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OPTIMAL INVERTER SIZING RATIO FOR PHOTOVOLTAIC POWER PLANTS IN MALAYSIA

Keen-Yip Lai[1], Boon-Han Lim[1*]

1 Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Bandar Sungai Long, Kajang, Selangor, Malaysia

ABSTRACT

Undersize the capacity of a solar inverter is a common practice in the industry to reduce capital expense. However, the optimal inverter sizing ratio (ISR) is a site- and system-dependent value. It can vary from 1.0 to 2.2, globally. So far, there is no study on the optimal ISR for photovoltaic (PV) power plants in Malaysia. The industrial practice assumes that the ISR is either the inverse of the performance ratio of the system or value of experience design from other countries, which do not share the same climate. In this paper, a generalised method, which separates the system-dependent and non-system-dependent values, is used to find the optimal ISR for eight different geographic locations in Malaysia. The chosen sites are distantly distributed and have different annual solar irradiation. Hourly solar irradiance data is used to find out the power clipped by the undersized inverter during high solar irradiance period. In addition, the simulation also considers the inverter can be overloaded to 110% of its rated capacity, which is a common specification of an inverter nowadays. This feature was not considered in other research articles. The optimal ISR for the eight sites, which was obtained based on the lowest the levelised cost of electricity (LCOE), falls within 1.475 to 1.525. The optimal ISRs show a strong linear correlation with the annual solar irradiation of the sites. The information is useful for the local industry to optimise the LCOE for their project quickly.

Keywords: inverter sizing ratio, photovoltaic, solar irradiance, tropical region, grid-connected, inverter size

1. INTRODUCTION

Inverter plays a vital role in a grid-connected photovoltaic (PV) power plant. Its primary function is to convert the generated power in the direct current (DC) form to the alternate current (AC) form. The price of an inverter is usually quoted in dollars per watt. Therefore, the larger the total rated power (called size, but not the physical size) of all inverters, the higher the capital expense of a PV power plant and thus the higher the levelised cost of electricity (LCOE) for the energy generated. During designing a PV power plant, the inverters are usually undersized as compared to the PV plant DC rated capacity, to reduce the capital expense. This technique is allowed if the solar irradiance of a site is mostly less than 1000 W/m^2 [1-2]. Besides, the operation of a PV system is subjected to various performance losses, especially loss due to the temperature effect [3]. Therefore, the performance ratio (PR) is usually less than 0.85 in Malaysia. As such, even if part of the solar irradiance is more than 1000 W/m^2, undersized is still possible for reducing the LCOE. When the input power of the inverter is beyond the maximum input power of an inverter, the inverter will clip the input power and maintain the output power at its maximum value. The loss of income due to the total clipped energy might be less than the cost saved from the undersized inverter.

Since the inverter rated power can be smaller, a specific term called “inverter sizing ratio” (ISR) is used to indicate the ratio of the DC power capacity of the PV array to the AC power capacity of the rated output power of an inverter. The optimal ISR for a PV power plant is affected by many parameters such as characteristic of solar resources, the PR of the system, the efficiency characteristic of an inverter [4, 5] and the performance

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degradation of the solar panels [1]. Consequently, the optimal ISR is site- and system-dependent. Optimal ISR has been discussed for a few countries [1-2, 6]. The optimal ISR varies from 1.6 to 2.2 for the cases in Finland [1]; 1.0 and 1.49 for the cases the United States, respectively [2]; 1.5 for a case in Goiania, Brazil [6]. However, there is no such study for the scenario in Malaysia, where the tropical solar irradiance distribution profile is unique.

For the PV industry in Malaysia, the ISR is recommended based on no power clipping during operation. As such, the ISR is assumed to be the inverse of the performance ratio [7], in which the ISR usually falls between 1.1 to 1.2. Otherwise, some designer may simply follow the ISR value of experience design in other countries which do not share the same climate. Owing to the rapid growth of large-scale solar power plants in Malaysia, as well as significant price declination of solar panels, it is essential to investigate the optimal ISR for this region. Nevertheless, an inverter can be overloaded to 1.1 times its rated capacity, which is a common specification of an inverter nowadays. This feature has not been considered in research articles yet [1-2, 5-6].

In this paper, a generalised method is used to quantify the clipped energy by undersized inverters for eight sites in Malaysia. Then, optimal ISRs are obtained based on the lowest LCOE. The values of optimal ISR can be an industry guideline for optimisation of the return of investment. The generalised method allows the readers to adopt the optimal ISR quickly and flexibly to their design, rather than struggling too much on the system-dependent parameters.

