Indonesian Journal of Electrical Engineering and Computer Science
Vol. 8, No. 1, October 2017, pp. 169 ~ 176
DOI: 10.11591/ijeecs.v8.i1.pp169-176

Sizing Optimization of Large-Scale Grid-Connected Photovoltaic System Using Cuckoo Search

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Abstract

This study presents the development of Cuckoo Search (CS)-based sizing algorithm for sizing optimization of 5MW large-scale Grid-Connected Photovoltaic (GCPV) systems. CS was used to select the optimal combination of the system components which are PV module and inverter such that the Performance Ratio (PR) is correspondingly optimized. The oversized and undersized of this large-scale GCPV system can give huge impact towards the performanceof this system. Before incorporating the optimization methods, a sizing algorithm for large-scale GCPV systems was developed. Later, an Iterative-based Sizing Algorithm (ISA) was developed to determine the optimal sizing solution which was later used as benchmark for sizing algorithms using optimization methods.The results showed that the CS-based sizing algorithm was unable to found the optimal PR for the system if compared with ISA. However, CS was outperformed ISA in producing the lowest computation time in finding the optimal sizing solution.

Keywords*: Grid-Connected Photovoltaic (GCPV), Cuckoo Search (CS), Performance Ratio (PR), Iterative-based Sizing Algorithm (ISA).*

1. Introduction

In past decades, RE seems to be the most reliable alternative energy resources to replace the conventional fuel resources. RE is a continuous natural resource that can be replenished without failure and will not be depleted throughout time [1]. There are a few types of RE resources such as wind energy, hydroelectric energy, thermal energy, wave energy, tidal energy, geothermal energy and solar energy. Recently, solar energy-based technology such as photovoltaic (PV) has become one of the fastest growing RE technologies [2]. PV technology utilizes solar cells to capture the energy from the sunlight and directly convert them into electricity. There are several types of solar cell technologies which available in the market nowadays which are based on different crystalline and non-crystalline based cells [3].

PV technology commonly divided into two main components which are Grid-Connected Photovoltaic (GCPV) and Standalone Photovoltaic (SAPV) system. For GCPV system, it can be installed either as distributed systems or as centralized systems [2]. The distributed systems are commonly installed at point of loads in smaller capacities when compared to centralized systems.

In contrast, centralized systems which are usually installed in large-scale capacities frequently have megawatt capacities. In large-scale GCPV systems, central inverters in large capacities are preferable when compared to string inverters with relatively smaller capacities due to ease of installation [12][14].

2. Research Method

2.1. Assessment of Solar Resources

Solar energy plays an important role in GCPV system's operation. The intensity of solar energy for a particular site is known as irradiation in Whm^{-2} [2]. Higher irradiation results in higher energy output from the system and vice versa. In this study, monthly solar irradiation profile for Kuala Terengganu at 10^{o} array tilt angle facing south was obtained from a previous work and annual irradiation used is 1755.4 Whm^{-2} [4].

Received June 19, 2017; Revised August 22, 2017; Accepted September 9, 2017

2.2. Selection of System Components

In this large-scale GCPV system, two main components were considered in sizing process, i.e. PV module and inverter [13].

2.2.1 Photovoltaic Module

The most common type of PV modules used for PV systems worldwide is the crystalline silicon modules [5]. This type of module comprises mono-crystalline and poly-crystalline module. The ratings of PV module required for the sizing process are rated maximum power of PV module at Standard Test Conditions (STC), P_{mp_stc}, in W, voltage at maximum power of the PV module at STC, V_{mp_stc} in V, current at maximum power at STC, I_{mp_stc} in A, short circuit current of the PV module at STC, I_{sc_stc}, in A, open circuit voltage at STC, V_{oc_stc}, in V, the temperature coefficient for open circuit voltage, γ_{Voc}, in % per °C, the temperature coefficient for short circuit current, γ_{Isc}, in % per °C, the width of each PV module in m is described as L_{width}, L_{length} is the length of each PV module in m and the temperature coefficient for maximum power, γ_{Pmp}, in % per °C.

