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Health Performance Assessment of Grid-Connected PV Systems using Safe Operating Area Concept

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ABSTRACT

The efficacy of a safe operating area (SOA) concept in assessing and sizing PV arrays with the inverter is highlighted in this paper. With substantial input data and using Mathcad's coding and some information derived from the inverter manufacturer, enables us to generate the SOA curve. Most of the simulation software, which is frequently offered on the commercial market by big solar firms, focuses on the early stages of designing and sizing, weather data information, as well as economic benefits. Dissimilar from other providers, the system integrators can effectively verify the current design using this concept, and it is also able to recognize the uncertainty behaviour that emerges during system operation. Concerning PV module technology, capacity size, and uncertainty in system behaviour, three different case studies have been chosen to verify the SOA concept and effectively demonstrate the SOA curve's ability to diagnose and correct system health. The findings also demonstrated some unpredictable behaviour, such as two cases exposed to undersized inverters that create clamping events due to inverter saturation and allow new adjustments to the configuration setups, while one oversized case when it has been verified by the SOA concept. Moving closer to the limit boundary of the SOA curve makes it more cost-effective to operate optimally and maximizes the system's production with its maximum characteristics.

1. Introduction

In real scenarios, it is common practice to implement a de-rating factor for a photovoltaic (PV) array to align its capacity with the size of the inverter. Even though in the field, PV modules might operate with higher irradiance and the cell temperature is higher than standard test conditions (STC).

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Consequently, ensuring the appropriate dimensioning and sizing of the PV array to the inverter is a matter of utmost importance [1,2].

Inverter saturation, commonly referred to as “clipping”, takes place when the power generated by the PV array surpasses the maximum input power capacity of the inverter, resulting in the loss or "clipping" of a portion of the PV power [3-5]. Nowadays, technological advances in the new era of PV modules such as PERC or half-cut cells and bifacial (bPV) modules present many advantages [6]. Modern PV modules come with added advantages like increased energy output, diminished shading effects, low-light conditions, and a reduced occurrence of hotspots [7,8]. Nevertheless, if an existing system is grappling with clipping problems due to inadequate dimensioning or sizing, these issues can significantly impede energy production [9-12]. Other than that, some researchers stated that the influence of environmental factors such as the distribution of solar irradiance, surrounding temperature, DC:AC ratio, cloud enhancement, and shaded factors, also give significance to this issue [11,13-16]. To address this situation, the inverter typically acts by modifying the DC voltage to reduce the DC power output. This adjustment involves raising the operational voltage beyond the Maximum Power Point (MPP) voltage, effectively decreasing the DC current. It's worth noting that while the majority of grid inverters such as string and central inverter topologies have this self-limiting capability, not all designers keep the array input voltage below the inverter’s maximum limit.

Many researchers discussed great techniques for sizing PV arrays with the inverter using several indicators such as PV/inverter or DC/AC ratios, current-voltage curve, power such as AC power versus irradiance, DC power limitation, and uncertainty factors [3-5,14,15,17-28]. However, it's noteworthy that their focus predominantly centres on the overall system, with none of the articles focused on the operation of the inverter operation itself. Since a grid inverter plays an important role in transforming DC power into AC power and feeding it directly to the grid, therefore studying on how the PV power interacts with the inverter as specified by the manufacturer can give confidence that the system works safely and economically [4]. Certain datasheets specified in the inverter’s datasheet are not fully discussed in detail by the manufacturers, particularly regarding the maximum limits of these parameters. Sometimes it is a misconception to interpret the meaning of maximum input DC current and maximum input DC voltage by assuming that the inverter should operate up to those limits at any condition. Relying on the maximum DC current to determine the maximum number of PV strings is not the correct way to design. Likewise, it's essential to note that the maximum DC voltage of the inverter should not be the sole parameter considered when establishing the number of PV modules in a series configuration.

To maximize the power output from the PV array, it's crucial to consider both factors when determining the module configuration of the PV array's power capacity. This paper emphasizes that the maximum power of the designed PV array should consistently remain below the maximum input DC power of the inverter, a concept that will be thoroughly explored in the subsequent discussion. This study sought to quantify the clipping issues using a Safe Operating Area (SOA) curve as a result of inverter saturation at a resolution of 5 minutes for PV arrays and inverters installed in Malaysia.