2. METHODOLOGY

2.1 Scope

The scope of this method focuses only on crystalline-silicon PV module because this type of PV module is popular in Malaysia. Besides, the PV power plant is of large-scale with open-air ground-mounted structure because this type of plants has very competitive bidding tariff and therefore ISR is critical. Also, the total capacity for this type of plants is rapidly increasing and could be the dominant type in Malaysia soon.

2.2 Calculation

The daily alternate current (AC) energy yield of a PV system, E_{AC_N} can be calculated as the following:

$$E_{AC\_N} = \sum_{t=0}^{t=23} [D \times (P_{PV} \times PR(t) \times G_{tilt}(t))] \quad (1)$$

where P_{PV} is the capacity of the PV system; $PR(t)$ is the performance ratio at the corresponding time, t; $G_{tilt}(t)$ is the global tilted solar irradiance received by the solar panels at the corresponding time, t; D is the duration for the discrete value of the output power. In this paper, the solar irradiance data for eight different geographic locations are obtained from PVGIS [8]. The chosen sites are distantly distributed and have different annual solar irradiation. For each site, 12 years of $G(t)$ from 2005 to 2016 are obtained and then the solar irradiances for different years but at the same corresponding time are averaged out. Since the data is in hourly format, t is in the one-hour interval, starting from 0 to 23, and D is equal to one hour.

In a PV system, the $PR(t)$ is aggregated by many derating factors or performance losses within the system. They are near shadings irradiance loss, incident angle modifier (IAM) factor loss, soiling loss, PV loss due to irradiance level, PV loss due to temperature, module quality loss, light-induced degradation (LID), module array mismatch loss, Ohmic wiring loss, inverter conversion loss, inverter loss over nominal inverter power, inverter loss due to threshold and night consumption loss. For each PV system design, the values for each type of losses are different and make the $PR(t)$ a design dependent parameter. Nevertheless, these losses can be classified into two groups for analysis of optimal ISR. Some of the losses are relatively “fixed” or less affecting the PR during power clipped such as Ohmic wiring loss, soiling loss etc. On the other hand, inverter conversion loss and PV loss due to temperature effect affect whether the inverter will clip the power during high solar irradiance conditions. Inverter conversion loss depends on the loading factor of an inverter while PV loss due to temperature primary depends on the solar irradiance and the ambient temperature. As such, $PR(t)$ can be re-written as the following:

$$PR(t) = PR_{fixed} \times \eta_{inv}(l) \times f_{temp}(t) \quad (2)$$

$$f_{temp}(t) = 1 + \gamma(T(t) - T_{STC}) \quad (3)$$

where $\eta_{inv}(l)$ is the inverter conversion efficiency based on the loading factor of the inverter. The loading factor of the inverter is the instantaneous input power of the inverter to the rated power of the inverter. $f_{temp}(t)$ is the derating factor for a PV module due to temperature, γ is temperature coefficient for power for the PV module, $T(t)$ is the instantaneous module temperature, and T_{STC} is the reference temperature given in the Standard Test Conditions (STC), i.e., 25 °C.

The module temperature, *T(t)* is calculated using the Ross coefficient [9] measured for the tropical climate and ambient temperature, $T_{amb}(t)$. As such, *T(t)* can be written as the following:

$$T(t) = T_{amb}(t) + G_{tilt}(t) \times \mathrm{C}_{Ross} \qquad (4)$$

where C_{Ross} is the Ross coefficient.

Combining **Eqn (1)** to **Eqn (4)**, the instantaneous output power, $P_{AC\_exp}(t)$, without any power clipping at the time, *t*, can be written as the following:

$$P_{AC\_exp}(t) = P_{pv} \times G_{tilt}(t) \times PR_{fixed} \times \eta_{inv}(l) \times \{1 + \gamma[(T_{amb}(t) + G_{tilt}(t) \times \mathrm{C}_{Ross}) - 25°\mathrm{C})]\} \qquad (5)$$

However, power will be clipped by an undersized inverter at high solar irradiance if $P_{AC\_exp}(t)$ is greater than the maximum AC output power of an inverter, P_{AC_max}. Nowadays, P_{AC_max} of branded inverters is usually designed to be 1.1 times larger than the rated power, P_{AC_rated} of the inverter [4]. This factor is incorporated in the simulation for this paper, and it is estimated to increase the value of optimal ISR. Hence, the actual output power of the PV system, $P_{actual}(t)$ is:

$$P_{actual}(t) = \begin{cases} P_{AC\_exp}(t) & \text{for } P_{AC_{\exp}}(t) < \mathrm{P}_{AC\_max} \\ \mathrm{P}_{AC\_max} & \text{for } P_{AC_{\exp}}(t) > \mathrm{P}_{AC\_max} \end{cases} \qquad (6)$$

$$\mathrm{P}_{AC\_max} = P_{PV} \div ISR \times 1.1 \qquad (7)$$

where $ISR = P_{PV}/P_{AC\_rated}$.

