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Iterative-based Sizing Algorithm for Stand-Alone Photovoltaic Systems

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ABSTRACT

This paper presents an iterative-based sizing algorithm for stand-alone photovoltaic (SAPV) system and hybrid stand-alone photovoltaic (HSAPV) system. In SAPV system, optimal photovoltaic (PV) module, solar battery, charge controller and inverter were selected from a component database. On the other hand, optimal PV module, solar battery, charge controller, inverter and diesel generator were selected from a component database for HSAPV system. In both systems, Iterative Sizing Algorithm (ISA) was developed to evaluate every possible combination of system components listed in the respective databases. The performance of ISA was compared with the performance of conventional sizing algorithm in terms of performance ratio (PR) and computation time. The results showed that ISA when tested in SAPV system produces the highest PR similar to PR achieved using conventional sizing algorithm with computation time approximately 15 times lower than the computation time required by conventional sizing algorithm executed in multiple runs. When tested in HSAPV system, ISA yields the highest PR similar to PR achieved using conventional sizing algorithm with computation time approximately 61 times lower than the computation time required by conventional sizing algorithm executed in multiple runs.

Key words : Performance Ratio (PR), Iterative Sizing Algorithm (ISA),Single Run (SR), Hybrid Stand Alone Photovoltaic System (HSAPV), Stand Alone Photovoltaic System (SAPV)

1. INTRODUCTION

Electricity is a crucial form of energy for the advancement of a civilization. It must be generated efficiently with minimum damage to the environment and helps to promote economic growth. Electricity can be produced using several types of energy resource such as fossil fuels, nuclear energy and Renewable Energy (RE). According to REN 21 Global Status Report 2019 [1], the world electricity production is still dominated by non-renewable based energy resources such as fossil fuels and nuclear energy with the latter minimally contributes to the total share. Approximately 73.8% of global electricity production comes from non-renewable electricity whereas about 26.2% comes from renewable electricity. Although fossil fuels are proven to be dominant in global electricity production, this energy resource is depleting in nature besides polluting the environment with the release of greenhouse gases (GHG).On the other hand, implementation of nuclear energy demonstrates safety and disposal issues in-spite of having much lower GHG emission when compared to fossil fuels. Due to the shortcomings of fossil fuels and nuclear energy,

RE is presented as an alternative energy resource for electrification. RE is a non-depleting resource an environmentally benign [2]. Examples of RE resource are solar, wind, hydro, geo-thermal and biomass. Among these resources, solar is one of the promising REs due to its broader availability when compared to other RE resources. Solar energy is used for either electricity generation or thermal generation [3]. In solar electricity generation, solar cells are used to convert solar energy from sunlight into electricity. This conversion is known as photovoltaic (PV).

The solar cells are normally interconnected and encapsulated to form a PV module before several PV modules are connected to one or a combination of power conditioning devices and energy storage to form a PV system. PV systems can be then widely classified into Grid-Connected Photovoltaic (GCPV) systems and Stand Alone Photovoltaic (SAPV) systems [4].

In GCPV systems, PV modules produce DC electricity which is then channeled to inverters for DC-AC conversion [5]. The AC power is then partially or fully injected to the grid depending on the chosen feed-in mechanism. On the other hand, an SAPV system typically consists of PV modules, inverters, charge controllers and solar batteries. DC electricity from PV modules is used to charge the solar batteries via charge controllers. Then, the DC power from the batteries is channeled to inverters for DC-AC conversion if AC load demand becomes the target load for electrification.

In a separate setting, SAPV systems are regularly used as a power generating systems in remote areas with absence of normal grid electricity supply. Also, it is known as off-grid PV system as it does not involve interaction with the utility grid [6]. Generally, SAPV system can be categorized into PV direct, PV-battery and PV-hybrid system. This type of SAPV system is known as Hybrid Stand Alone Photovoltaic (HSAPV). PV direct systems are usually straightforward systems where it used for powering up small electrical loads without charge storage. Meanwhile, the PV-battery system used in conjunction with a battery back-up to provide a higher load demand and typically for the house. The PV-hybrid system is used to provide electricity to a larger scale such as supplying electricity to some houses or more than one village.

