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PV array and inverter optimum sizing for grid-connected photovoltaic power plants using optimization design

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Abstract. This paper aims to select the optimum inverter size for large-scale PV power plants grid-connected based on the optimum combination between PV array and inverter, among several possible combinations. Inverters used in this proposed methodology have high-efficiency conversion in the range of 98.5% which is largely used in real large-scale PV power plants to increase the financial benefits by injecting maximum energy into the grid. To investigate the PV array-inverter sizing ratio, many PV power plants rated power are considered. The proposed method is based on the modelling of several parts of the PV power plant taking into account many design variables and constraints. The objective function is the levelized cost of energy (LCOE) and the optimization is performed by a multi-verse algorithm. The optimization method results in an optimum inverter size that depends on the PV plant rated capacity by providing an optimum number of inverters required in the installation site. The optimum sizing ratio (Rs) between PV array and inverter were found equal to 0.928, 0.904, and 0.871 for 1 MW, 1.5 MW, and more than 2 MW, respectively, whereas the total power losses reached 8% of the total energy generation during the PV power plant operational lifetime.

Keywords: Grid-connected PV power plants, Optimization, Inverter, Sizing ratio, PV array

1. Introduction

At first, PV technology was installed in buildings, houses, farms, and industries with a small capacity (≤ 1 MW). Recently, the deployment of PV power generation is increased quickly to include large (≥ 1 MW) and very large-scale PV power plants (≥ 100 MW). The rapid growth of PV power generation is mainly due to the technology development of PV modules, inverters, and transformers along with the reduction in their prices. Therefore, the advanced technology of components has improved significantly the overall performance of PV power plants. Consequently, grid-connected PV power plants' cost of energy per kW is continuously decreasing and compete with other renewable energy and fossil sources. At the end of 2019, China leads the PV power generation market with a yearly added capacity of around 26%, followed by the United States with approximately 12% that have built thousands of PV power plants of different capacities [1].

Several methods in the literature proposed an optimal configuration of PV power plants using evolutionary algorithms or commercially available software tools. Generally, these methods used meteorological data, economic parameters, PV modules, and inverters components [2–4]. Additionally, the PV plant design was set for technical, environmental, and economic targets. PV inverter's optimum size depends on PV modules generated energy, cost ratio, and inverter performance. Under low solar radiation levels, PV modules output power represents only part of its rated capacity and leading to decrease inverter efficiency as part of the input power is consumed to ensure different functions [5]. On the other hand, and under overloading conditions, the excessive PV modules output power greater than

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the inverter rated power is lost. Besides, the oversizing or under-sizing of inverters causes an increase in energy cost. However, it is important to optimize the inverter sizing to increase significantly the efficiency and the feasibility of PV systems [6]. Optimum PV array/inverter sizing ratio was investigated in [7] for PV power plants in European locations. The simulation was carried out using the TRNSYS software tool. The sizing ratio is defined as the quotient of the PV modules' total capacity to the inverter rating capacity. It was found that the optimum sizing ratio for a high-efficiency inverter PV system should be in the range of 1.1–1.2 and 1.3–1.4, respectively for high and low solar irradiance locations, whereas optimum sizing ratio for high and low solar irradiance locations should be in the range of 1.2–1.3 and 1.4–1.5 in case of low-efficiency inverter PV system.

The study in [8] provided an analytical method to calculate the optimum inverter size, energy yield, and inverter efficiency for grid-connected PV power plants in different locations. Therefore, the inverter was determined using a simple proper method due to some aspects of the grid-connected PV power plant that play important roles. The developed analytical model was validated comparing the simulation outputs to the measured data. Another method in [9] aimed to maximize the energy yield of PV power plants grid-connected using the optimum sizing ratio of the PV system. The simulations were carried out for 27 sites in Europe to investigate the effect of the location and the inverter efficiency on both the annual generated energy and the sizing ratio. It suggested that the sizing ratio should be higher at low latitudes and, conversely, lower at high latitudes. Using high-efficiency inverters increased the sizing ratio and locations with high irradiance levels leading to a high sizing ratio. An iterative method is presented in [10] to optimize PV inverter sizing in different locations in Malaysia with taking into account low, medium, and high loads, the sizing ratio was optimized using the available commercial inverters models. A Matlab model for PV modules and inverter is developed based on hourly solar radiation and ambient temperature records. The main aim of the developed model was to estimate the efficiency of the inverter in terms of PV modules output capacity and inverter rated capacity. The obtained values of the optimum sizing ratio should be varied from 1.21 to 1.43. The research suggested in [11] examined the various factors that influence the strategy of sizing the inverter in a grid-connected PV system. Such considerations include environmental conditions such as solar radiation and ambient temperature, economic criteria such as electricity rates, and lastly inverter specifications such as overload protection schemes and efficiency curves. Therefore, optimum inverter size can vary from one geographic location to another.