2.2.2 Inverter

Another main component of a GCPV system is inverter. The inverter converts the DC electricity from the PV array into AC electricity that matches the grid-electricity. The ratings of inverter required for the sizing process are the maximum input voltage rating of the inverter, V_{max_inv} in V, minimum Maximum Power Point Trackers (MPPT) input voltage of inverter, $V_{min\_inv\_MPPT}$ in V, nominal output power of inverter, $P_{nominal\_inv}$ in W, maximum input current of the inverter, I_{dc_inv} in A and efficiency of inverter, η_{inv} in %.

2.2.3 Site Layout

The selected site encompasses approximately 199,900.2 m^2 of land area available for PV array installation using free-standing mode and the erection of power house. The installation of PV array is distributed in form of blocks to facilitate maintenance activities. In addition, a reserved perimeter area surrounding the plant is allowed for similar purpose. The distance from the last PV array block to the edge of the land border is set to be 4 meters, except for one side of the land which allows 6 meters distance from the last array block to the border of the land for the construction of power house, the number of rows per block, N_{row_block} in integers, the length and width of the usable land area for the solar farm, denoted as L_{D1} and L_{D2} respectively in meters, the reserve distance around the available space area, rsv_x, rsv_z and rsv_y in meters, the horizontal gap between the adjacent PV array blocks, f_x in meters, the gap between the PV modules, G in meters and the reserve area for build the power house rsv_ph_y in m. The PV array is tilted at a tilt angle β in °. The width of the area covered by a PV module tilted at β°, W_{1_PV} in meters, the height of a PV module tilted at β°, H_{1_PV} in meters, the length required for the metallic spars at a vertical line, B_{1_vert} in meters, the total length of the vertical spars of each side of a vertical line, B_{tot_vert} in meters, the total number of vertical line, n_{b_vert} in integers, the total length of row in a block, L_{T_row} in meters, the total length of the intermediate spars of each side of a vertical line, B_{2_vert} in meters, the total volume of the foundation of the concrete bases, $B_{B\_concrete}$ in meters^3, the concrete wall's height and the concrete responding thickness, h_{w_height} and t_{w_thick} in meters. These important parameters will be used in sizing procedure to determine the optimal sizing of solar farm.

2.3. Development of Iterative-based Sizing Algorithm (ISA)

Conventional Sizing Algorithm (CSA) was initially developed as the basic sizing algorithm in this study. The CSA requires the designer to select a set of PV module and inverter before he or she proceeds with the sizing process. If there are more than one combination of PV modules and inverters, the CSA needs to be repeated [15][16]. The CSA method is seems to be very time consuming when its deal with numerous sets of system components. Thus, Iterative-based Sizing Algorithm (ISA) has been developed to evaluate every possible set of system components such that the optimal set could be determined in a single run.

Step 1: Determine the range of optimal number of PV modules, N_t for a specific inverter based on the optimal range of inverter-to-PV array sizing ratio in integers.

$$ru\left(\frac{P_{nominal\_inv}}{P_{mp\_stc} \times f_{d1}}\right) \leq N_t \leq rd\left(\frac{P_{nominal\_inv}}{P_{mp\_stc} \times f_{d2}}\right)$$

$P_{nominal\_inv}$ is the nominal output power of the inverter in W while P_{mp_stc} is the maximum power of the PV module at standard test conditions in W. f_{d1} and f_{d2} represents the minimum and maximum of inverter-to-PV array sizing ratio. In Malaysia, f_{d1} and f_{d2} were found to be 1.00 and 0.90 respectively [6].

