voltage inverter. A small quantity of data points of the operating DC voltage has exceeded the maximum allowable input window voltage of inverter, $V_{max\_win\_inv}$ at various readings of PV module temperature, this meant that it may affected by the rain days or cloud covers as described in Fig. 6 and Fig. 7. If operating DC voltage is higher than the maximum allowable input voltage, the inverter will act to shut down itself to prevent the incoming over-voltage from the PV array. Also, the open circuit voltage, V_{oc_stc} of the PV array should never greater than the maximum allowable input voltage for the inverter to ensure the maximum open circuit voltage will not damage the inverter. Fig. 6 also explains the electrical characteristics of the inverter performance behaviour toward solar irradiance profiles. In the morning, the inverter will start-up automatically whenever DC voltage supply from the PV array is sufficient or reach the minimum allowable input voltage. The initial operating DC voltage supply to inverter quite lower depends on the quantity of solar irradiance level received by the PV array at a particular time. The PV array reduces the operating DC voltage at lower solar irradiances (100 W/m^2 and below). This is a situation when the solar irradiances receives during morning and evening condition. However, the value of operating DC voltage is constant when the solar irradiance is higher. In other word, operating DC voltage doesn't influence by solar irradiance when the value of solar irradiance is approximately 100 W/m^2 and above.

The DC voltage from PV array is affected by PV module temperature. This meant that PV module temperature increases significantly with decreases DC voltage. Thus the combined effect gives a decrease in power output. A scatter plot in Fig. 7 below shows the pattern of operating DC voltage looks tilted when the PV module temperature significantly increases.

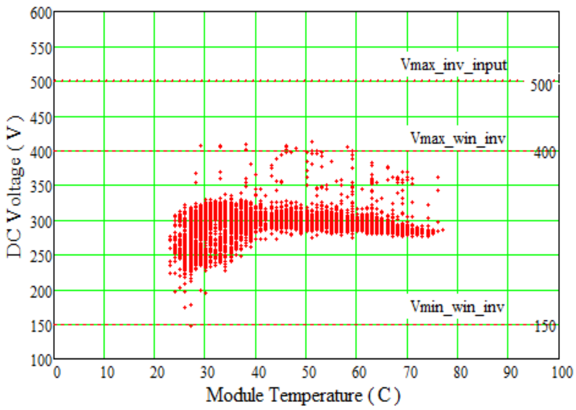

Fig. 7. The relationship between operating DC voltage and PV module temperature at MGTC- Pack B throughout the one-year period.

C. *Performance of The Inverter*

There are several constraints when dealing with selection of inverter such as operating temperature range, peak power rating of the PV array, AC grid frequency and etc. The operating DC voltage of the PV array should fall within the allowable window range of input DC voltage in the inverter during daytime operation. Because the higher input DC voltage may burn the transformer of the inverter, and the lower input DC voltage below the minimum allowable window voltage may not even enough to run the inverter.

The inverter characteristics and actual DC-AC side performances are determined using power-voltage analysis as illustrated in Fig. 8 and Fig. 9. It can be observed that the operating DC power output was operating higher than the inverter nominal power in a few instances. Apart from that, the scatter plot below explains the actual operating DC power with respect to the operating DC voltage and it will be used to determine the actual value of de-rating factor, *k*. In addition, the phenomenon due to clamp power output or inverter clipping had been seen in this case as illustrates in Fig. 8 part A. The disadvantage of under-sizing the inverter power too high is to allow the overheating to the inverter and push the inverter operates at a higher temperature condition [20].

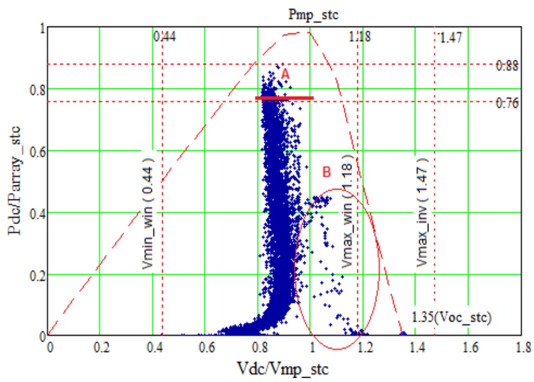

Fig. 8. DC power–voltage characteristic of a-Si thin-film modules before power losses for MGTC- Pack B in 2010.