2. Methodology

Three types of PV module technologies, including mono-crystalline silicon, poly-crystalline silicon, and thin-film amorphous silicon, were investigated. Each of these systems was installed at locations with nearly identical latitudes and tilt angles, under similar climates. Detailed information about the system is tabulated in Table 1.

Table 1
Three different types of the installed GCPV system

Description	A	B	C
PV Module Technology	Poly-crystalline	Mono-crystalline	Thin-film amorphous
Mounting System	Retrofitted	Retrofitted	Free-standing
Capacity (kWp)	6.0	10.0	0.9
Array Configuration	2p x 13s	2p x 20s	5p x 3s
Max. input DC current (A)	15/15	33/12.5	12.6/12.6
MPP voltage (V)	125/175...440	150/320...800	100…320
Max. input voltage (V)	550	1000	400
Max. input DC power (W)	5300	8200	1320
Efficiency (%)	97	98.1	92.1

In general, all electronic components have their safe operating area. Operating the devices within the SOA limit keeps the devices in a safe condition and prolongs their lifetime. Since advanced grid-connected photovoltaic (GCPV) inverter comprises numerous electronic components and power-switching devices, it becomes important to determine its SOA. Usually, the SOA is not highlighted in many inverter manufacturers' datasheets and the standard data given by the inverter manufacturer is the limit of electrical parameters such as voltage, current, and power. Those limits are used to plot the SOA curve of the inverter. A typical SOA of a GCPV inverter formula, as shown in Figure 1, is plotted using MathCad software according to the following Eq. (1):

$$V\_dc_j := \frac{Pac\_inv\_max}{C\_dc_j \times Eff\_inv} \tag{1}$$

Where *Eff_inv* and *Pac_inv_max* can be found in the inverter's datasheet. In addition, DC current, j can be ranged from $j := 1 \cdots 60000$. Noted that, if the DC current is more than 60 A, then adjust j accordingly.

$$C\_dc_j := \frac{j}{100} \tag{2}$$

Utilizing from Eq. (1), the DC voltage conditional statements are written as;

$$V\_dc_j := \begin{cases} V\_dc_j \ if \ V\_dc_j < Vmax\_inv \\ Vmax, \ \ otherwise \end{cases} \tag{3}$$

$$V\_dc_j := \begin{cases} V\_dc_j \ if \ C\_dc_j < C\_dc\_max\_inv \\ 0 \qquad otherwise \end{cases} \tag{4}$$

The conditional statement of DC current needs to be set as Eq. (5);

$$C\_dc_j := \begin{cases} C\_dc_j \ if \ C\_dc_j < C\_dc\_max\_inv \\ C\_dc\_\max \ \_inv \qquad otherwise \end{cases} \tag{5}$$

The SOA is an area where the PV array operates safely with the inverter. In practice, it's more economical to design a PV array with its maximum characteristic close to the SOA curve limit boundary.