Step 2: Determine the potential maximum open circuit voltage, V_{oc_max} in V and the minimum voltage at maximum power, V_{mp_min} in V for the chosen PV module.

$$V_{oc\_max} = V_{oc\_stc} \times \left\{1 + \left[\left(\frac{\gamma_{voc}}{100\%}\right) \times \left(T_{c\_min} - 25\right)\right]\right\}$$
$$V_{mp\_min} = V_{mp\_stc} \times \left\{1 + \left[\left(\frac{\gamma_{pmp}}{100\%}\right) \times \left(T_{c\_max} - 25\right)\right]\right\}$$

where V_{oc_stc} and V_{mp_stc} are the open circuit voltage and the voltage at the maximum power of the PV module at STC. γ is the temperature coefficient value in % per deg C while T_{c_min} and T_{c_max} are the minimum and maximum effective cell temperature respectively in deg C.

Step 3: Determine the maximum and minimum allowable number of PV modules per string, N_{s_max} and N_{s_min} in integers.

$$N_{s\_max} = round\ down\left[\frac{V_{\max\_inv} \times f_{s1}}{V_{oc\_max}}\right]$$
$$N_{s\_min} = round\ up\left[\frac{V_{\min\_inv\_MPPT} \times f_{s2}}{V_{mp\_min} \times f_{cab}}\right]$$

V_{max_inv} is the maximum input voltage rating of the inverter in V while $V_{min\_inv\_MPPT}$ is the minimum MPPT window voltage of the inverter in V. The values of safety margin f_{s1}, f_{s2}, are 0.95 and 1.10 while the value for cable loss factor, f_{cab} is 0.95 respectively [7].

Step 4: Determine the maximum number of strings in parallel, N_{pmax} in integers.

$$N_{pmax} = round\ down\left[\frac{I_{dc\_inv}}{I_{sc\_stc} \times f_{s3}}\right]$$

where I_{dc_inv} is the maximum input current of the inverter in A and I_{sc_stc} is the value of the short circuit current of PV module at the STC in A. A value of 1.25 was chosen for f_{s3} in this study.

Step 5: Determine the optimal PV array configuration for each inverter by selecting the number of PV modules per string, N_{s_PV} and the number of parallel strings, N_{p_PV}. The total number of PV modules connected to each inverter, N_{PV_INV} in integers is calculated using

$$N_{PV\_INV} = N_{p\_PV} \times N_{s\_PV}$$

At this stage, N_{PV_INV} must be in the range of N_t.

Step 6: Determine the required total number of PV modules for the whole solar farm, N_{PV_all} in integers that are distributed to the total number of inverters for the solar farm, x_{i_inv}.

$$N_{PV\_all} = round\ up\left(\frac{P_{arr\_req}}{P_{mp\_stc}}\right)$$

$$x_{i\_inv} = round\ down\left(\frac{N_{PV\_all}}{N_{PV\_INV}}\right)$$

$$N_{actual\_1} = x_{i\_inv} \times N_{PV\_INV}$$

$$N_{bal} = N_{PV\_all} - N_{actual\_1}$$

where P_{arr_req} is the total array power capacity required from the solar farm in W. In this study, 5MW solar farm is set for the design case study. N_{actual_1} is the actual total numbers of the PV modules designed for the solar farm in integers while N_{bal} is the balance of the PV modules that will be connected to a single inverter.

Step 7: Determine the width of the block, W_{T_block} in meters.

$$W_{T\_block} = W_{1\_PV} \times N_{row\_block}$$

$$W_{1\_PV} = L_{width} \times \cos\beta$$

where L_{width} is the width of each PV module in meters. The value of tilted angle β° used in this study is 10° facing south based on the allocated solar farm which is at Kuala Terengganu, Terengganu [4] and the typical value used for N_{row_block} is between 3 to 4 [8]. Then, the value selected to be used in this study is 3.