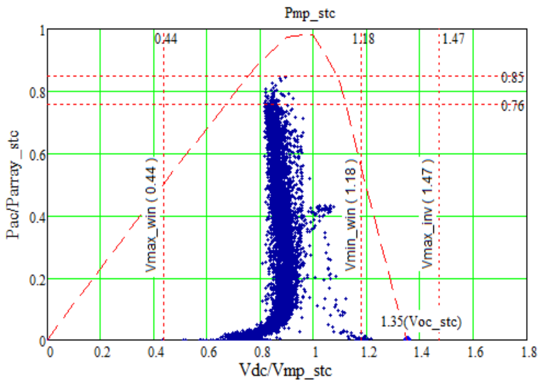

Fig. 9. AC power–voltage characteristic of a-Si thin-film modules after power losses for MGTC- Pack B in 2010.

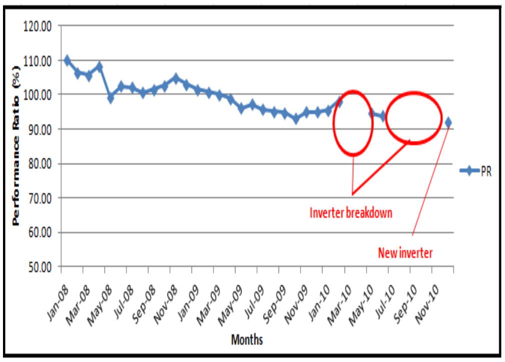

Fig. 10. Monthly performance ratio (PR) for MGTC- Pack B over the monitored period.

Consequently, it will reduce the actual lifespan of the inverter than the warranty period claimed by the inverter manufacturer [2]. Based on calculation design for MGTC-Pack B of a-Si thin-film modules before losses is 0.76 lower than the actual value is around 0.88 in 2010. In other words, the actual value of de-rating factor, k is ~90% after three years operation. So, this meant that the peak power rating of PV array is oversized than the inverter power rating, hence the inverter will clamp the power if the power exceeds than 0.76. If the calculation on designed value is higher than the actual value, it will contribute the wastage on the system cost in terms of the BOS component. However, by appropriate sizing factor of inverter-to-PV array power in optimum way, contributes the inverter operates cooler, longer lifespan, and capture the more energy in the short bursts of extra power generated by the a-Si PV array. Therefore, it is recommended for thin-film modules under Malaysia's climate in between k = 0.9 - 1.1. The optimum system design procedures is the most important to determine the design-quality of GCPV system from any power losses and minimize the system failures. Besides that, it also can be observed the data points mistracking in Fig. 8 part B exceeds by P_{MP_STC}. Due to the inverter clipping power and uncommon higher array voltage comes from DC side push the inverter to produce more heats during its operation, consequently to the inverter resulting a shorter lifespan. In this case, it can be seen that data points mistracking behaviour had been occurred and can be observed in Fig. 8 part B and Fig. 9. As the expected result from clamping power occurred in part A for both DC-AC side and the data points mistracking in Fig. 8 part B exceeded the P_{MP_STC} , the present key findings of this study shows a new replacement of Fronius inverter after three years monitoring performance according to inverter damage in the November 2010.

Fig. 10 also demonstrates the inverter failures had occurred. No data being recorded in data collection system in March and April 2010, and August until November 2010. The MGTC-Pack B system was inoperative for six months in year 2010 due to inverter faults as an early sign phenomenon before a new inverter is replaced in the December 2010 during the three years monitored. Besides that, system performance of the monthly performance ratio (PR) is also depicted in Fig. 10 to show that the performance ratio ranged from 110.2% to 101.5% in the beginning 2009 whereas a second year operation, the values varied from 95.5% until the end of December 2010 with 92.1% of the performance ratio over the monitored period. After the 16-

month installation, the PR values had decreased drastically above 100% according to the "initial module power stabilization" effect before it exhibit a stable performance [8,21,22]. This effect usually happens in thin-film modules characteristics, which are expected to degrade and then stabilized with respect to the time.

