Sizing of photovoltaic systems: a review

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Abstract - *Artificial intelligence (AI) techniques are becoming useful as alternate approaches to conventional techniques or as components of integrated systems. They have been used to solve complicated practical problems in various areas and are becoming popular more and more nowadays. AI techniques have the following features: can learn from examples; are fault tolerant in the sense that they are able to handle noise and incomplete data; are able to deal with non-linear problems; and once trained can perform prediction and generalization at high speed. AI-based systems are being developed and deployed worldwide in a myriad of applications, mainly because of their symbolic reasoning, flexibility and explanation capabilities. AI have been used and applied in different sectors, such as engineering, economic, medicine, military, marine, etc. They have also been applied for modelling, identification, optimization, prediction, forecasting, and control of complex systems. The main objective of this paper is to present an overview of the alternative approach and AI techniques for sizing of photovoltaic (PV) systems: stand-alone PV, grid-connected PV system, PV-wind hybrid system, etc). Published literature works presented in this paper show the potential of AI as a design tool in the optimal sizing of PV systems. Additionally the advantage of using an AI-based sizing of PV systems is that it provides good optimisation, especially in isolated areas, where the weather data are not always available.*

Résumé – *Les techniques de l'Intelligence Artificielle (IA) sont plus utiles que les approches alternatives des techniques conventionnelles ou comme composants de systèmes intégrés. Elles ont été utilisées pour résoudre des problèmes pratiques complexes dans différents domaines et sont en train de devenir de plus en plus populaires de nos jours. Les caractéristiques des techniques (IA) sont les suivantes: peut-on apprendre à partir d'exemples; elles tolèrent des pannes dans le sens qu'ils sont en mesure d'absorber le bruit et des données incomplètes, et sont capables de faire face à des problèmes non linéaires, et une fois formés peuvent effectuer rapidement la prévision et la généralisation. Les techniques (IA) sont mises au point et employées dans le monde entier pour une multitude d'applications, principalement en raison de leur raisonnement symbolique, de la souplesse et de la capabilité d'explication. Les techniques (IA) ont été utilisées et appliquées dans différents secteurs, tels que: l'ingénierie, l'économie, la médecine, l'armée, la marine, etc. Elles sont également appliquées dans la modélisation, l'identification, l'optimisation, la prédiction, la prévision et le contrôle de systèmes complexes. Le principal objectif de ce document est de donner un aperçu de l'approche alternative et des techniques (IA) pour le calibrage des systèmes photovoltaïques (PV): stand-alone PV, raccordés au réseau système PV, système hybride (PV-éolien). Les travaux de la littérature présentés dans cet article montrent le potentiel de l'Intelligence Artificielle (IA) comme un outil de conception optimale dans le dimensionnement des systèmes photovoltaïques. En outre, l'avantage d'utiliser une IA basée sur le calibrage des systèmes PV est qu'il offre un bonne optimisation, en particulier dans les régions isolées, où les données météo ne sont pas toujours disponibles.*

Keywords: Photovoltaic (PV) systems - Artificial intelligence technique - Sizing.

1. INTRODUCTION

Renewable Energy (REN) resources have enormous potential and can meet the present world energy demand. They can enhance diversity in energy supply markets, secure long-term sustainable energy supplies, and reduce local and global atmospheric emissions. They can also provide commercially attractive options to meet specific needs for energy services (particularly in

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developing countries and rural areas), and offer possibilities for local manufacturing of equipment [1]. In addition, the use of REN resources have been charted specifically in many of the roadmaps of the developed countries. One of the most promising REN technologies is photovoltaic (PV) technology. PV systems are popularly configured as: stand-alone, grid-connected, and hybrid systems. They are developing rapidly in the world, both in the developed and developing nations. In any PV system, sizing represents an important part of PV systems design, i.e. the optimal selection of the number of solar cell panels, the size of the storage battery and the size of wind-generator to be used for certain applications at a particular site is an important economical task for electrification of villages in rural areas, telecommunications, refrigeration, water pumping, and water heating,… Besides being an economic waste, an oversized system can also adversely affect further utilization of solar cells and the pollution-free PV energy. Undoubtedly, at the present stage of the development of PV technology, the major impediment to a wider market penetration, as noted by Haas [2], is the high investment costs of the PV systems. However, estimation of the sizing parameters PV-array area, useful capacity of battery, wind generator is very useful to conceive an optimal PV systems as well as conceiving an optimal and economic PV systems particularly in isolated sites (Sahara regions, small island archipelagos, remote areas in developing nations, mountainous locations, rural regions, etc.). Hybrid energy systems use different energy resources such as solar and wind energy and diesel gensets. They are an economical option in areas isolated from the grid.