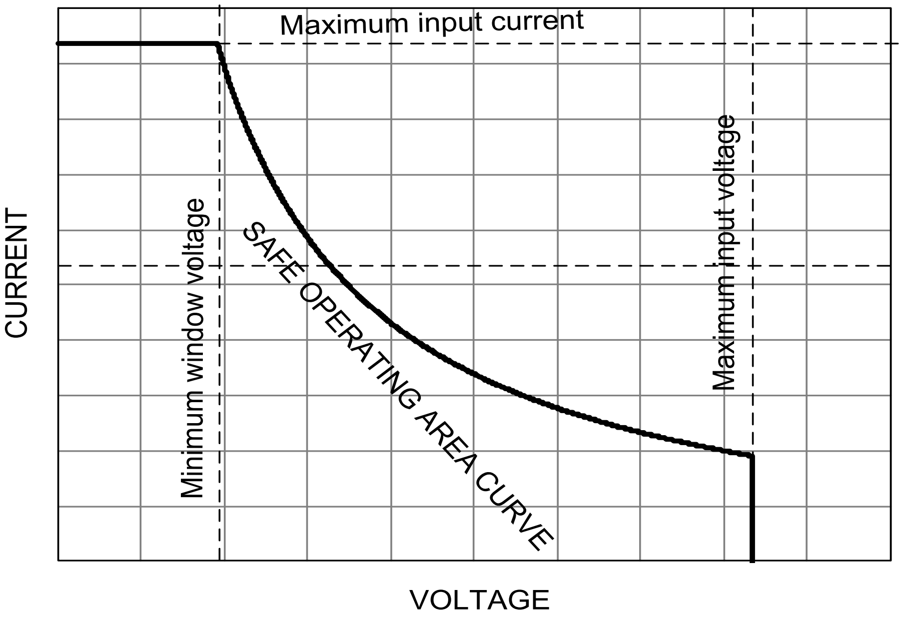

Fig. 1. A typical SOA of a grid-connected inverter

Referring to Figure 1, although the inverter manufacturer states that the maximum limit of *Idc_max* in the datasheet, the actual current is dependent on the PV string voltage and has an exponentially decreasing relationship. It is common practice to design a string operating voltage to be in the middle of the inverter window voltage, but the actual current flow through an inverter is limited to almost half of the maximum current specified in the datasheet.

Several recommendations should be considered, where it is very important to take precautions against two extreme regions, such as the maximum input voltage and the maximum input current as stated in the inverter specifications. In addition, most inverter manufacturers warn either in datasheets or instruction manuals to avoid system integrators sizing or designing PV string voltages above the maximum input voltage. If it exceeds a certain limit, it might permanently damage the inverter. Last, but not least, most grid-connected PV inverters are current source inverters, where the inverter clamps any excess DC current to its maximum limit.

3. Results

In this section, the first two years of operation of the inverters with sufficient rated power during exposure to the elements showed little effect on the inverter's performance. As a case study, three GCPV systems were investigated. The case study is divided into three subsections.

3.1 Case Study 1 - Poly-crystalline PV Module Technology

For Case 1, the array configuration is 2p x 13s using poly-crystalline PV module technology and SB 5000TL-20. Figure 2 shows that the inverter is undersized where the inverter clamps the current and limits it up to the SOA curve. By looking at the graph below, it is obvious that the inverter clamps the current at 16 A when the string voltage is approximately 350 V. Based on the inverter datasheet, it states that the maximum input DC current is 15 A (input A: 15 A and input B: 15 A). This means that the grid inverter will limit the current harvested by the PV array.

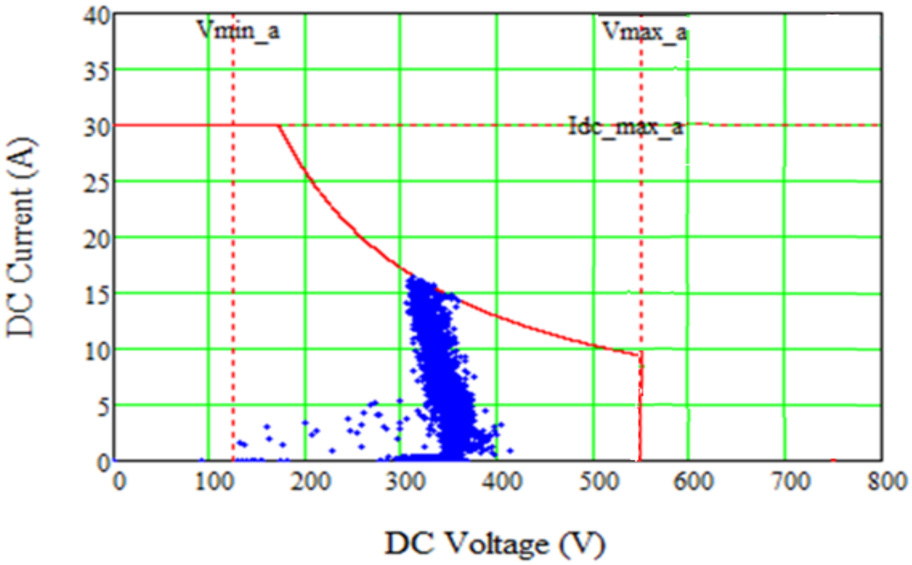

Fig. 2. The actual relationship between DC current and DC voltage is based on system A with an SB5000TL-20 inverter (2p x 13s)

This limitation should be avoided as a result of power loss, and consequent loss of return on investment (ROI). The clamping current also gives inaccurate information regarding the system yield and performance ratio. The system could be improved by shifting the blue dots to the left by reducing the number of PV modules in the series connection. To prevent the SB5000TL inverter's current clamp, it is suggested to reduce the total installed array power by arranging the new array configuration.

In Figure 3, the array power generation can be harvested up to 13.3%, however, the power clipping limit is found at 5,300 W. That means the inverter always operates at full capacity during peak irradiance levels. This issue can be detected when using the SOA curve related to the inverter/PV ratio during the sizing stage.