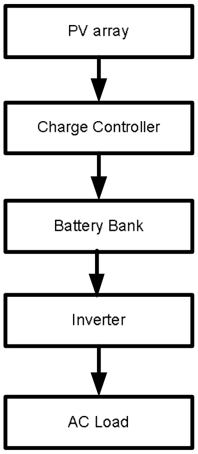
Overall, PV-hybrid systems consist of PV array which is hybridized with other generators such as diesel generators, wind generators, and hydropower generators. Usually, the PV-battery system and PV-hybrid system is commonly referred to as Individual Energy Systems (IES) and the Community Energy System (CES), respectively. Normally, the PV-hybrid system is fully funded and maintained by the government while PV-battery systems are usually privately funded and managed by the owner of the system itself.

However, if there is more than one SAPV model, the sizing process is repeated to achieve the most suitable parameters for the design [7]. The design models are explained the Iterative Sizing Algorithms (ISA) technique. ISA are presented to show the real sizing process when there are numerous set of system components available for assessment before the optimal set of system components is determined to be the optimal sizing solution [8].

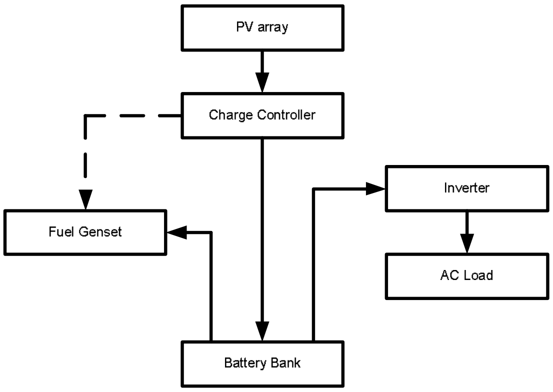
This paper is to optimize the sizing for both Stand Alone Photovoltaic System and Hybrid Stand Alone Photovoltaic System based on load profile. There are two systems have been developed, used to determine the optimum PV modules, battery, charge controllers, inverters, and diesel generator. The outcome of Iterative Sizing Algorithm (ISA) serves as benchmark for the computational intelligence – based sizing algorithms development. The outcome of ISA is performed the computational intelligence-based sizing algorithm approach.

2. SYSTEM DESCRIPTION

This section illustrates the method for sizing solar photovoltaic system. The flow process involved for sizing in Figure 1. (a) shows that the block diagram of SAPV system while Figure 1. (b) shows the block diagram of HSAPV system.



(a)



(b)

Figure 1: Block Diagram of Solar Photovoltaic System

The load profile is the main requirement before performing the SAPV and HSAPV system. This study collected data from rural area in Kalabakan, Sabah, Malaysia. Table 1 and Table 2 shows the estimated average daily load profile for typical house and monthly solar radiation.

2.1 Sizing System Procedure

The sizing procedure was adopted in [10]. It is outlined as follows:

Step 1: Obtain the load profile of the site. In this study, the load profile being used is shown in
Table 1.

Step 2: Compute the total required daily load demand, E_{req_daily} in Wh for the system.

$$E_{req\_daily} = E_{AC} / \eta_{inv} \tag{1}$$

Where *EAC* is the total energy required daily for AC load as delivered by the battery in Wh, and η_{inv} is the efficiency of inverter.

Step 3: Determine the system voltage (SV) in SAPV and HSAPV system. The SV can be selected based on in equation (1). The criteria for selecting SV are illustrated in Table 3.