The present paper aims at reviewing the current state of PV systems sizing based on alternative approach and a new approach based on the application of Artificial Intelligence (AI) techniques. This is followed by a review of work reported by several authors. This paper also gives a brief introduction of AI-techniques, followed by an overview of the conventional methods for sizing a PV system. The application of AI-techniques in sizing a PV system is presented and discussed in the final section.

2. ARTIFICIAL INTELLIGENCE TECHNIQUES

2.1 Artificial intelligence

Artificial intelligence (AI) is a term, in its broadest sense would mean the ability of a machine or artefact to perform similar kinds of functions that characterize human thought [3]. The term AI has been applied to computer systems and programmes that can perform tasks more complex than straightforward programming, although still far from the realm of actual thought. AI consists of many branches, such as, expert systems (ES), artificial neural networks (ANN), genetic algorithms (GA) and fuzzy logic (FL) and various hybrid systems, which are combinations of two or more of the branches mentioned previously [4]. AI technologies have a natural synergism that can be exploited to produce powerful computing systems. A theme that can be found in these alternatives is the attempt to make up for deficiencies in the conventional approaches. In some cases, the goal is to produce better, more efficient and effective computing systems. Sometimes this requires adding features associated with human intelligence such as learning and the ability to interpolate from current knowledge. The appropriate use of intelligent technologies leads to useful systems with improved performance or other characteristics that cannot be achieved through traditional methods [5].

2.2 Artificial neural networks

An ANN is a collection of small individually interconnected processing units. Information is passed through these units along interconnections. An incoming connection has two values associated with it, an input value and a weight. The output of the unit is a function of the summed value. ANN's while implemented on computers are not programmed to perform specific tasks. Instead, they are trained with respect to data sets until they learn patterns used as inputs. Once they are trained, new patterns may be presented to them for prediction or classification. ANN's can automatically learn to recognize patterns in data from real systems or from physical models, computer programs, or other sources. An ANN can handle many inputs and produce answers that are in a form suitable for designers [4].

2.3 Fuzzy logic

Fuzzy logic (FL) is used mainly in control engineering. It is based on fuzzy logic reasoning which employs linguistic rules in the form of IF–THEN statements. Fuzzy logic and fuzzy control feature a relative simplification of a control methodology description. This allows the application of a 'human language' to describe the problems and their fuzzy solutions. In many control applications, the model of the system is unknown or the input parameters are highly variable and unstable. In such cases, fuzzy controllers can be applied. These are more robust and cheaper than conventional PID controllers. It is also easier to understand and modify fuzzy controller rules, which not only use human operator's strategy but, are expressed in natural linguistic terms [4].

2.4 Genetic algorithm

GA's are inspired by the way living organisms are adapted to the harsh realities of life in a hostile world, i.e. by evolution and inheritance. The algorithm imitates in the process the evolution of population by selecting only fit individuals for reproduction. Therefore, a GA is an optimum search technique based on the concepts of natural selection and survival of the fittest. It works with a fixed-size population of possible solutions of a problem, called individuals, which are evolving in time. A GA utilizes three principal genetic operators: selection, crossover, and mutation [4].

2.5 Hybrid-systems

Hybrid systems combine more than one of the technologies introduced above, either as part of an integrated method of problem solution, or to perform a particular task that is followed by a second technique, which performs some other task. For example, neuro-fuzzy controllers use neural networks and fuzzy logic for the same task, i.e. to control a process, whereas in another hybrid system a neural network may be used to derive some parameters and a GA may be used subsequently to find an optimum solution to a problem [4].

3. OVERVIEW ON THE CONVENTIONAL METHODS FOR SIZING PV-SYSTEMS

3.1 Stand-alone PV-system

Photovoltaic (PV) applications may offer a promising alternative especially in remote areas as isolated small power generation for the essential electric power. All around the world there are a number of small isolated communities, like the Saharan sites, rural villages of Algeria, island archipelagos and mountainous regions, without access to the grid. Furthermore, in many places due to the remoteness and due to the cost, it is unlikely that main grid connection will be ever established. However, the need for power still exists. Power systems which can generate and supply electricity to such remote locations are differently termed 'decentralized, autonomous or stand-alone'. These may come as individual energy systems (IES) or community energy systems (CES). The technology for power production from renewable energy (REN) resources is available and reliable so the penetration of the technology depends mainly on the economic feasibility and the proper sizing of the components in order to avoid outages as well as ensuring quality and reliability of supply. Several models have been developed, simulating and sizing PV systems using different operation strategies. The estimation of the excess of energy provided by PV generators using the utilisability method was developed by Liu and Jordan [6]. The excess energy provided by PV systems for an installation having a constant load was also evaluated by Klein [7]. Siegel *et al.* [8] evaluated the monthly average output, the excess of energy and the storage capacity of the batteries. Evans *et al.* [9] described a method to consider the monthly average output of PV fields, Gupta and Young [10]. Clark *et al.* [11] use the average utilisability function. All these methods are based on the energy balance of the systems studied to determine their storage capacity and output. Other methods estimate the performance of PV systems based on the Loss of Load Probability (LLP) technique, defined as the ratio between the energy deficit and the energy demand, both on the load, there are developed by Bucciareli [12], Klein and Beckman

