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Optimal sizing of stand-alone photovoltaic system by minimizing the loss of power supply probability

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ABSTRACT

This paper presents Firefly Algorithm-based Sizing Algorithm (FASA) for sizing optimization of a Stand-Alone Photovoltaic (SAPV) system. Firefly Algorithm (FA) was used to optimally select the model of each system component such that a technical performance indicator is consequently optimized. Prior to implementation of FASA, an Iterative-based Sizing Algorithms known as ISA had been developed to determine the optimal solutions which were used as benchmark for FASA. Although ISA was capable in determining the optimal design solutions when there are numerous models for each system component being considered, the computation time of ISA can be very long as ISA tested every possible combination of PV module, battery, charge controller and inverter during sizing process. Therefore, FASA was introduced to accelerate the sizing optimization for SAPV system. FA was incorporated into sizing algorithm with the technical performance indicator was set to optimize the Loss of Power Supply Probability (LPSP). Besides that, two design cases of PV-battery system, i.e. system with standard charge controller denoted as Case 1 and system with MPPT-based charge controller denoted as Case 2 were investigated. The results showed that FASA had successfully found the optimal LPSP in all design cases. In addition, sizing algorithm with FA was also discovered to outperform sizing algorithm with selected computational intelligence in producing the lowest computation time in the sizing optimization.

1. Introduction

Electricity plays an important role in the development of a civilization. It is used to power up residential and office buildings, industries, information and communication equipment as well as vehicles and transportation. Electricity in a conventional power system is generated using several types of energy resources such as fossil fuels, nuclear energy and renewable energy (RE). Recent statistics in REN21 (2015) revealed that the world electricity generation is currently dominated by the usage of fossil fuels, followed by renewable energy and nuclear energy. However, fossil fuels are basically a finite energy resource which is depleting with respect to time. In addition, the burning of fossil fuels results in greenhouse gases (GHG) emission (Hosseini and Wahid, 2013). As a result, the quality of the surrounding environment is highly compromised when using fossil fuels as mode of electricity generation. Due to the drawback of the fossil fuels, nuclear energy offers a more attractive solution towards a cleaner mode of electricity generation as it does not release GHG to the environment. Nevertheless, there are other issues related to the implementation of nuclear power plant such as safety and disposal of nuclear waste (Lior, 2010). Therefore, renewable energy is introduced as its energy resource is inexhaustible and environmentally benign (Ellabban et al., 2014).

RE can be defined as a continuous natural resource that can be replenished without failure and will not be depleted throughout time (Dincer, 2000). RE technologies are developed using several types of energy resource such as solar, wind, hydro, biomass and geothermal. However, solar energy is one of the most popular REs as the sunshine is ample and available in wider region as compared to other RE resources. In electricity generation, solar energy is converted to electricity via photovoltaic (PV) effect. Therefore, a solar energy-based electricity generation system is known as PV system. A review paper in Muhammad-Sukki et al. (2012), Aman et al. (2015) reported that PV system has the fastest market growth worldwide when compared with other RE technologies. The PV systems can be implemented using either Grid-Connected Photo-

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voltaic (GCPV) systems or Stand-Alone Photovoltaic (SAPV) systems. A GCPV system is a PV system which injects the solar electricity to a power utility grid network while an SAPV system is a PV system which is used to directly power up the electrical loads. Apart from that, a GCPV system typically consists of two major components i.e. the PV modules and inverter while an SAPV system consists of PV modules, charge controller, batteries and inverter. However, due to the ease of interconnection and small number of components involved, GCPV systems have become more widely used when compared to SAPV systems especially in locations with readily available utility grid network. In addition, GCPV system offers a distinctive advantage, i.e. the utility grid provides an energy backup to meet the load demand whenever the system fails. As a result, the design of GCPV system is often less critical when compared to SAPV system since the reliability of electricity supply for a particular location is often not an issue. In contrast, the issue of reliable electricity supply for an SAPV system continues to prevail in areas which are deprived of utility grid electricity since there is no back-up power to meet the load demand during the event of rainy or cloudy days as well as when there is a system failure. Therefore, reliability of electricity supply for an SAPV system is frequently given the top priority in its system design. The dimensioning, selection and matching of SAPV system components are known as sizing (Sulaiman et al., 2011), which is the issue that has been addressed in this paper. If the system is poorly sized or designed, the operation of the system would be interrupted, thus reducing the overall reliability of the system as a power supply entity. In addition, as there are numerous models of system components in the market, selection of the optimal model for each component has always become a challenging task for the system designers (Sulaiman et al., 2012). Apart from that, existing studies on SAPV system sizing frequently focus on the determination of optimal number of PV modules, capacity of PV module, number of batteries, battery capacity, number of inverters, number of charge controllers and array configuration of SAPV system which makes the practicality of sizing results is limited for usage as the dimensioning among the system components were not investigated in the study. Although sizing can be accelerated using various commercial sizing software in the market, the usage of the software is inflexible as the sizing task is limited to the sizing sequence and assumptions used by the individual software. Moreover, sizing software frequently requires trial-and-error inputs from the designer while the sizing process is executed based on a pre-determined system components selected by the system designer. If there are numerous models for each system component that need to be evaluated, the selection of the optimal model for the system components becomes tedious and time consuming since every design option need to be evaluated before determining the optimal design option. In fact, the search for the optimal design option would obviously turn out to be impractical when the design time is a primary concern among the designers. Due to these drawbacks, the sizing software is merely utilized as a comparative tool to evaluate the sensibility of sizing results. Thus, the usage of the software is often limited.