Subsequently, the daily energy yield with occasionally clipped of output power, $E_{AC\_N\_actual}$, can be obtained by modifying **Eqn (1)** to become the following equation:

$$E_{AC\_N\_actual} = \sum_{t=0}^{t=23}[D \times P_{actual}(t)] \qquad (8)$$

Then, the yearly energy yield is calculated by summing up all the daily energy yield. However, for a different year, the generation is subjected to the degradation of the PV module. Therefore, the energy yield, $E_{AC\_y\_actual}$ for a specific year, *y*, is given as:

$$E_{AC\_y\_actual} = (1 - yd) \sum_{N=1}^{N=365} E_{AC\_N\_actual} \qquad (9)$$

where *N* is the day number, and *d* is the yearly degradation rate of the PV module.

The sum of energy yield, $E_{AC\_S\_actual}$, across a specific time frame, *L* is given as:

$$E_{AC\_S\_actual} = \sum_{y=1}^{y=L} E_{AC\_y\_actual} \qquad (10)$$

L is usually the project time frame where the tariff is given for selling the generated electricity or the lifespan of an inverter. For calculating energy yield without considering power clipping, $E_{AC\_N\_actual}$ in **Eqn (9)** is replaced with E_{AC_N} of Eqn (1). Similarly, $E_{AC\_y\_actual}$ and $E_{AC\_S\_actual}$ are replaced by E_{AC_y} and E_{AC_S}, respectively.

LCOE for this generalised method is calculated as follows:

$$LCOE = \frac{Capital + Maintenance\ Cost}{E_{AC\_S\_actual}} \qquad (13)$$

Financial cost and incentives are not included as well as the net present value of the future cost. The capital is the cost after considering the saving from the undersized inverter. It is given as follows:

$$Capital = P_{PV}\left[Price_{PV\_sys} - Price_{inv}(1 - \tfrac{1}{R})\right] \qquad (14)$$

where $Price_{PV\_sys}$ and $Price_{inv}$ are the specific prices for a PV system and inverter in RM/W, respectively.

A case study with a PV array capacity of 10 MW is conducted for eight sites in Malaysia. **Table 1** lists the parameters used for the case study. The listed values are the frequently used values for a design in this region, and hence it can be considered as generalised values, especially for *d*, PR_{fixed}, *γ*, *y*, $Price_{inv}$, *Capital* and *Maintenance Cost*. Any other deviation resulted from the design variation can be studied in future through the sensitivity analysis.

Table 1 List of parameters used for the case study

PV System Size, P_{PV}	10 MW
Ross coefficient, C_{Ross}	0.0234 °C per W/m^2
The degradation rate of PV module, *d*	0.65% per year
PR_{fixed}	0.92
$\eta_{inv}(l)$ curve	Sungrow's SG2500HV curve as stated in PVsyst
PV module temperature coefficient for power, *γ*	-0.0038 per °C
Project operation years, *y*	21 years
Inverter specific price, Price_{inv}	RM 0.328/W

Nominal PV system specific cost, $Price_{PV\_sys}$	RM3.84/W
Yearly maintenance cost	RM 150,000 per year
The currency conversion rate for USD to RM	1: 4.1

An experiment that compared the temperature of various crystalline silicon modules in a side-by-side setting up was conducted at Bukit Kayu Hitam (BKH) for two months. The average Ross coefficient obtained is 0.0234 ^{o}C per W/m^2, and the deviation between types of modules is only 0.001 ^{o}C per W/m^2. Therefore, this value can be adopted as a generalised value. The module performance degradation rate, *d*, is taken as 0.65% per year because most of the modules with the latest technology can warranty for the performance of 82~84% by the 25th years. The inverter specification given in PVsyst software for Sungrow inverter with model SG2500HV is chosen as the $\eta_{inv}(l)$ curve. The efficiencies for various loading factor do not deviate more than 1% for other branded inverters. Similarly, the chosen input voltage, which will affect the conversion efficiency, is based on the nominal voltage suggested by the inverter company, and it is usually the optimal efficiency curve.