Step 8: Determine the maximum height, H_{T_block} of each block in meters.

$$H_{T\_block} = H_{1\_PV} \times N_{row\_block}$$

$$H_{1\_PV} = L_{width} \times \sin\beta$$

Step 9: Determine the required distance between adjacent blocks in front-back position, F_{y_adj} in meters.

$$\delta_{dec} = 23.4° \sin\left[\frac{360(N_{day} - 80)}{365}\right]$$

$$\omega_{hour} = (12 - T) \times 15°$$

$$F_{y\_adj} = H_{T\_block} \times \frac{\sin\varphi_{lat} \times \cos\delta_{dec} \times \cos\omega_{hour} - \cos\varphi_{lat} \times \sin\delta_{dec}}{\sin\varphi_{lat} \times \sin\delta_{dec} + \cos\varphi_{lat} \times \cos\delta_{dec} \times \cos\omega_{hour}}$$

where δ_{dec} and ω_{hour} are the solar declination angle, in ° and the solar hour angle, in ° respectively. Next, N_{day} is the day number of the year and T is the actual time in hour between 0 and 24 hours [9]. φ_{lat} is described as the latitude of the site in °. In this study, φ_{lat} is set to be 5.32N [4]. In determining F_{y_adj}, only the highest value of F_{y_adj} obtained will be used as the distance between front and back blocks.

Step 10: Determine the total number of vertical and horizontal PV modules arrangement, N_{b_vert} and N_{b_horz} in integers.

$$N_{b\_vert} = round\ up\left[\frac{\left(L_{D2} - (rsv_x + rsv_y)\right)}{W_{T\_block} + F_{y\_adj}}\right]$$

$$N_{b\_horz} = round\ up\left[\frac{\left(L_{D1} - (rsv_z + rsv\_ph_y)\right)}{(L_{length} + G) \times (N_{s\_PV} + f_x)}\right]$$

where L_{length} is the length of each PV module, in meters. The value of f_x used in this study is 2 m and G is 0.02 m.

Step 11: Determine the total number of array blocks in front-back positions, N_{block_PV} in integers.

$$N_{block\_PV} = Round\ up\ \frac{N_{PV\_all}}{N_{b\_vert} \times N_{row\_block}}$$

Step 12: Determine the actual dimension of the required installation area for the large-scale GCPV system, D_{1_DIM} and D_{2_DIM} in meters. D_{1_DIM} is the total actual dimension of the horizontal PV module arrangement and D_{2_DIM} is the total actual dimension of the vertical PV module arrangement.

$$D_{1\_DIM} = N_{b\_horz} \times L_{length}$$

$$D_{2\_DIM} = N_{b\_vert} \times L_{width}$$

$$D_{1\_DIM} \leq L_{D1}$$

$$D_{2\_DIM} \leq L_{D2}$$

In order to make sure the required installation area is between the ranges of the available space area, the conditions above were implemented.

Step 13: Determine the total length of the metallic spars, B_{tot_spars} in meters used for the mounting structures using.

$$B_{tot\_spars} = B_{1\_vert} \times n_{b\_vert}$$

$$B_{1\_vert} = 2 \times \left(B_{tot\_vert} + H_{T\_block} + L_{T\_row}\right) + \left(B_{2\_vert} + 2\right) \times L_{width}$$

$$B_{tot\_vert} = \sum_{i=1}^{B_{2\_vert}} i \times 2$$

$$L_{T\_row} = N_{row\_block} \times L_{width}$$

$$B_{2\_vert} = Round\ down \frac{H_{T\_block}}{2}$$

$$n_{b\_vert} = Round\ up \frac{N_{PV\_all}}{N_{row\_block}}$$

$$B_{B\_concrete} = \left(2 + B_{2\_vert}\right) \times h_{w\_height} \times t_{w\_thick} \times L_{length} \times n_{b\_vert}$$

Step 14: Determine the total area covered for the large-scale GCPV system in meters^2.

$$L_{vert\_A} = L_{D2} - (rsv_x + rsv_x)$$

$$L_{horz\_A} = L_{D1} - \left(rsv_z + rsv\_ph_y\right)$$

$$A_{Land} = L_{vert\_A} \times L_{horz\_A}$$

L_{vert_A} and L_{horz_A} are the vertical and horizontal length of the available space to install the PV module in meters and A_{Land} is the available area that can used to install the PV module, in meters^2. The total area covered for the GCPV system including the space required to build the power house. L_{D1} and L_{D2} for this study are 447.102 m each.