A custom flexible solar array method was introduced combining with solar radiation data in the city of Barcelona, Spain, to evaluate the optimum sizing ratio of a PV array-inverter using an experimental study to maximizing the PV power plant energy yield [12]. The work presented in [13] highlighted DC input voltage role on PV power plant grid-connected DC/AC conversion efficiency. Thin-film cadmium telluride (CdTe) and crystalline silicon (c-Si) commercially PV modules and two PV inverters were characterized. It was found that the sizing ratio depends on PV module technology. Therefore, the recommended PV array-inverter sizing ratio for CdTe and c-Si were 0.95, 1.05 respectively, independently of the selected PV inverter at México. An iterative method was proposed recently in [14] for optimally sizing an inverter in grid-connected PV power plants based on hourly radiation and ambient temperature data. A comparison was carried out between a system with optimized inverter size and a conventional sized PV system in which the inverter capacity is equal to the PV array rated capacity. It was found that the annual energy generation for the optimum sizing system is higher than the conventionally sized PV system and the PV system using an optimized PV inverter has better performance.

Work discussed in [15] aimed at studying the effect of the inverter capacity on the performance of PV power plants. Findings from operational PV power plants and simulation using the Pvsyst analysis tool have been used to evaluate in-depth the effect of inverter capacity on the performance of the PV plant. As result, central inverter topology produced a high amount of energy with minimum energy losses, string inverter topology generated a medium amount of energy with medium energy losses, and micro inverters topology generates the least amount of energy with high losses. Therefore, the usage of high-capacity inverters reflects a greater contribution to PV power plant performance. A recent study in [16,17] investigated the PV arrays sizing influence on the reliability and lifetime of PV inverters. PV array oversizing could have negative impacts on the PV inverter reliability and lifetime since the rating

power of the PV arrays is higher than the inverter rating power. Besides, the sizing ratio R_s is usually less than 1 and has a typical value in the range of $1 \leq R_s \leq 1.5$ which varies with the installation fields. The impact of inverter technology and PV module degradation factor on the grid-connected PV system design optimization [18]. They concluded that high-efficiency current inverters have a wider band of sizing factors to achieve maximum energy generation.

The present work aims to investigate PV array-inverter sizing ratio (*Rs*) for large scale PV power plants using a comprehensive optimization design methodology. The simulation was performed for PV power plants rated power of 1 MW, 1.5 MW, and more than 2 MW with a location in Kuala Lumpur, Malaysia (3.1390° N, 101.6869° E).

2. PV power plant components

Large-scale PV power plants could be installed on the ground or large rooftops. A successful PV project requires careful consideration of optimal design. To achieve this, large-scale PV plants do not only require an accurate high amount of solar radiation, but also the quality of the installed components. The main PV power plant electrical components are described in this section.

2.1. PV modules

The photovoltaic cell is the main unit of the photovoltaic module and transforms the sunlight directly into active power. However, the produced energy depends on the PV cell performance, the quality of the available light, and the voltage at its terminals. At present, monocrystalline and polycrystalline PV modules technology reached a high efficiency of 25% and 21% respectively, whereas thin-film (CdTe) PV modules technology presents an efficiency of around 22%. [19,20]. The PV cell can be presented using a mathematical model. Besides, five parameters single-diode model is one of the most popular physical models used to show the electric characteristics of a single PV cell [21]. Besides, seven parameters two-diode model was discussed in reference [22] and aimed to increase the accuracy of the PV cell [23]. Most studies related to the performance of PV systems require the use of a model to convert the irradiance received by the PV module and ambient temperature into the corresponding maximum DC power output of the PV module. The models recorded in the literature vary in accuracy and complexity as reviewed in [24].