[13], Barra *et al.* [14], and Bartoli *et al.* [15]. These analytical methods are simple to apply but they are not general. On the other hand, the numerical methods presented by Bucciarelli [16], Groumpos and Papageorgiou [17], Graham *et al.* [18], Aguiar *et al.* [19], Richard and Chapman [20, 21] and Abouzahr [22] present a good solution, but these need a long period solar radiation data record. Egido and Lorenzo [23] reviewed methods for computing capacity of PV arrays and battery storage and suggested analytical model based on LOLP, where it uses more complex methods which allow the improvement of the precision of the LLP calculation according to the dimension of the PV-array area and the storage capacity. An optimal method for the panel area of photovoltaic system in relation to the static inverter practical results has been developed by Keller and Affolter [24]. Hadj Arab *et al.,* applied the LLP for sizing PV system in some sites in Algeria [25]. Nevertheless, a detailed evaluation of the sensitivity of a numerical sizing method developed by Notton *et al.* [26], has shown that the influences of some parameters on the sizing, i.e., simulation time step, input and output power profile are very important. It is therefore important to have knowledge of the daily profile at least on an hourly basis. The authors have highlighted that optimal solution can be obtained if PV contributes for 75 % of the energy requirements.

The cost of electricity generated from a hybrid PV system is also one of the decision-making parameters. Marwali *et al.* [27] developed a methodology for calculating production cost of hybrid PV battery system in which the size of PV system is calculated on the basis of not-met electrical requirements. Shrestha and Goel [28] demonstrated a method to find optimal combination of PV array size and battery to meet the refrigeration load, by using statistical models for both solar radiation and the load. The author had designed a stand-alone PV system based on irradiation derived from METEOSAT images. Using a combination of both daily based on WEFAX satellite images and a TAG model, hourly global solar irradiation data on a horizontal plane are synthesized with a good accuracy (RMSE < $80 Wh.m^{-2}$) [29]. Sidrach-de-Cardona and Mora López [27] have developed a general multivariate qualitative model for sizing stand-alone PV systems based on LOLP, and they have also developed a simple model for sizing stand alone PV systems [30, 31]. A new technique for sizing parameters for stand-alone solar-energy systems has been designed by Agha and Sbita [32]. Athanasia *et al.,* reviewed the economics of PV stand-alone residential households in various European and Mediterranean locations [33]. Benghanem has been developed a suitable methodology based on LLP for sizing PV-system in Algeria [34]. Bhuiyan and Asgar [35] optimized PV battery system for Dhaka, Bangladesh with respect to power output for different tilt and azimuth angle for optimum performance of hybrid PV system. Mellit *et al.*, have presented a simplified methodology for sizing PV-system based on spatial interpolation of optimal sizing PV-system in Algeria [36]. Kaushika *et al.* [37] developed a computational scheme for stand-alone solar PV systems with interconnected arrays have been investigated for optimal sizing of the array and battery bank. The loss of power supply probability (LPSP) is used to connote the risk of not satisfying the load demand. A method of sizing stand-alone PV systems regarding the reliability to satisfy the load demand, economy of components, and discharge depth exploited by the batteries is developed by Balouktsis [38].

The economic analysis of PV stand-alone residential systems carried out in this paper verifies the predictions for the brilliant future of PV technology even for this demanding type of application. A new sizing approach is applied in this paper to stand-alone PV systems design, which is based on systems configurations without shedding load, is developed by Fragaki and Markvart [39]. The investigation is based on a detailed study of the minimum storage requirement and an analysis of the sizing curves, the analysis reveals the importance of using daily series of measured solar radiation data instead of monthly average values.