3. RESULTS AND DISCUSSION

The solar irradiance distribution profiles for eight sites are depicted in **Fig 1**. It is observed that all sites in Malaysia show similar distribution profile and have a relatively high component of solar irradiance between 600 W/m^2 to 800 W/m^2. The distribution is quite different from that of Finnish [1], and therefore, the expected optimal ISR should be smaller.

Fig 2 shows the variation of LCOE when ISR changes. For all the sites, the relatively lower LCOEs are achieved for the range of ISR between 1.475 to 1.525, which is significantly higher than the local industrial practice that considers no power clipping should be allowed. The consideration of using 1.1 times of the inverter rated capacity also justifies a higher range of optimal ISR.

Comparing to the study carried out for Finland [1], the optimal ISR for Malaysia is apparently much lower where it is generally above 1.6 for Finland. Nevertheless, the range obtain is closed to that of Brazil [6], and it could be because of the same climate. The range is narrower as compared to that of the United States [2] where the sites were chosen crossing multiple types of climate. Another reason is a different type of incentive was imposed in the United States, whereas Malaysia has only one scheme for the large-scale solar plant.

Among the eight sites, Bayan Lepas gives the lowest LCOE because of its higher annual solar irradiation as well as the higher composition of high solar irradiances (See **Fig 1**). The relation between the annual solar irradiation for the site and the LCOE is given in **Fig 3**, where LCOE shows an inverse linear relationship with solar irradiation of a site. On the other hand, the optimal ISR for a site shows partial inverse linearly change with the annual solar irradiation of the site. For Kuching where the annual solar irradiation is less than 1700 kWh/m^2, the optimal ISR supposes to be the highest according to the trend. However, the optimal ISR is lower. It is found that although Kuching has a lower annual solar irradiation, it has higher composition of high solar irradiaces. From our data, there is 1160 points of solar irradiances more than 600 W/m2 while Johor Bahru has only 1092 data points. That explain why Kuching has a relatively lower optimal ISR as compared to Johor Bahru. Similar to the case for Pekan and Bdr. Sg Long, Bdr. Sg Long has 1356 data points with solar irradiances more than 600 W/m2 while Pekan has 1333 data points. That is why Bdr. Sg Long has a slightly lower optimal ISR.

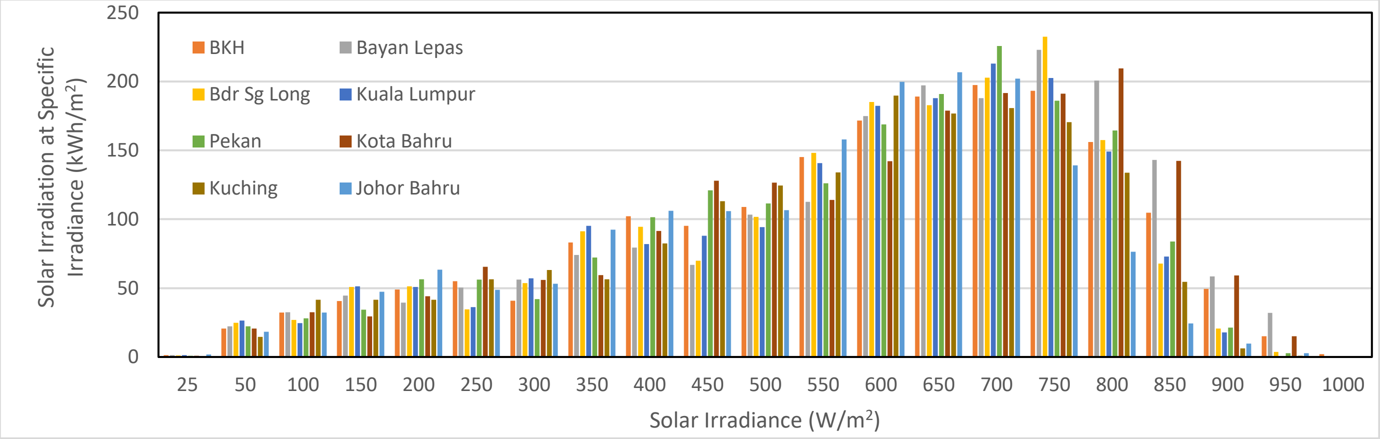

Fig 1 Solar irradiance distribution profile for various irradiance levels for eight sites in Malaysia