2.2. Inverters

The inverter converts DC power into AC power. In the PV power plant, the inverter output is synchronized automatically to have the same voltage level and frequency as that of the electric grid. The selected PV inverter has to control the power amount that should meet different standards requirements based on the location, e.g., EN 50106, IEEE 1547.1–2005, IEC61727, and VDE0126-1-1 [25]. The PV inverter selection can highly affect large-scale PV plant optimal design due to its electrical characteristics such as maximum open-circuit voltage, input voltage, and inverter nominal power. The inverter in PV power plants grid-connected functions as the interface between the PV modules side and the electric network side [26]. In a PV power plant, the inverter can have a single stage of conversion from dc to ac or two stages of conversion where an additional dc-dc converter should be used [25,27]. Single-stage conversion is used in the case of central, string PV plant topology. In contrast, two stages of conversion are required in the case of multi-string PV plant topology. Many types of research are still ongoing on the dc-dc converter. The dc-dc converters in PV plants are divided into two groups, namely isolated (with transformer) and non-isolated (without transformer) converters [28]. The difference is mainly due to the galvanic isolation between the PV modules side and the electric network side [26]. Both isolated and non-isolated dc-dc converters were reviewed, analyzed, and studied in [29,30] and [31] respectively.

2.3. Transformers

The PV inverters output power requires a further step-up in voltage to ensure the network connection. The main purpose of transformers used in the large-scale PV power plant is to provide suitable voltage levels for transmission across the site and export to the electric grid, and it is depending on the grid voltage level from 33 kV up to 110 kV. Moreover, large-scale PV power plants still use on line frequency

(i.e. 50 or 60 Hz) transformers to isolate and step-up the inverter's output power to the grid voltage level. The transformer efficiency is a measure of the different losses during the power conversion from DC to AC. In large-scale PV power plants, the cost of the transformers can represent more than one-third of the inverter cost. A recent study showed that transformers in Brazil for a range of 500 kVA dry type can reach a cost of 4.14 ¢/watt [32].

3. Methodology

In this section, the applied methodology to find the most suitable PV array- inverter combination using the optimization design the PV power plant is discussed in detail taking into account the technical and economic aspects of the PV system. PV power plant sizing is an important process before the realization of the project especially the optimal combination between PV array and inverter. The suggested optimization method targets to inject maximum electricity to the electric grid with minimum associated costs. Several aspects have been included in this work. The developed methodology proposed a list of actual PV modules and inverters, calculation of junction boxes according to a rating power of 100 kW, calculation of DC cables including size and length with taking into account the losses, calculation of foundation concrete and metallic rods, two alternatives for central and string topologies, components arrangement within the installation area according to the actual PV plant field model, real hourly measurement data including wind speed and calculation of the partial shading. All the components and aspects of the developed methodology are optimally selected by the optimization algorithm based on several design variables in which most of them are newly proposed. Furthermore, the multi-verse optimization technique (MVO) is applied for the optimum design of the large scale PV power plant grid-connected. Figure 1 illustrates the suggested method that targets to achieve the optimal combination between PV array and inverter and the PV power plant overall design for technical and economic aspects using LCOE objective function.

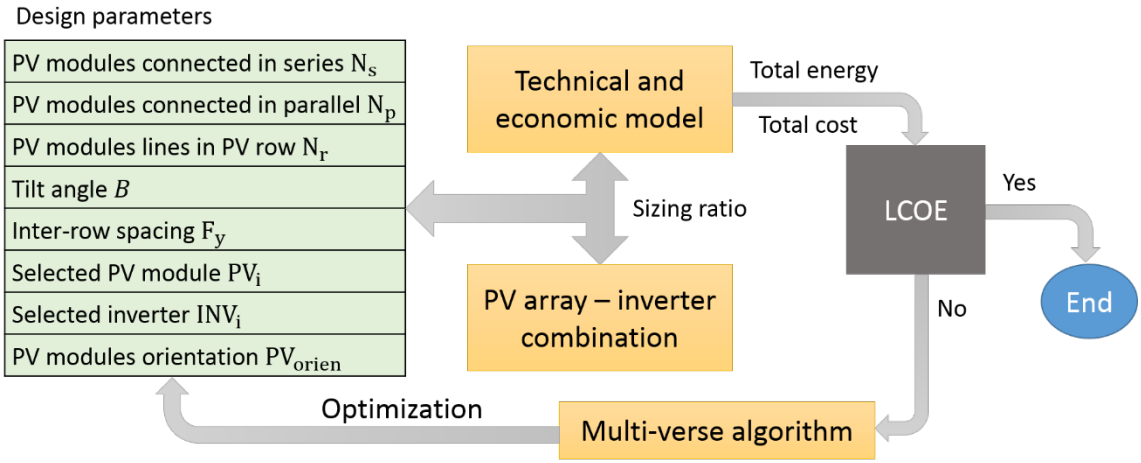


Figure 1 Design optimization procedure for optimum size of grid-connected PV plants inverter.