3.2 Grid-connected PV system

At the beginning of the 1990's, the main PV applications were stand-alone systems for communication and consumer products. However, PV grid-connected systems (PVGCS) have had the largest growth since 2000. In fact, PVGCS residential applications are estimated to have risen from a small 3.3 % of the world PV market in 1993 to a large 55.5 % in 2003 [1]. A part from environmental awareness, this development has been brought mainly by means of a continuous decrease trend in PV costs together with a wide variety of promotion strategies and supporting programs that different developed countries have launched. Despite this optimistic horizon, cautious prospective owners, when approached by PV designers and marketers, obviously demand some information concerning the economic feasibility of their investment. In fact, profitability may be achieved under some conditions at present. Grid-connected applications are the fastest growing segment of the photovoltaic (PV) market with premium feed-in tariffs available in many countries. Peippo and Lund [40] have proposed an optimal ratio of the nominal PV-array capacity to the rated inverter input capacity in PVGCS based on numerical simulations for several locations. Keller *et al.*, [41] have developed a methodology for solving the problem of poor sizing. PVGCS systems which often under exploit the capacity of the static inverter resulting in reduced efficiency and an increase in the cost of energy. A simple process for the evaluation of the optimal size of grid-PV-generator in building has been developed [42] and has been used as a useful tool for the PV designer in the choice of sizing the PV system capable for supplying the maximum building electricity consumption with a minimum cost. Optimum PV/inverter sizing ratios for PVGCS in selected European locations were determined in terms of total system output, system output per specific cost of a system, system output per annualized specific cost of a system, has been described [43]. In [44] the authors have discussed how the time resolution of solar radiation data influences the correct sizing of PV plants. And they have demonstrated that using instant (10 s) irradiation values instead of average hourly irradiation values leads to considerable differences in optimum inverter sizing.

3.3 Hybrid PV systems

Hybrid PV systems are best suited to reduce dependence on fossil fuel by using available solar radiation. Hybrid PV system includes the PV generator, diesel generator and/or battery system. Battery storage increases the flexibility of system control and adds to overall system availability [45, 46]. These energy systems have good prospects and many opportunities in hot climates. These energy systems are termed as one of the cost effective solutions to meet energy requirements of remote areas. A procedure is described in [47], which determines the sizes of the PV array and wind turbine in a PV/wind energy hybrid system. Using the measured values of solar and wind energy at a given location. A new technique for the sizing of PV array and battery storage for a stand-alone hybrid wind-photovoltaic system has been developed [48]. This new technique has the following important advantages over the original two event techniques: A probabilistic approach is used to get to the results. A general method has been developed to jointly determine the sizing and operation control of hybrid-PV systems. With this method the interdependency of hybrid operation strategies and system sizing can be incorporated. The operation control and sizing selection method is based on genetic optimization techniques [49]. Kellogg *et al.*, have developed a simple numerical algorithm for generation unit sizing of wind, PV, and hybrid wind/PV power generating systems for utilization as stand-alone systems [50]. Marwali *et al*., [51] developed a methodology for calculating production cost of hybrid PV battery system in which the size of PV system is calculated on the basis of not-met electrical requirements. A methodology based on probabilistic performance assessment of autonomous solar–wind energy conversion systems was developed by Karaki *et al*., [52]. A methodology is developed to determinate the optimal size of PV-hybrid subsystems and to optimize the stand-alone system management [53]. Various models including probabilistic or deterministic approaches have been developed to assess the performance of hybrid PV system and to find optimal mix of PV with diesel. The energy system modelled includes both, the system with battery storage and system without battery storage. Modelling battery storage system with respect to the state of charge, optimal size of a hybrid PV system can also be obtained [54]. Celik [55] presented a techno-economic analysis based on solar and wind biased months for autonomous hybrid PV/wind energy system. The authors have observed that an optimum combination of the hybrid PV/wind energy system provides higher system performance than a single system, for the same system cost and battery storage capacity. It was also observed that the magnitude of the battery storage capacity has important bearing on the system performance of single PV and wind energy systems. A complete set of match calculation methods for optimum sizing of PV/wind hybrid system is presented in by Ai *et al.,* [55]. In this method, the more accurate and practical mathematic models for characterizing PV module, wind generator and battery are adopted; combining with hourly measured meteorological data and load data, the performance of a PV/wind hybrid system is determined on an hourly basis; by fixing the capacity of wind generators, the whole year's loss of power supply probability (LPSP) values of PV/wind hybrid systems with different capacity of PV array and battery bank are calculated, then the trade-off curve between battery bank and PV array capacity is drawn for the given LPSP value [57]. A general optimization model for finding an optimal combination of community-based hybrid energy systems is developed for Indian conditions [58]. This compatible model is applicable to renewable power generation in any rural village. Performance of hybrid PV system is evaluated on the basis of reliability of power supply under widely varying conditions. Reliability is expressed in terms of loss of power supply probability (LOLP) [59]. Richardss and Conibeerb [60] have compared the performances of three different solar based technologies for a stand-alone power supply (SAPS) using different methods to address the seasonal variability of solar insolation.