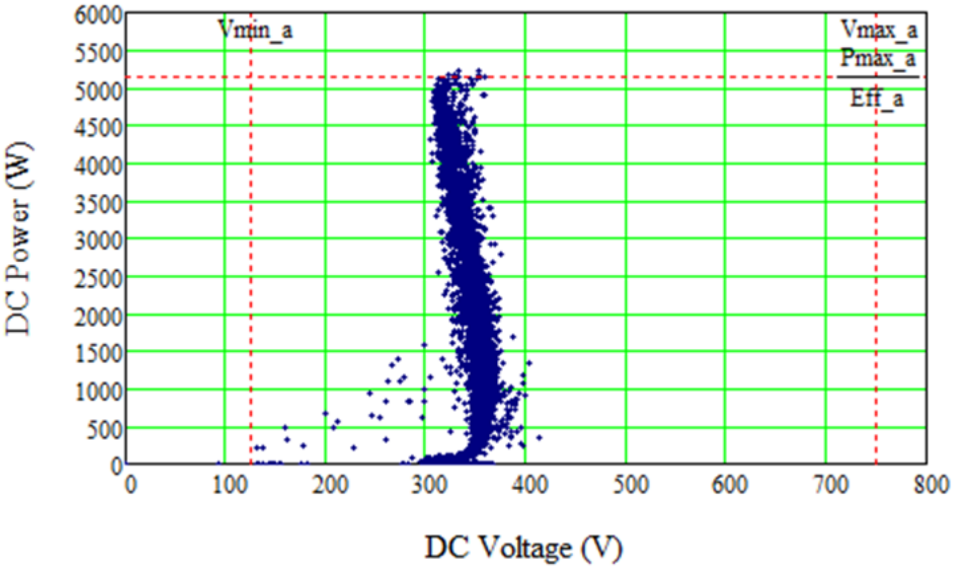

Fig. 3. Input power to the inverter using poly-crystalline PV module technology

Subsequently, a new arrangement was made due to this issue, where the new array configuration for string 1 is 1p x 12s and 1p x 11s for string 2 (5.405 kWp). It can be seen in Figure 4, where DC current shows normal operation after the new adjustment has been made.

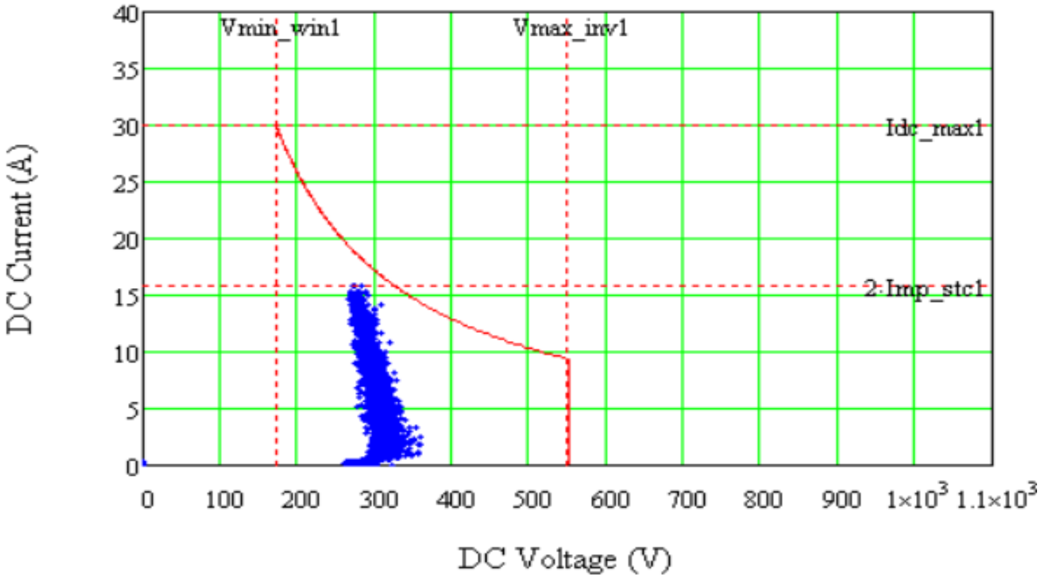

Fig. 4. The actual relationship between DC current and DC voltage after new array adjustment (string 1: 1p x 12s and string 2: 1p x 11s)

3.2 Case Study 2 –Mono-crystalline PV Module Technology

For Case 2, the array configuration is 2p x 20s using mono-crystalline PV module technology and STP8000TL-10. From Figure 5, this SOA shows the occurrence of excessive current clamping by the inverter. It can be said that the design of the inverter/PV ratio is undersized. The inverter clamps the input current at 16 A when the string voltage is approximately 500 V. Although the inverter datasheet states the maximum current is 33 A (input A: 22 A and input B: 11 A).