3.1. Technical model

The primary input parameters for this methodology can be divided into two main groups, technical and economic. The first input parameters category deals with inverters and PV modules specifications at standards test conditions including a list of several alternatives, installation site coordinates, and hourly measurement data for solar irradiation, ambient temperature, and wind speed during the year. Figure 2 illustrates the annual solar irradiance, ambient temperature, and wind speed for the selected location. The second type of input parameter deals with the different costs such as the costs of the components such as transformers, protection devices, cables, and junction boxes costs, construction of the PV mounting structures cost, and used land cost as well the local economy. The design parameters of the proposed optimization method are considered as input parameters to achieve the most suitable design of the PV power plant and the optimum PV array-inverter combination among several possibilities.

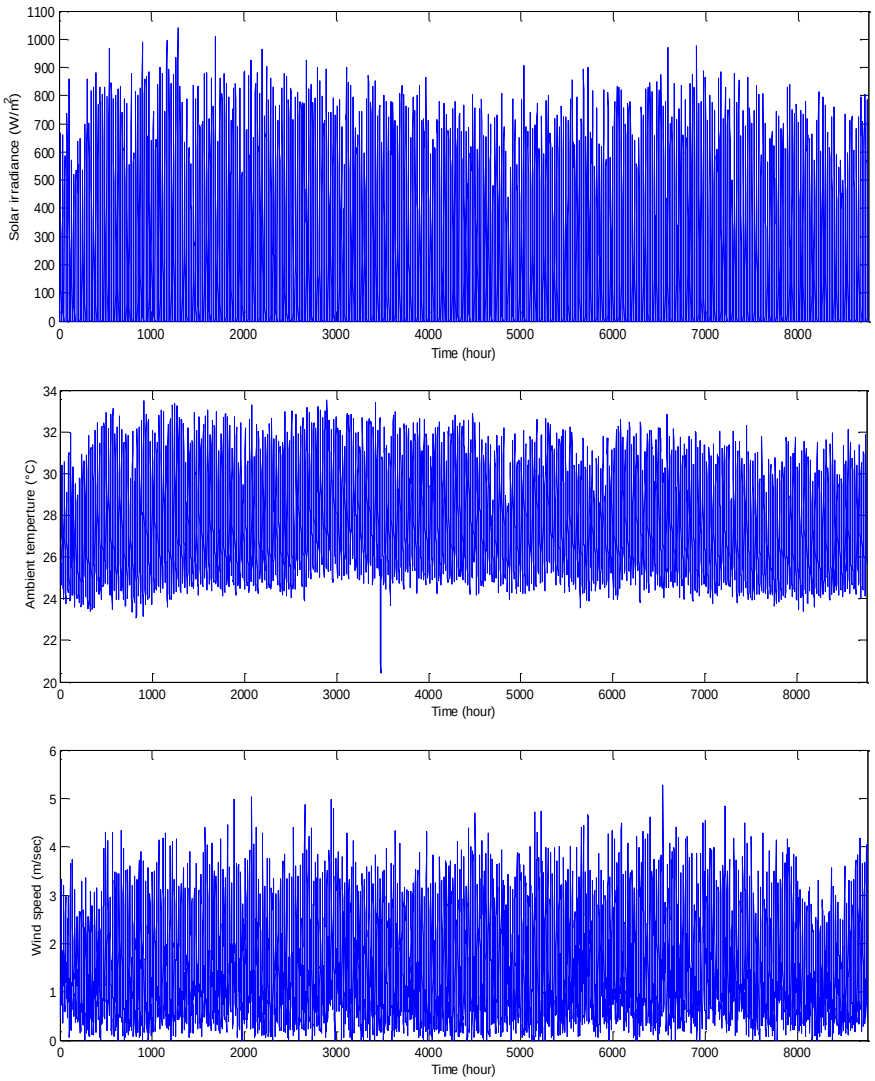


Figure 2 Annual hourly solar radiation, ambient temperature, and wind speed

The isotropic sky model is used in this proposed methodology to calculate the total solar irradiance on the inclined PV module surface. However, in this method PV modules are installed in the PV plant field facing the south. The total irradiance on an inclined PV module surface is the sum of three main components direct, diffuse, and reflected radiation. The calculation process of the irradiance model uses the tilt angle which is one of the design parameters to capture maximum solar energy and convert it into electricity. Besides, declination, local latitude, surface azimuth angle and hour angle are used as input parameters for the irradiance model.