Step 4 : Calculate the required Ah demand of the battery bank, C_{req_batt} in Ah using

$$C_{req\_batt} = \frac{E_{req\_daily}}{SV} X \frac{T_{autonomy}}{DOD_{\max}} \tag{2}$$

where DOD_{max} is the maximum discharge depth of the battery. The $T_{autonomy}$, indicates the expected number of days on which the load demand is covered by the battery bank without availability of sunlight.

Table 1 : Average Daily load Profile for typical house in Kalabakan

AC Appliance	Number of Units	Power	Power factor,θ	Usage Time	Energy	Usage Time	Energy
				Weekdays		Weekend	
		W		h	Vah	h	Vah
Incandescent bulb	4	40	0.8	10	2000	12	2400
Television	1	80	0.9	6	533.33	8	533.33
Water pump	1	120	0.8	3	450.00	5	750.00
Ceiling Fan	3	60	0.75	5	1200	8	1920
Radio	1	10	0.9	8	88.89	10	88.89
Refrigerator	1	50	0.9	24	1333.33	24	1333.33
Daily average load demand					4316.67		5016.67

Table 2 : Monthly Solar Irradiation for Tawau, Sabah [9]

Month	Average daily PSH, h	Month	Average daily PSH, h
January	4.43	July	4.78
February	4.8	August	4.87
March	4.96	September	4.99
April	5.11	October	4.78
May	4.87	November	4.68
June	4.83	December	4.37

Step 5 : Determine the revised required capacity of battery bank, $C_{rev\_batt\_req}$ in Ah with considering temperature effect using

$$C_{rev\_batt\_req} = \frac{C_{rev\_batt}}{f_{temp\_batt}} \tag{3}$$

where f_{temp_batt} is the battery temperature correction factor.

Step 6 : Calculate the total load current from the battery bank, $I_{total\_load\_current}$ and the battery bank discharge rate, T_{bank_disch}

$$I_{bank\_dish} = \frac{1}{SV} X \left[\sum\nolimits_{1}^{z} \frac{P_{AC}}{pf} \right] \tag{4}$$

$$T_{bank\_dish} = \frac{C_{rev\_batt\_req}}{I_{bank\_dish}} \tag{5}$$

where z is the load number, P_{AC} is rated power of a specific load and PF is the power factor of the load. T_{bank_disch} is the discharge rate of battery bank in h.

Step 7 : Calculate the battery bank configuration, i.e. the number of battery in series string, N_{s_batt}, number of battery strings in parallel, N_{p_batt} and bank capacity of the selected battery, $C_{bank\_selected}$,

$$N_{s\_batt} = \frac{SV}{V_{nom\_batt}} \tag{6}$$

$$N_{p\_batt} = \frac{C_{rev\_batt\_req}}{C_{per\_batt}} \tag{7}$$

where V_{nom_batt} is the nominal battery voltage and C_{per_batt} is the AH capacity which can selected from the datasheet.

Step 8 : Determine the maximum number of series PV module based on open circuit voltage. $N_{s\_max\_Voc}$

$$N_{s\_\max\_Voc} = \frac{0.95 x V_{\max\_cc}}{V_{\max\_oc}} \tag{8}$$

Where V_{max_cc} is the maximum input voltage rating of the charge controller and V_{max_oc} is the maximum open circuit voltage rating of PV module.

Step 9: Determine the maximum number of series PV module based on maximum power voltage, $N_{s\_max\_Vmp}$

$$N_{s\_\max\_Vmp} = \frac{0.95 x V_{\max\_window\_cc}}{V_{\max\_mp}} \tag{9}$$

Where $V_{max\_window\_cc}$ is the maximum window voltage of the charge controller and V_{max_mp} is the maximum voltage at maximum power at PV module.

Step 10: Determine the minimum number of PV modules per string to the charge controller, N_{s_min} using

$$N_{s\_\min} = \frac{1.1xV_{\min\_window\_cc}}{V_{\min\_mp}x\eta_{pv\_cc}} \tag{10}$$

where 1.1 is the coefficient set to ensure that the expected minimum voltage of PV array.