2.3.1 Evaluation of Technical Performance Indicator

The technical performance indicator used in this study is the Performance Ratio (PR). The steps towards determining the PR of the design are explained below.

Step 1: Determine the Final Yield, Y_F in kWh for the plant and the reduction factor due to temperature, f_{temp_ave} using

$$Y_F = (\frac{P_{arr\_req}}{1000}) \times PSH \times f_{temp\_ave} \times f_{dir} \times n_{inv} \times n_{pv\_inv}$$

$$f_{temp\_ave} = 1 + \frac{\gamma_{pmp}}{100} (T_{cell} - 25)$$

where PSH is Peak Sun Hour in hour, f_{dir} is dirt factor considering dirt and dust accumulation on PV modules and f_{age} is the aging factor of the PV module. n_{pv_inv} is the expected cabling efficiency from the PV array to inverter.

Step 2: Determine the actual rated power of the PV array, P_{arr_stc} in W.

$$P_{arr\_stc} = N_{s\_PV} \times N_{p\_PV} \times P_{mp\_stc}$$

Step 3: Determine the expected annual Specific Yield, *SY* of the plant in kWh per kWp.

$$SY = \frac{Y_F}{P_{arr\_stc}/1000}$$

Step 4: Determine the Performance Ratio, *PR* of the plant in %.

$$PR = \frac{Y_F}{P_{arr\_stc}/1000} \times \frac{1}{PSH}$$

PR is the ratio of the expected energy output from the system with respect to the ideal energy output is theoretically available [10, 11].

2.3.2 Cuckoo Search (CS) Algorithm

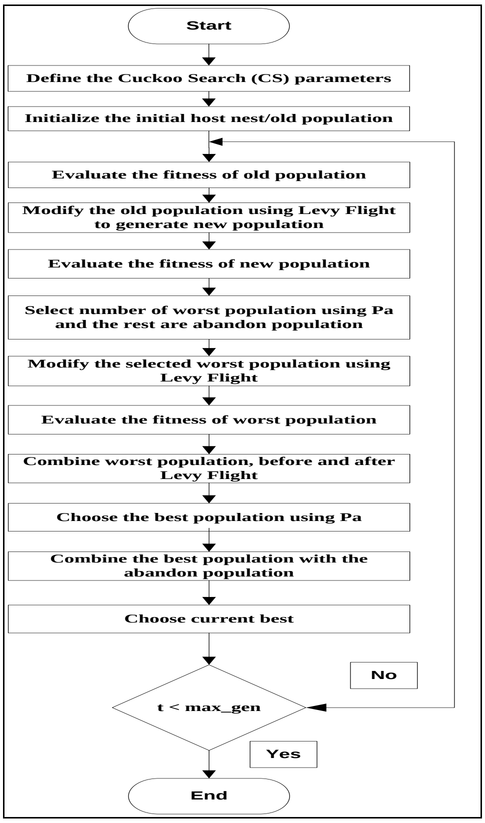

Figure 1. Flowchart of sizing optimization using Cuckoo Search (CS).

Figure 1 showed the flowchart of sizing optimization using CS algorithm. Later, CS algorithm will be used as a comparison in term of technical performance indicator with the ISA method.