The selection of the optimum PV module to build the PV power plant is very important since they have different rated power, technology, and sizes. In this method, many alternatives of PV modules are considered as input parameters to find a suitable candidate that results in an optimum combination with the PV inverter. PV modules specifications at standard test conditions used in this study are nominal maximum power ($P_{mpp,stc}$), optimum operating current ($I_{mpp,stc}$), optimum operating voltage ($V_{mpp,stc}$), current temperature coefficient (K_i), voltage temperature coefficient (K_v), open-circuit voltage ($V_{oc,stc}$), wind speed temperature coefficient (K_r), PV module ($L_{pv,1}$) length and width ($L_{pv,2}$) as illustrated in Table 1.

Table 1. PV modules specifications at standard test conditions.

Specification	Unit	PV1	PV2	PV3
$\mathbf{P_{mpp,stc}}$	W	285	295	335
$\mathbf{I_{mpp,stc}}$	A	9.02	9.22	8.96
$\mathbf{V_{mpp,stc}}$	V	31.6	32	37.4
$\mathbf{K_i}$	(%/C)	0.0005	0.0003	0.0005
$\mathbf{K_v}$	(%/C)	-0.0032	-0.0029	-0.0031
$\mathbf{V_{oc,stc}}$	V	38.3	38.5	45.8
$\mathbf{K_r}$	-	1.4684	1.4684	1.509
$\mathbf{L_{pv,1}}$	m	1.65	1.65	1.96
$\mathbf{L_{pv,2}}$	m	0.992	0.992	0.992
Efficiency	%	17.4	18	17.23
Type	-	Poly	Mono	Poly

The calculation of the PV cell temperature is required since it affects the PV module output power. Therefore, it can be calculated based on the hourly meteorological data. Besides, the PV module energy generation is calculated for each hour in the function of its specifications at STC and the PV cell temperature. The energy generation of the PV power plant is injected directly into the electric network as its configuration is grid-connected.

The available land can be used to determine the maximum capacity of the PV power plant that can be installed. Consequently, the available land is taken into account as a constraint in this method. In case there is no limit of the area, the PV plant rated power is used as the main constraint and it can be set by the PV plant designer as an input parameter.

PV modules are arranged in PV rows and each row may contain many PV lines (Nr) which is one of the design parameters. PV rows are installed using the area coordinates with the corresponding length of each row. The PV row height and width are calculated based on the PV module dimensions and the number of PV lines. All PV rows are considered to be similar but with different lengths.

The selection of the optimum inverter is necessary to inject the maximum possible PV plant output power into the grid since inverters have different rated power and voltage level. In this proposed method, many alternatives of inverters are considered as input parameters to find a suitable candidate that results in an optimum combination with the PV array. Nominal power (P_i), minimum input voltage ($V_{i,min}$), maximum input voltage ($V_{i,max}$), maximum MPPT voltage ($V_{i,mppt,max}$), power loss ($P_{i,sc}$) and efficiency (η_{inv}) are the inverter specifications at standard test conditions as illustrated in Table 2.

Table 2. Inverters specifications at standard test conditions.

Specification	Unit	INV1	INV2	INV3
$\mathbf{P_i}$	kW	500	875	1645
$\mathbf{V_{i,min}}$	V	450	525	550
$\mathbf{V_{i,max}}$	V	1100	1100	1000
$\mathbf{V_{i,mppt,max}}$	V	825	825	850
$\mathbf{P_{i,sc}}$	W	490	650	1800
η_{inv}	%	98.6	98.7	98.5

On the one hand and as aforementioned, PV modules arrangements within the available area lead to determine the total number of PV modules installed in each PV row and the PV power plant as well. On the other hand, total PV modules to each inverter can be obtained by multiplying the number PV modules connected in series and parallel which are considered as design parameters of the proposed method and their values are calculated by the optimization process. Consequently, the total number of inverters required to be installed in the PV power plant can be determined using PV module and inverter rated

power at STC, total PV modules connected to the inverter, the total number of installed PV modules in the field.

Once PV plant components have been arranged, the cable length can be calculated according to the location of PV modules and inverters at the PV plant installation site. In this proposed methodology, the optimal length of cables depends mainly on the selected topology by the optimization process, which may be central or string structure. However, to optimally choose a cross-section of the cables, it is essential to obtain the maximum permitted ampacity and voltage drop during the calculation process. In the case of a central inverter configuration, two different cables should be identified. The cable from PV modules to junction boxes (L_{mbi}), and the cable from junction boxes to the inverter ($L_r + L_c$). In string inverter topology, junction boxes are not required to be placed in the PV plant installation site. However, string inverters are installed instead. As stated above, two calculation levels are needed to select the optimum cable cross-section of the PV power plant. The first level deals with the calculation of the maximum current value between PV modules – junction box – inverter. It allows the optimal value of the cable cross-section to be chosen from the set of various ampacity values. The second calculation level is to check the selected value of the cable cross-section based on the estimated voltage drop of the longest cable from PV modules to the main combination unit. The value of the voltage drop is limited to 5% of the value of the rated voltage. However, the upper cable cross-section value is defined by the optimization process in case the initially selected cross-section value does not satisfy the criteria.