Step 11: Calculate the total number of PV modules in the PV array, N_{t_pv} and the number of parallel PV strings, N_{p_pv} using

$$N_{t\_pv} = \frac{E_{req\_daily}xf_o}{P_{mp\_stc}xPSHx\eta_{pv\_cc}} \tag{11}$$

$$N_{p\_pv} = \frac{N_{t\_pv}}{N_{s\_pv}} \tag{12}$$

Step 12: Calculate the number of charge controllers for the system using

$$N_{cc} = \frac{P_{array\_stc}}{P_{nom\_cc}} \tag{13}$$

$$P_{array\_stc} = N_{t\_pv}XP_{mp\_stc} \tag{14}$$

where P_{nom_cc} is the nominal power of charge controller and P_{array_stc} is the maximum power of PV array at STC in W.

Step 13: Calculate the output of the system which is Performance Ratio (PR)

$$PR = \frac{E_{sys\_\exp}}{P_{array\_stc}XPSH_{annual}} \tag{15}$$

where $E_{sys\_\exp}$ is expected output of annual energy and PSH_{annual} is the estimated value of PSH obtained from Table 1.

3. RESULTS AND DISCUSSION

This section describes the performance of ISA against SR in both SAPV and HSAPV systems. In SAPV and HSAPV system, the performance of ISA and SR are shown in Table 3. ISA produces computation time of 3,596.125 seconds while SR yields computation time of 54,326.24 seconds. The computation time of SR was obtained by adding the computation time of SR for total number of runs involving 20,736 combinations. Therefore, ISA is approximately 15 times faster than SR being run for all possible combinations. Apart from that, both SR and ISA had recorded maximum PR of 0.7918 with PV module, battery, charge controller and inverter code of 12, 12, 8 and 12 respectively.

In HSAPV system, for the computation time, ISA was found to be 11,087.94 seconds while SR produced 677,594.42 second as valid solutions. The computation time of SR was obtained by adding the computation time of SR for total number of runs involving 248, 832 combinations. Therefore, ISA is approximately 61 times faster than SR being run for all possible combinations. Apart from that, both ISA and SR had recorded maximum PR of 0.7839 with PV module, battery, charge controller, inverter and diesel generator code of 11, 12, 8, 12 and 12 respectively.

These means, for both system show that ISA is capable of achieving the maximum PR similar to the one obtained using SR, but with much lower computation time.

4. CONCLUSION

An iterative based sizing algorithm is presented to determine the optimal system components for SAPV and HSAPV systems with the highest PR. ISA was employed by recursively evaluate all possible combinations of system components derived from component databases. ISA when tested in SAPV system produces the highest PR similar to PR achieved using SR with computation time approximately 15 times lower than the computation time required by SR executed in multiple runs. On the other hand, when tested in HSAPV system, ISA yields the highest PR similar to PR achieved using SR with computation time approximately 61 times lower than the computation time required by SR executed in multiple runs. As a conclusion ISA is the best solution in term of computational time.

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Table 4 : Results of SR and ISA for SAPV System

Description	SAPV		HSAPV	
	SR	ISA	SR	ISA
Optimal PV module code*	12	12	11	11
Optimal battery code*	12	12	12	12
Optimal charge controller code*	8	8	8	8
Optimal inverter code*	12	12	12	12
Optimal diesel generator code *	-	-	12	12
Ns_pv, in integer	4	4	2	2
Np_pv, in integer	4	4	3	3
Nt_pv, in integer	16	16	6	6
Ns_batt, in integer	8	8	8	8
Np_batt, in integer	1	1	1	1
Ncc, in integer	1	1	1	1
Ninv, in integer	1	1	1	1
Ndiesel generator, integer	-	-	1	1
Optimal Performance Ratio (PR), in decimal	0.7918	0.7918	0.7839	0.7839
Overall computation time, in seconds	54326.24	3596.125	677,594.42	11,087.94

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