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Optimal economic designing of grid-connected photovoltaic systems with multiple inverters using linear and nonlinear module models based on Genetic Algorithm

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ABSTRACT

Nowadays installed power capacity of grid-connected photovoltaic (GCPV) systems has an exponential increase around the world. Since these systems are more expensive than other conventional electricity resources, optimal economic designing is much necessary. In this paper, a new intelligent-based approach is proposed to design GCPV systems using Genetic Algorithm (GA). By defining the net present value (NPV) of system as the objective function and considering electrical constraints, the optimal value for sizing factor and also system configuration are determined. In order to calculate the annual produced energy of system with high accuracy, the accurate efficiency model and power equations are used for inverter and PV module, respectively. Also, five-parameter, i.e. linear and five-point, i.e. nonlinear, models of PV module are used to evaluate the behavior of PV array in different temperature and solar radiation conditions. This approach is presented for GCPV systems in all sizes including two or more inverters even with different topologies. The proposed method is applied for designing of a power plant system with multiple inverters.

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1. Introduction

Concerns of global warming, reduction of fossil fuel resources, energy security and increase in oil prices result in a nearly exponential increase in installed GCPV systems around the world. In these systems, solar radiation energy is converted to electrical energy through PV cells. These cells are assembled into a PV panel or module which then connected to create an array. PV modules are connected in series which is called string and then in parallel as needed to reach a specific voltage and current requirements for the array. The direct current (DC) electricity generated by the array is then converted by an inverter to useable alternating current (AC) that can be consumed by local loads or injected to the electricity grid. GCPV system sizes varies from small residentials (2–10 kW) to commercials (100–500 kW) and also, to large utility scales (>10 MW) [1].

The optimal inverter size determination and configuration selection, called “designing GCPV system”, nowadays has an important role in PV industry. In this way, extraction of maximum available output energy that makes the project economically justified, and also safe performance of inverter in different weather conditions, are guaranteed. To do this, iterative algorithm is the simplest approach. In this method, PV module and inverter of GCPV system should be selected by system designer from available PV modules and inverters. For each combination of selected PV modules and inverters, the electrical constraints should be checked. For a GCPV system with specific array size, combinations which satisfy all limitations are feasible designs. This procedure should be repeated for all possible combinations. For power plant systems, typically larger than 500 kW and systems with more than one inverter, finding these feasible designs is difficult. Reference [2] is an example of the iterative approach. This article presents a method for designing GCPV systems considering electrical, economical and environmental aspects. Via using the monthly average of solar radiation and considering the losses of possible shading over the PV modules, DC cable, inverter and PV array, the yearly produced energy of system is computed. Economic analysis is done through calculating the profit of sold produced energy, which is assumed to be more expensive than the bought energy, capital and maintenance cost of system. To do this, the Internal Rate of Return (IRR), PayBack period Time (PBT), aggregate profit and Net Present Value

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(NPV) for specific annual inflation rate and rate of interest in system site are determined. Also, in this analysis the loan provided by the government and taxation fee of sold produced energy are considered. For environmental analysis, the pollution of required fossil fuel for other conventional sources to generate the same electric power is calculated. Finally, the system configuration is determined according to electrical constraints. Since the annual output energy of system is computed by using the monthly average of solar radiation data and inappropriate model for PV module and inverter, it seems that the calculated energy is not precise. Also, since this procedure should be done for different sizes of inverter and PV module, for large GCPV systems, this approach is ineffective, i.e. time consuming. Recently, different methodologies are proposed based on Evolutionary Algorithms (EA) such as Particle Swarm Optimization (PSO) and GA to find the economically or environmentally optimal design. In Ref. [3], a new algorithm is introduced based on PSO to find the best economic design for a GCPV system with predetermined size, module and inverter. In this algorithm, initially, the combinations which satisfy electrical constraints are chosen. Then irradiance and ambient temperature data with one-hour resolution are used to calculate the annual produced energy by simulating the system operation for a one year period. Finally, net present value of system as the objective function is maximized so that optimum total module number, optimum number of modules connected to each inverter and optimum module tilt angle are determined. In addition to PV array and inverter costs, in Ref. [3], cost of land required for installation and mounting structures of PV modules are considered in total capital cost. Furthermore, the effect of subsidization and taxation rates on the system NPV is evaluated. Although, all parameters that can effect on annual produced energy are considered except losses of DC and AC cables, but since simple models for PV module and inverter are assumed, the calculated energy is not accurate. As an example, inverter efficiency is assumed to be constant in all operating conditions while it depends strongly on its input power, i.e. output power of PV array. Also, voltage constraint considered in Ref. [3] does not guarantee inverter operation in the maximum power point region. In Ref. [4], an approach based on PSO is proposed to find a set of the best designs called Pareto front, in a multiobjective function including economical and environmental aspects. However, since this approach does not considered electrical constraints, it is not guaranteed that the solutions can be surely implemented. The environmental and economical equations in the multiobjective function are computed as in Refs. [2,3], respectively. By simulating the presented method, Pareto front as an output is determined including the optimal number of PV modules, optimal tilt angle, optimal placement of the PV modules within the available installation area and optimal number of PV modules connected to each inverter. In Ref. [5], a new approach is proposed based on GA to find feasible designs for residential GCPV systems considering only string inverters. The sizing factor is determined so that the GCPV system daily average of produced energy being as close as possible to the predetermined value. Since the proposed objective function not included the economic analysis, it cannot guarantee the optimal system performance. Furthermore, solar radiation and ambient temperature of installation site are not considered in computing the daily energy production of the system.