V. CONCLUSION

As a conclusion, improper sizing and design such as T_{cell_max} , T_{cell_min} , MPP-voltage inverter range and incorrect de-rating factors, $f_{de\text{-}rating}$ for k value especially in Malaysia's climate for thin-film PV technologies affected the inverter lifespan. Through our observation at MGTC-Pack B as a case of study, the Fronius inverter needed to be replaced after three years of monitoring period due to the effect of inverter's MPP-voltage and inappropriate of the $f_{de\text{-}rating}$ used. During initial design stage, the designer often does not consider the input DC voltage that should fall into an admissible of the inverter's MPP-voltage range. Selection inappropriate both input, e.g. solar irradiance and temperature parameters, will significantly impact the sizing PV array and inverter respectively. So, it suggested a minimum expected PV module temperature for T_{cell_min} changed from 20°C to 22°C. However, T_{cell_max} = 75°C is maintained because the measured operating PV module temperature is higher than 75°C is very uncommon for BIPV application in Malaysia. These issues are highlighted and needed more attention for designing GCPV system and determining the performance of the inverter. If inverters operate under normal condition and adequate ventilation cooling, the inverter manufacturers generally offer their product warranty of 5 up to 20 years of inverter lifespan [23]. Nevertheless, the lifespan for both inverter types, i.e. central and string strongly dependent on the environmental conditions, mainly operating ambient temperature and the solar irradiance distribution level at PV installation site. The appropriate criteria selection and optimum design-quality will give the overall PV performance system installed in good performance in terms of durability and durability of the system. Furthermore, by sizing a proper system design and accurate sizing procedures for every component used, contributes to the higher power output of GCPV system. In addition, the inverter will give better performance when operating closer to its rated power rather than exceeded from its rated power. Oversized and undersized inverter rated power sizing had also been considered to match PV array and inverter in order to ensure the GCPV system is optimized and reliable. Typically, thin-film modules exhibit higher initial degradation in the power level in the first installation before reach their stabilized period [24-25] and thin-film PV module manufacturers often do not give precise indications. So, the system designer need to take consideration on the thin-film modules behavior and characteristics especially installation in warm and hot climate. For recommendation, optimal de-rating factor of k for thin- film modules ranges from 0.9 to 1.1. This power-voltage analysis approach would help to the inverter-to-PV array power sizing factor for design task of a GCPV system installation. Besides, needed long-term monitoring period and more data on the GCPV systems under Malaysia's climate.

VI. NOMENCLATURE

G_I	Total solar irradiance on the plane of the PV array, in W/m^2
P_{array_stc}	Nominal power of the PV array at STC, in kWp
P_{nom_inv}	Nominal power output of the inverter, in W
E_{sys}	Expected annual energy output, in kWh
$f_{de\text{-}rating}$	Reduction factor for array output, dimensionless
T_{cell_max}	Expected maximum effective cell temperature of the PV array, in °C
T_{cell_min}	Expected minimum effective cell temperature of the PV array, in °C
$V_{max\_inv\_input}$	Maximum input DC voltage of the inverter, in V
$V_{max\_win\_inv}$	Maximum allowable input window voltage of the inverter, in V
$V_{min\_win\_inv}$	Minimum allowable input window voltage of the inverter, in V
V_{oc_stc}	Open circuit voltage at STC, in V
V_{mp_stc}	Voltage at maximum power at STC, in V
P_{mp_stc}	Maximum power at STC, in W

VII. SUBSCRIPT

STC	Standard Test Condition
BOS	Balance-of-System
MPP	Maximum Power Point

MGTC	Malaysia Green Technology Corporation
MMD	Malaysian Meteorological Department
UNDP	United Nations Development Programme

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