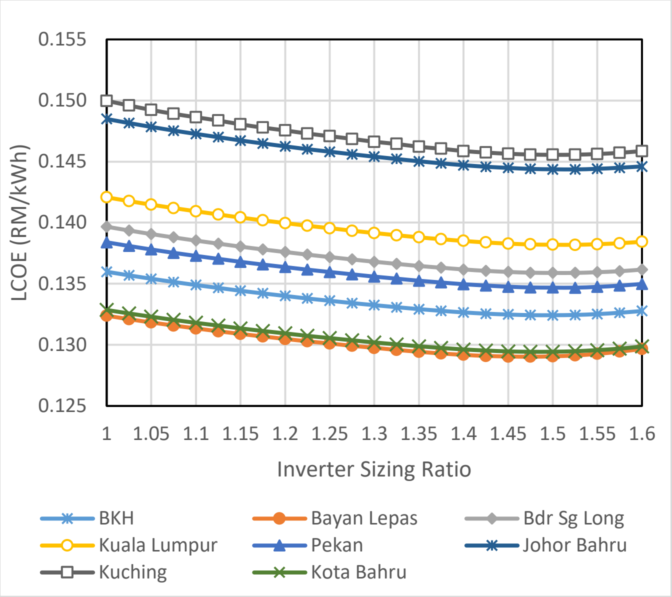

Fig 2 LCOE against the inverter sizing ratio for a 10 MW PV plants for eight sites in Malaysia

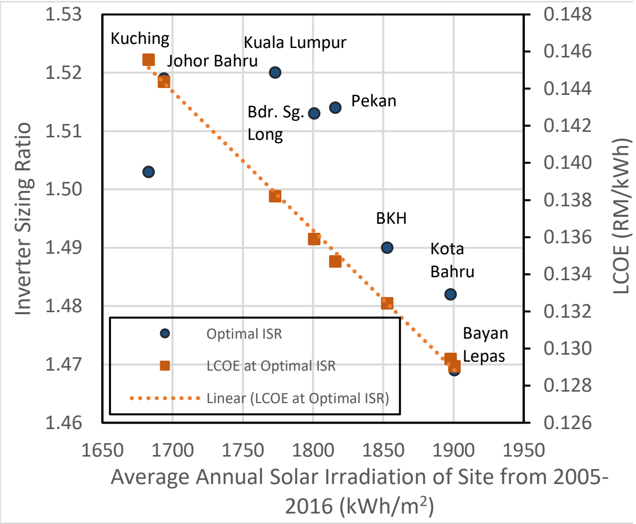

Fig 3 The relationship of optimal inverter sizing ratio of sites to the solar irradiation of the sites

4. CONCLUSIONS

A simulation was done to find the optimal ISR for PV plants located in distinct geographic locations in Malaysia, using generalised values except for performance loss due to temperature, solar irradiance data (hourly resolution) and conversion efficiency of an inverter. This method has grouped some of the site-dependent and system-dependent factors to a fixed PR. A user can flexibly perform this method as long as the derating factors of the system can achieve a similar PR. The optimal ISR, which was obtained based on the lowest LCOE, falls within 1.475 to 1.525 for the eight sites. This optimal range is higher than the previous value widely used in the industry. The optimal ISRs show a strong linear correlation with the annual solar irradiation of the sites. It also shows a narrower optimal range of ISR as compared to the cases in Finland and the United States.

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REFERENCE

[1] Väisänen J, et al. Optimal sizing ratio of a solar PV inverter for minimizing the levelized cost of electricity in Finnish irradiation conditions. Sol Energ 2019;185:350-362.

[2] Chen S, et al. Determining the optimum grid-connected photovoltaic inverter size. Sol Energ 2013;87: 96–116.

[3] Mah CY et al. Investigating the performance improvement of a photovoltaic system in a tropical climate using water cooling method. Energy Procedia 2019;159: 78-83.

[4] SG2500HV-20 data sheet, accessed on 27 May 2019. https://en.sungrowpower.com/upload/knowledge_download/7/e2ea28df7b6576e25bdec7aa3089a107.pdf

[5] Wang HX et al. Optimum inverter sizing of grid-connected photovoltaic systems based on energetic and economic considerations. Renewable Energy 2018;118:709-717.

[6] Paiva GM et al. Analysis of inverter sizing ratio for PV systems considering local climate data in central Brazil. IET Renew. Power Gener 2017;11(11):1364-1370.

[7] Shaari S. et al., 2010. Solar Photovoltaic Power: Fundamentals. Ministry of Energy, Green Technology and Water Malaysia, Putrajaya.

[8] PVGIS, European Commission, accessed on 20 May 2019. http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#DR

[9] Ross Jr RG. Interface design considerations for terrestrial solar cell modules. Proceedings of the 12th IEEE Photovoltaic Specialists Conference. 15-18 November 1976, Baton Rouge, LA, USA: 801–806.