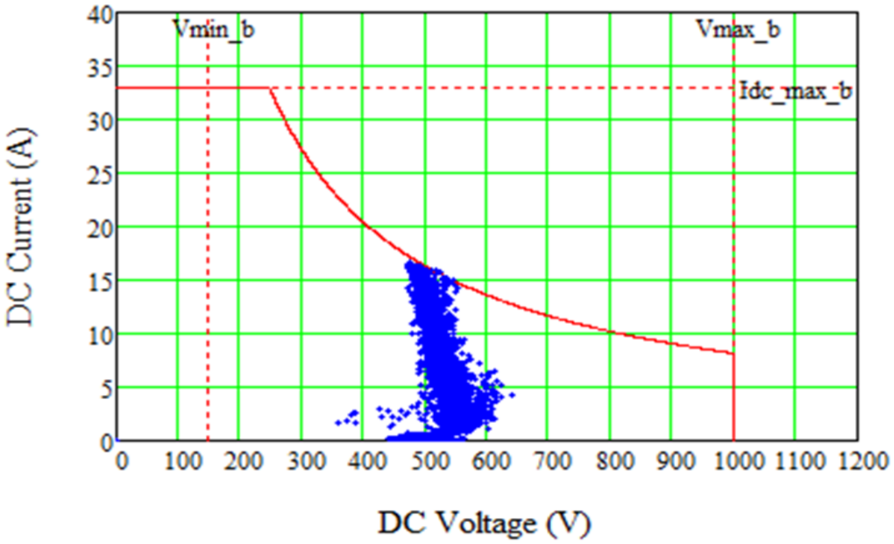

Fig. 5. The actual relationship between DC current and DC voltage is based on system B with an STP8000TL-10 (2p x 20s)

In terms of power generation versus voltage, it's evident that DC power experiences an approximately 18% reduction, equivalent to roughly 8,200 W during the peak irradiance level, as illustrated in Figure 6. This occurrence can significantly hamper energy production, potentially affecting the owner's return on investment and shortening the inverter's lifespan.

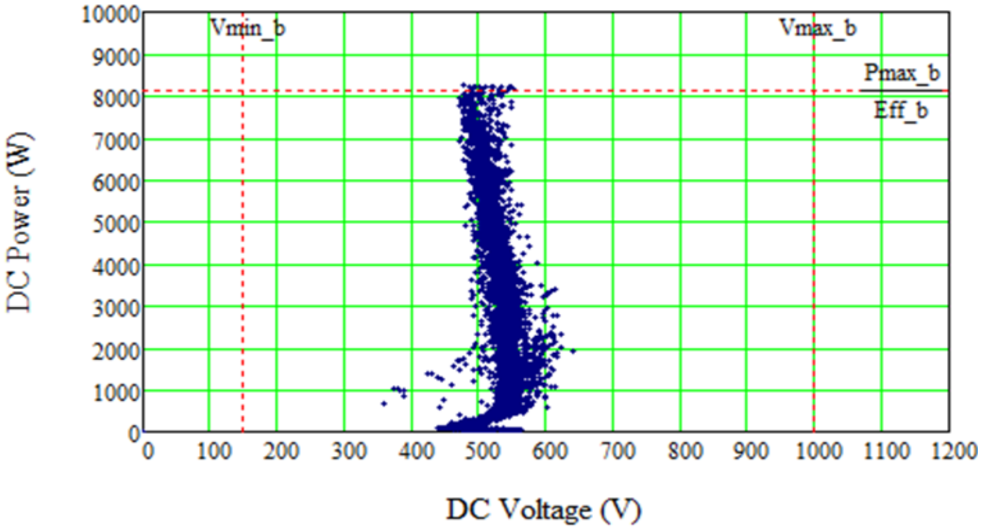

Fig. 6. Input power to the inverter using mono-crystalline PV module technology

As previously discussed, the system faced clamping issues with the old array configuration of 2p x 20s. After implementing the new adjustment, the array configuration was modified from 20 to 18 modules, resulting in a total power capacity of up to 9.0 kWp. Notably, the clamping of DC current has been resolved with this adjusted configuration, 2p x 18s as depicted in Figure 7.