The limitation of sizing software for SAPV systems had opened to many studies on sizing optimization. The sizing optimization algorithms were commonly developed using various types of Computational Intelligence (CI). Koutroulis et al. in Kornelakis and Koutroulis (2009) and Koutroulis and Kolokotsa (2010) used Genetic Algorithm (GA) to determine the optimal number of wind generators, PV modules, batteries, charge controllers, PV module tilt angle and wind generators' installation height such that the total system cost is minimized for a hybrid SAPV system. Although the optimal model of each system component had been investigated, it was not selected using GA. The optimal model was only chosen by repeating the GA-based sizing algorithm for each possible combination of system components available from the respective components' database. Apart from that, Sinha in Sinhaa and Bajpai (2012) presented a Particle Swarm Optimization (PSO)-based sizing algorithm for a PV-fuel cell-battery system. PSO was used to determine the optimal PV array capacity, battery capacity, fuel cell capacity, minimum and maximum state of charge of the battery such that the total system cost is minimized as long as the sizing penalty factor is less than 5%. The results showed that PSO performs better than GA in finding the optimal solution. It was also found that PSO could be implemented using lower number of iterations as compared to the GA. However, technical reliability of the system as a power entity might be questionable as the technical performance indicator of the system was not quantified in the sizing process. In addition, besides excluding the evaluation of system technical performance indicator, the dimensioning and matching characteristics among the system components were absence in the sizing simulation. Dimensioning of the system components is important as it involves the determination of configuration of system components, i.e. the number of components in series and parallel. Thus, the practicality of the sizing results is limited for usage.

This paper presents a Firefly Algorithm (FA) for sizing optimization of SAPV system as FA is expected to be faster than existing Computational Intelligences used for sizing optimization of SAPV systems. FA was used to select the optimal system components such as PV module, battery, charge controller and inverter such that the technical performance of the system is optimized. In addition, unlike the previous studies mentioned above, the dimensioning of PV array and battery bank was included to improve the usability of the sizing algorithm. Besides that, two types of charge controller technology, i.e. the standard charge controllers and Maximum Power Point Tracking (MPPT)-based charge controllers which are commercially available in the market were tested using the sizing algorithm.

2. Methodology

Sizing of SAPV system involves selection and determination of sizing parameters such as the model, capacity and configurations of the PV system components such that the load demand can be met (Aziz et al., 2014; Shen, 2009). In this study, the sizing of SAPV system is conducted for a house located in Kalabakan, Tawau, Sabah, Malaysia. Since the sizing is conducted to meet the load demand for one house only, a PV-battery system is considered. The system consists of PV module, battery, charge controller and inverter.

Firstly, the sizing of SAPV system was initiated with the formulation of Conventional Sizing Algorithm (CSA). CSA is capable of sizing system with only single set of system components. Later, an Iterative-based Sizing Algorithms known as ISA was developed to consider numerous models of each system component for the system sizing. This sizing approach is significant as the practical design effort by system designers frequently involves multiple design options being considered before an optimal solution for the design is determined. Besides that, the results from ISA are also used as benchmark for the development of FA-based sizing algorithm (FASA) presented in this study.

3. Conventional-based sizing algorithm approach

The conventional sizing of SAPV system is conducted using a prescribed sizing procedure. In this study, CSA was developed in Matlab. The CSA initially requires the system designer to select a set of system components consisting of PV module, battery, charge controller and inverter before trying to match the characteristics of