Junction boxes with a power of 100 kW, are used in the central configuration as mentioned above. If the capacity of a PV row is less than 60 kW, therefore there is no need to mount a single junction box for that row. In this case, connections are oriented to other closer junction boxes.

The calculations of the PV module mounting structures are taken into account and aims to include costs of metallic rods and concrete foundation bases in this optimal design methodology. Besides, the cost of PV module mounting structures has a significant effect on the total cost of large scale PV power plants. However, the modelling of the PV module mounting structures is done. Metallic rods are used in the construction of the PV modules structures and the estimated cost can be calculated according to the metallic rods total length that is necessary to build the PV power plant.

The shadow area on the inclined surface of PV modules can have a negative impact on the output power of the PV power plant. Besides, it can lead to an increase in energy losses and the cost of the produced energy per kW. To outcome this issue, the shadow is considered in this method using the inter-row distance between two adjacent rows, and tilt angle as a design variable and their values are computed by the optimization process. Besides, declination, local latitude, and hour angle are used as input parameters for the shadow model.

The PV power plant total energy generation during its operational lifetime is computed in two ways depending on the inverter topology selected by the optimization process. In the case of inverter topology, the total PV plant output power can be obtained based on the inverter output power, the total number of installed inverter in the PV plant area, transformer efficiency, AC cable losses, and interconnection cable losses. In the case of the central inverter structure, the PV plant output power is obtained according to the sum of PV rows output power, efficiencies of PV components, and cable losses. Finally, the total energy generation during the PV power operational lifetime is achieved taking into account the energy availability factor.

3.2. Economic model

The total cost of the PV power plant is comprised of two types of costs, the first one presents the cost of the installation and the second handle with operations and maintenance costs. On the one hand, the PV plant installation cost includes the cost of the different PV components such as PV modules, inverter, transformer, cables, protection devices, and monitoring structures as well as the cost of the land and mounting structures. On the other hand, the operations and maintenance costs are described as a function of the operational lifetime of the PV power plant, and the local economy parameters such as inflation rate and nominal annual interest rate.

From an economic viewpoint, the minimum levelized cost of energy gives a better indication of the cost of energy production for PV power plants. Besides, it is chosen as the predefined target set in this

proposed methodology. The LCOE can be obtained by dividing the produced energy for 25 years over the PV plant's total cost.

3.3. Sizing ratio and power losses

In PV systems, the sizing ratio (R_s) is the ratio of the PV array nominal power at the STC, $P_{PV(rated)}$, over the nominal power of the inverter $P_{PV(rated)}$. However, in this method, the PV module and the inverter are selected by the optimization process to provide an optimum combination between PV array-inverter. The sizing ratio (R_s) is given in equation (1).

$$R_s = \frac{P_{PV(rated)}}{P_{i(rated)}} \tag{1}$$

The nominal power of the PV array $P_{PV(rated)}$ can be obtained using equation (2).

$$P_{PV(rated)} = P_{mpp,stc}.\ N_s.\ N_p \tag{2}$$

where $P_{mpp,stc}$ is the PV module nominal maximum power at standard test conditions, (N_s) and (N_p) are the number of PV modules connected in series and parallel, respectively. (N_s) and (N_p) are design parameters and their optimum values are computed by the optimization process.

The PV plant losses during its operational lifetime can be calculated by subtracting the PV plant total output power from the PV array total output power as expressed in equation (3). An optimum PV array-inverter combination should reduce the losses of the PV plant and inject more produced energy to the electric grid.

$$\sum P_{losses} = \sum P_{PV} - \sum P_{plant} \tag{3}$$

4. Optimization process

In this section, the single objective function used to find the minimum levelized cost of energy (LCOE) is presented and the optimization is performed by a multi-verse algorithm which is a recent metaheuristic optimization method.