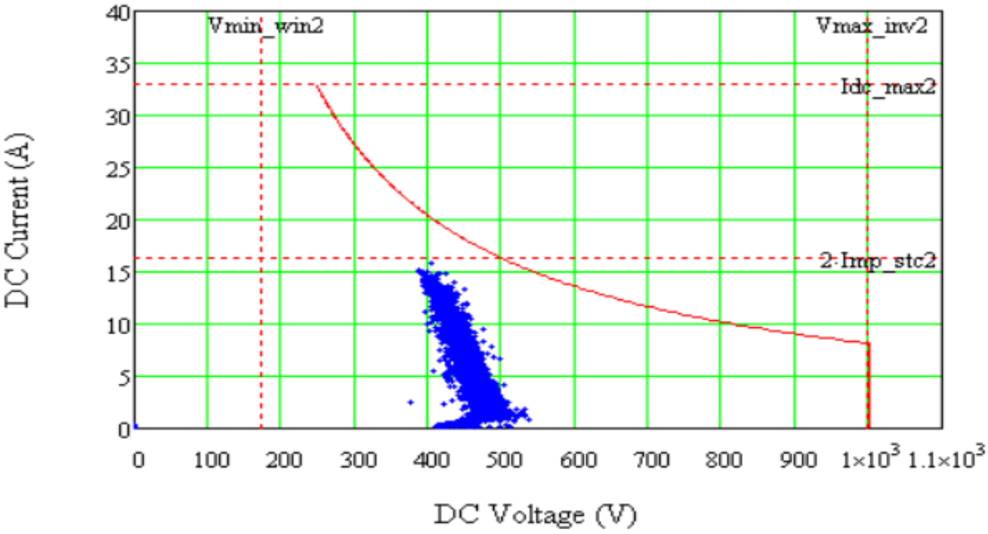

Fig. 7. The actual relationship between DC current and DC voltage after new module adjustment (2p x 18s)

3.3 Case Study 3 –Thin-Film PV Module Technology

For Case 3 (thin film), the maximum input DC current is 12.6 A according to the inverter datasheet. As shown in Figure 8, the peak DC current of the thin-film GCPV system operates safely within the SOA curve limit boundary at 6.0 A. The designed system was demonstrated to be lower than the rated DC current; hence, the design inverter is oversized by 24.2%.

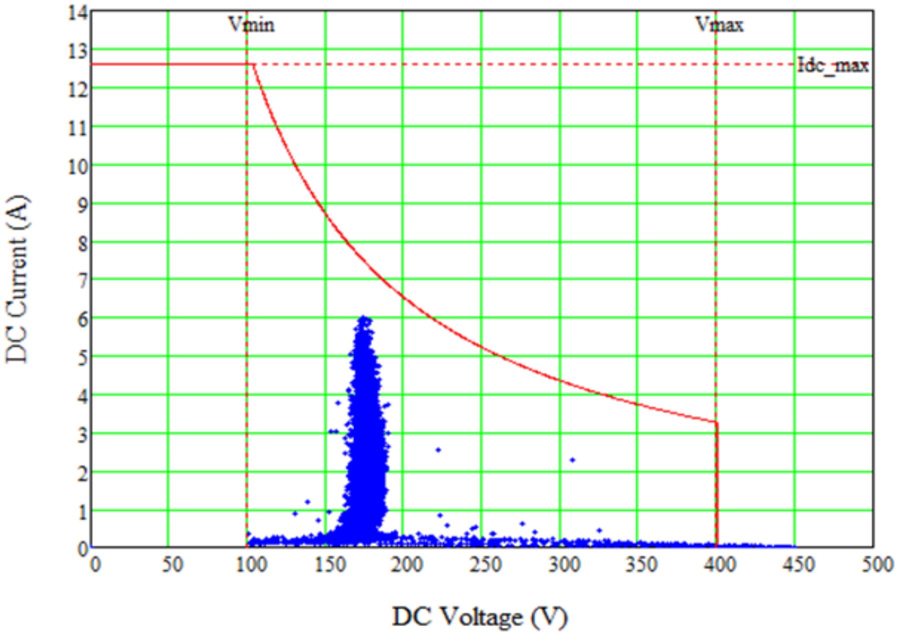

Fig. 8. The actual relationship between DC current and DC voltage is based on system C with an SB1200 inverter

Based on the findings, a few thin-film PV modules can be added in series until the peak voltage is very close to the power limit boundary, as shown in Figure 9. Consequently, when PV modules are added in series, the power increases and should be close to *Pdc_max* to optimize the system. However, it should consider the nature of metastable behaviour due to light-induced degradation (LID) in the design of thin-film systems, as recommended by the previous studies [1,29].