In order to overcome the mentioned drawbacks, in this paper a novel approach based on GA is proposed to design GCPV systems using multiple inverters even with different topologies. Also, it can be applied to all system sizes including residentials, commercials and power plants. In the proposed algorithm, technical data of PV module and inverter, weather and economic data of the installation site are used to determine the outputs. Then the outputs including the optimum sizing factor and system configuration including number of used inputs in multi string and central inverters, parallel strings connected to each input and series modules in every string are determined. These outputs are determined through deployment of the system NPV as the objective function and modified voltage and current equations as electrical constraints. Electrical constraints are modified so that the algorithm can be applied to all inverter topologies including string, multi string and central. Also, to determine the net present profit of the system, the annual produced energy should be computed. To do this, solar radiation data with one-minute resolution is used. Besides, high resolution for weather data, efficiency versus input power model for inverter, and both five-point and five-parameter models for PV module are used. Therefore, the computed energy in this paper is significantly accurate. Furthermore, since all effective factors on the system NPV are considered, the proposed algorithm is so reliable. Finally, in economical analysis, the sensitivity analysis of effective parameters such as subsidization and taxation rates on NPV, IRR and PBT as the decision variables is done.

The rest of paper is organized as follows: in Section 2, one-diode model of PV module is explained. Furthermore, five-point and five-parameter models known as the most common models using analytical approach to evaluate the behavior of PV module in different locality weather conditions, are introduced. In order to achieve the optimum system design, some characteristics of grid-connected inverters are required. These characteristics are described in Section 3. Calculation procedure of system produced energy and NPV as the objective function and also the modified electrical constraints are introduced in Section 4. The performance of the proposed algorithm is then tested through one power plant PV system simulation in Section 5. Furthermore, sensitivity analysis of economic parameters on decision variables is discussed in this section. Finally, the conclusion is presented in Section 6.

2. Module characteristics

In PV systems, sunlight energy is converted to electrical energy through PV cell which is known as the basic element of PV systems. PV cells are connected in series to make PV module or panel. To reach a specific voltage and current, these modules are connected in series called string and then in parallel to make PV array. PV module behavior can be determined through nonlinear voltage-current curve (V–I) according to the equivalent circuit shown in Fig. 1, called one-diode model. Mathematical equation of this model which is the most common model of PV module in normal operating condition, can be expressed as:

$$I = I_{\mathrm{PV}} - I_0\left[\exp\left(\frac{V + R_{\mathrm{s}}I}{V_{\mathrm{t}}a}\right)\right] - \frac{V + R_{\mathrm{s}}I}{R_{\mathrm{p}}} \tag{1}$$

where I_{PV}, I_0, R_s, R_p and a are photocurrent, reverse saturation current of the diode, series resistance, shunt resistance and diode ideally constant, respectively [6].

Mathematical model of PV module can be used in study of some fields like inverters dynamic analysis, inverter maximum power

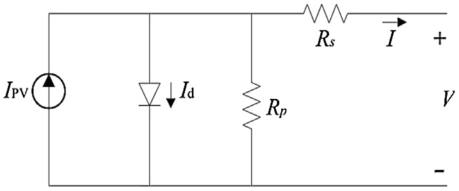

Fig. 1. One-diode model of PV module.

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