4.1. Objective function and design parameters

In this design procedure, the objective function is set as the minimum LCOE. Besides, the design parameters include the number of PV modules connected in series (N_s) and parallel (N_p), PV module tilt angle (β), the inter-row distance between adjacent PV rows (F_y), the number of PV lines in each PV row in the PV plant (N_r), the selected PV module (PVi) and inverter (IN_i) based on the optimum combination and the PV module orientation that can be installed within the PV plant horizontally or vertically (PV_{orien}). Moreover, the optimization design presents many constraints such as the limitation of the available area, the PV plant rated power, and the equally constraints to select the PV plant components such as PV modules and inverters. All the design parameters are also limited by lower and upper bounds. The objective function is given in the following equation:

$$\min_{\vec{X}} \text{LCOE} = \min_{\vec{X}} \left(\frac{C_{tot}(X)}{E_{tot}(X)} \right) \tag{4}$$

where C_{tot} is the total cost and E_{tot} is the total energy generation during the operational lifetime of the PV power plant.

4.2. Brief description of the MVO approach

The multi-verse optimization algorithm inspiration is based on three concepts in cosmology: white hole, black hole, and wormhole. The MOV is a stochastic population-based algorithm. The mathematical models of these three concepts are developed to perform exploration, exploitation, and local search, respectively [33]. MVO was compared with four powerful algorithms such as genetic algorithm and particle swarm optimization, the results showed that the MOV algorithm can provide very competitive results compared to other existing algorithms in the literature.

5. Results and Discussion

The proposed method has been implemented using Matlab programming language and an optimum inverter sizing for grid-connected PV power plants has been done with location in Kuala Lumpur, Malaysia (3.1390° N, 101.6869° E). The optimum PV inverter size was optimally selected using the design optimization of the PV power plant from a list of candidates with different characteristics to be optimally combined with the PV array based on an optimal number of PV modules connected in series (*Ns*) and parallel (*Np*) to achieve maximum power output from the PV power plant. Besides, the PV module was also optimally selected from a list of many alternatives and the rated capacity of the PV array must be optimally matched with the installed inverter's rated capacity. The inverters used in this proposed methodology have high-efficiency conversion in the range of 98.5% which is largely used in real large-scale PV power plants to increase the financial benefits by injecting maximum energy into the grid. MVO algorithm was applied to find the minimum LCOE and to achieve the optimum inverter size based on the mathematical modelling of large scale PV power plants that take into account all aspects affecting the PV plant performance since in case of neglecting one or some aspects during the design process of the PV system, it will not provide an accurate energy generation. In this study, different cases based on the PV power plant nominal power were used to determine the most suitable inverter size for each PV system.

Table 3 shows the obtained optimal design parameters and the LCOE for each PV plant nominal power. It can be seen that PV power plants have completely different structures. In contrast, the LCOE has almost the same values in all cases. The optimal LCOE for 1 MW, 1.5 MW and more than 2 MW rated capacity are 0.038 ($/kWh), 0.0375 ($/kWh) and 0.0378 ($/kWh) respectively. It can be seen that in the case of the PV plant with 1 MW rated power, the optimally selected inverter was INV1 which used 500 kW. In the case of 1.5 MW and more than 2 MW rated capacity, the optimization process selected INV2 which used 875 kW, but the number of inverters was not similar. The selected PV module was polycrystalline PV3 that used 335 W for 1 MW and 1.5 MW PV plants and monocrystalline PV2 that used 295 W for more than 2 MW PV plant. The values of PV modules connected in series (*Ns*) and parallel (*Np*) have different values from one case to another due to the selected combination between inverter and PV array. However, INV2 was the same for 1.5 MW and more than 2 MW rated capacity PV plant but (*Ns*) and (*Np*) have different values due to selected the PV module, PV3 was selected for 1.5 MW and PV2 was selected for more than 2 MW.

Table 3. Optimal design variables for each PV plant.

Design parameters	1 MW	1.5 MW	> 2 MW
N_s	22	17	19
N_p	63	139	136
N_r	2	5	4
β	11	11	11
F_y	0.567	1.419	1.135
PV_i	PV3	PV3	PV2
INV_i	INV1	INV2	INV2
PV_{orien}	1	1	1
LCOE ($/kWh)	0.0380	0.0375	0.0378

The optimum combination between the PV array and inverter was achieved and Table 4 shows the optimal results of the different cases. The optimum sizing ratio (R_s) between the rated capacity of PV array and the rated capacity of the inverter was found equal to 0.928, 0.904, and 0.871 for 1 MW, 1.5 MW, and more than 2 MW, respectively. It can be seen that number of inverters required was equal to 2 in the case of 1 MW and 1.5 MW and was equal to 3 for PV plant rated power exceeds 2 MW.