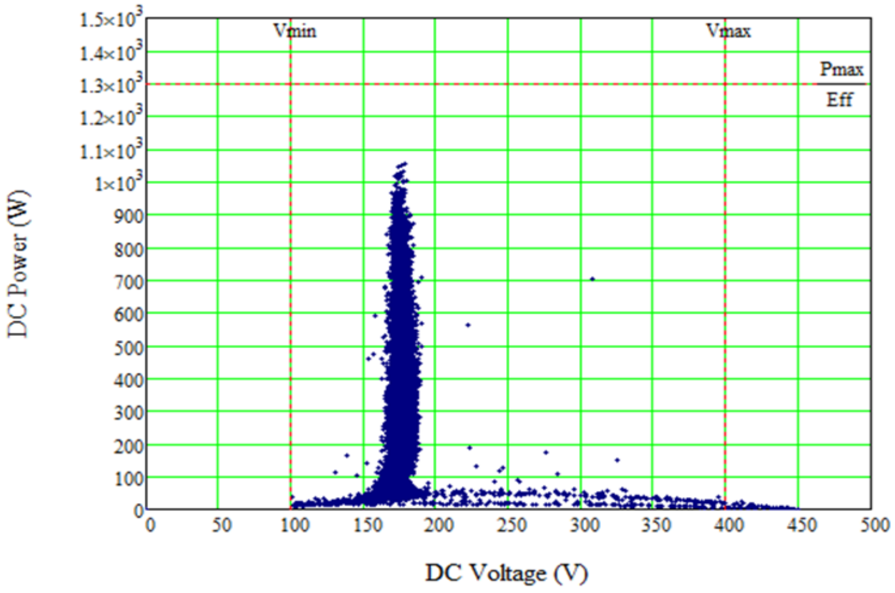

Fig. 9. Input power to the inverter using thin-film PV module technology

3.4 Comparative Case Studies for Outdoor Performance

Based on the results obtained, two cases involving crystalline types have encountered clipping issues due to the PV array exceeding the rated power rating of the inverter. Consequently, new adjustments have been made concerning the PV array configuration. For case 3, the PV array is undersized than the rated power rating of the inverter, an optimal performance can be achieved by adding 5 additional PV modules. This results in a recommended array configuration of 5p x 4s, yielding approximately 1.2 kWp. However, it is worth noting that the thin-film module brand used in this case is now obsolete and no longer in production by the manufacturer. A comparison of the three investigated cases is summarized in Table 2.

Table 2
Summary of three different cases of the installed GCPV system

Description	Case 1	Case 2	Case 3
Old Array Configuration	2p x 13s	2p x 20s	5p x 3s
Dimensioning & Sizing	PV Oversized	PV Oversized	PV Undersized
Issue	Clipping	Clipping	NA
Value %	13.3%	18%	24.2%
New Array Configuration	1p x 12s and 1p x 11s	2p x 18s	5p x 3s
New PV capacity (kWp)	5.405	9.0	0.9

4. Conclusions

The health performance of GCPV inverters for three cases was analyzed. The obtained results have shown that these inverters restrict excessive DC current, even when it remains below their rated maximum input current. This behavior aligns with the inverter's Safe Operating Area (SOA) limits. The negative consequences of oversizing PV arrays are evident, particularly in crystalline-type systems, where losses of 13.3% and 18% were observed due to limited power transfer to the grid. Similarly, oversizing inverters by 24.2%, especially in thin-film systems, proves to be uneconomical in the context of long-term investment. To ensure optimal performance and safety, it is crucial to dimensioning and sizing systems that ensure a proper match between the PV array and inverter, keeping them within their respective safety limits. This approach has been successfully demonstrated in three case studies employing different PV module technologies, all validated using the SOA curve within the Malaysian environment. These results can be used to rectify and diagnose the health of the GCPV system, which requires further detailed explanation. With huge investments in boosting solar PV programmes such as FiT, NEM, and SELCO, this inverter issue needs to be scrutinized.

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