3. Result and Discussion

3.1 Maximizing Performance Ratio

This section describes the results of GCPV system design using ISA in maximizing PR. The performance of ISA in maximizing PR is shown in Table 1. The total computation time or elapsed time was found to be 3,115.9987 seconds while the maximum PR was discovered to be 92.08722 % using PV module code 21 and inverter code 10. The optimal PR obtained in ISA is used as benchmark for the sizing algorithms using CIs at later stage.

Table 1. Sizing Result of large-scale GCPV System based on Performance Ratio (PR) using ISA

Sizing parameters	Value
PV module code, x1	21
Inverter code, x2	10
N_{s_pv}, in integer	17
N_{p_pv}, in integer	1
N_{bal}, in integer	4
X_i, in integer	1,131
N_{PV_all}, in integer	19,231
P_{arr_stc}, in watt (W) per inverter	4,420
N_{b_vert}, in integer	505
N_{b_horz}, in integer	15
N_{block_PV}, in integer	13
Y_F (kWh)	7,144.926
SY (kWh per kWp)	1,616.499
PR (%)	92.08722
Elapsed Time, t (s)	3,115.9987

3.8 Maximization of Performance Ratio using Cuckoo Search Optimization Algorithm (CS)

The maximization of PR in CS-based sizing algorithm using different population size is tabulated in Table 2. The maximum PR achieved with all population sizes is 92.08132% with 5 becomes the minimum population size discovered for the CS-based sizing algorithm. In short, CS had failed to assist the sizing algorithm in achieving the optimal PR although the elapsed time of the optimal CS with population of 5 was approximately 4 times faster than ISA.

Table 2. Sizing results using different number of iteration for CS based on Performance Ratio (PR).

Results	Number of Populations					
	ISA	5	10	15	20	25
x1*	21	8	4	2	3	9
x2#	10	10	10	10	10	10
N_{s_pv}, in integer	17	14	15	15	15	14
N_{p_pv}, in integer	1	1	1	1	1	1
N_{bal}, in integer	4	0	0	9	7	7
X_i, in integer	1,131	1,171	1,130	1,169	1,149	1,190
$N_{PV\ all}$, in integer	19,231	16,394	16,950	17,544	17,242	16,667
$P_{arr\ stc}$, in W	4,420	4,270	4,425	4,275	4,350	4,200
$N_{b\ vert}$, in integer	505	524	375	518	518	524
$N_{b\ horz}$, in integer	15	172	14	14	14	172
N_{block_pv}, in integer	13	11	16	12	12	11
Y_F, in kWh	7,144.926	6,902.009	6,926.817	6,910.091	7,031.321	6,788.861
SY, in kWh per kWp	1,616.499	1,616.396	1,565.382	1,616.396	1,616.396	1,616.396
PR, in %	92.08722	92.08132	92.08132	92.08132	92.08132	92.08132
Elapsed Time, in seconds	3,115.9987	754.5178	1875.3751	3316.0371	5716.5135	8546.8001

4. Conclusion

This paper presented the sizing optimization of large-scale Grid-Connected (GCPV) system using Cuckoo Search (CS). Firstly, the sizing algorithm initially involved the development of CSA for large-scale GCPV system considering single set of system components for optimizing a performance indicator for the design. Next, an iterative-based sizing algorithm (ISA) was developed with consideration of different possible sets of PV modules and inverters which were stored in a component database. The ISA is capable of searching for the optimal set of PV module and inverter that produces the optimal performance of the prospective GCPV system. The results from ISA were then used as benchmark for the CS-based sizing algorithm. At later stage, CS-based sizing algorithm was developed to determine the optimal set of PV module and inverter that produces the optimal performance of the prospective large-scale GCPV system. The results showed that ISA was better than CS in term of producing optimum fitness value. However, CS was better than ISA in producing lower computation time.

5. Acknowledgement

This work was supported in part by the Fundamental Research Grant Scheme (FRGS), Ministry of Education (Ref: 600-RMI/FRGS 5/3 (120/2015)) and Universiti Teknologi MARA (UiTM) Malaysia.

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