According to the obtained results, the total output power from 1 MW PV plant is 37263.85 MWh and total power losses are 3110.32 MWh during its operational lifetime. The power losses present 8.34 % of the total energy generation of the PV power plant. In the case of 1.5 MW PV plant, the total energy production is 58832.01 MWh, while the total power losses are 4842.84 MWh presenting 8.23 % of the

total energy generation. The total energy generation from more than 2 MW PV plant reached 82046.16 MWh. Meanwhile, the total energy losses are 6729.77 MWh, corresponding to 8.20 % of the produced energy of the PV plant during its lifetime.

It can be concluded that using the proposed optimization methodology for different PV power plant rated capacities can lead to an optimum sizing ratio (R_s) between the PV array and inverter, and the PV power plant total losses during its operational lifetime in the range of 8 %.

Table 4. Optimal results for each PV plant nominal power.

PV plant parameters	1 MW	1.5 MW	> 2 MW
Number of PV modules	3034	4785	7580
Number of PV inverters	2	2	3
Number of junction boxes	18	15	26
Number of PV rows	35	18	34
Total energy generation (MWh)	37263.85	58832.01	82046.16
Total energy losses (MWh)	3110.32	4842.84	6729.77
Total energy losses (%)	8.34	8.23	8.20
Sizing ratio R_s	0.928	0.904	0.871

Figure 3 illustrates the diagram of the PV power plant monthly energy production. The difference between the produced energy from one month to another during the year is due mainly to the available amount of solar irradiation and the local climate conditions.

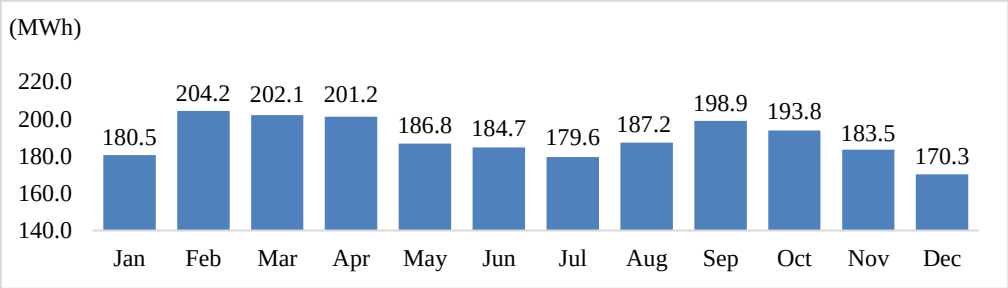


Figure 3 Monthly energy generation for 1.5 MW PV power plant.

Figure 4 illustrates the distribution of the PV power plant installation and maintenance costs among the main groups computed by the optimization process based on the economic model. PV modules present around 47 % PV plant total cost while the inverter cost presents approximately 8 %.

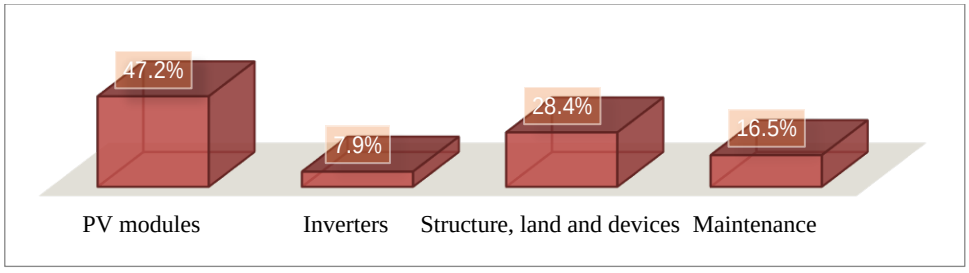


Figure 4 Installation and maintenance costs of 1.5 MW optimal PV plant.

6. Conclusion

The optimum inverter for PV power plants grid-connected was achieved using an optimization design including several aspects of the PV power plant such as hourly solar irradiance, ambient temperature, wind speed, components specifications, and location characteristics. The optimal combination between the PV array rated capacity and inverter rated capacity was determined based on the LCOE objective

function. The simulation was carried out for different PV power plants rated capacities to investigate the sizing ratio of the system. The optimization process results in an optimum size of the inverter that depends on the PV plant rated power by providing the optimal number of inverters required for the PV plant. The optimum sizing ratio (R_s) values between PV array and inverter were found close and equal to 0.928, 0.904, and 0.871 for 1 MW, 1.5 MW, and more than 2 MW, respectively, whereas the total power losses were 3110.32 MWh, 4842.84 MWh and 6729.77 MWh for 1 MW, 1.5 MW and more than 2 MW, respectively, presented approximately 8 % of the total energy generation during the PV plant operational lifetime.

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