4. APPLICATION OF ARTIFICIAL INTELLIGENCE TECHNIQUES IN SIZING PV SYSTEMS

The conventional methodology (empiric, analytic, numeric, hybrid, etc.) for sizing PV-systems have been used for a location where the required weather data (irradiation, temperature, humidity, clearness index, wind speed, etc.) and the information concerning the site where we want to implement the PV system are available. In this case these methods present a good solution, particularly hybrid method for sizing PV-systems. However, these techniques could not be used for sizing PV systems in remote areas, in the case where the required data are not available. Moreover, the major of the above methods need the long term meteorological data such as total solar irradiation, air temperature, wind speed, etc. for its operation. So, when the relevant meteorological (met) data are not available, these methods cannot be used, especially in the isolated areas. In order to overcome this situation, more recent methods have been developed in the literature for sizing parameters for PV-systems based on AI-techniques [61]. In fact, this section deals with an overview of the application of AI-techniques in PV-systems sizing. Mellit *et al.,* [62] have developed an ANN model for the estimation of the sizing parameters of stand-alone PV-systems. In this model, the inputs are: latitude, and longitude of the site, while the output are the sizing parameters (f, u). These parameters allow the designers of PV-systems to determine the number of solar PV modules and the storage capacity of the batteries necessary to satisfy a given consumption. In addition, several AI-based sizing of PV systems have been developed in order to select the optimal sizing parameters of PV system in remote areas [63-67], in which the results obtained have been compared and tested with experimental values. Hontoria *et al.,* [68] have developed a suitable technique for drawing the iso-reliablite curves by using a simplified recurrent neural network. This technique has been applied for Spanish locations. A methodology for optimal sizing of stand-alone PV/wind-generator systems was developed by Koutroulis *et al.*, [69], in which the proposed methodology is based on the GA and compared with linear programming. The simulation results verify that hybrid PV/wind-generator systems feature lower system cost compared to the cases where either exclusively wind-generator or exclusively PV sources are used. A hybrid model for determining the optimal sizing parameters of PV-system is developed by Mellit *et al.*, [70], in which it combines neural network and fuzzy logic, called Neuro-Fuzzy. It can be used for predicting the optimal sizing coefficient of PV-systems based only on the geographical coordinates. Tomonobu *et al.,* [71] have developed an optimal configuration of power generating systems in isolated islands with REN using Genetic Algorithm (GA). This methodology can be used for determining the optimum number of solar array panels, wind turbine generators, and batteries configurations. GA and neural networks have been used for determining the optimal sizing parameters in isolated areas in Algeria. Firstly the GA has been used for optimizing the sizing parameters relative to 40-sites in Algeria, and the ANN has been used for predicting the optimal parameters in remotes area [72]. The results obtained by different AI-techniques have been compared and analysed by Mellit [73]. It should be noted that the proposed hybrid model which combines ANFIS and GA present more accurate results compared to alternative ANN's [73]. A novel strategy, optimized by genetic algorithms, to control stand-alone hybrid renewable electrical systems with hydrogen storage is presented in [74]. The optimized hybrid system can be composed of REN resources (wind, PV and hydro), batteries, fuel cell, AC generator and electrolyzer. Hernándeza *et al.,* [75] have presented a new systematic algorithm to determine the optimal allocation and sizing of PVGCS's in feeders that provides the best overall impact onto the feeder.

5. CONCLUSION

In this paper, different conventional and AI-techniques for sizing PV systems: stand-alone, grid-connected and hybrid, have been reviewed at the global level. Conventional sizing methods such as empiric, numeric, analytic and hybrid present a good solution, when all required data are available (met data, information concerning the sites, etc.). However, in the case where these data are not available, the conventional techniques could not be used. However, these methods should not be disregarded totally since the new proposed AI-techniques for sizing PV systems are based mainly on the conventional methods such as the hybrid-technique.

Generally, AI-techniques have demonstrated the possibility for sizing PV-systems based on some available data. Published literature on the sizing of PV-systems based on AI-techniques indicates its popularity, particularly in isolated area. This shows the potential of AI as a design tool in the optimal sizing of PV systems. The number of applications presented here is neither complete nor exhaustive, but merely a sample of applications that demonstrate the usefulness and possible applications of AI-techniques. AI-based sizing PV systems has been applied for many countries such as Algeria, Spain, Greece, Ireland, Island and Turkey.

Thus based on the review work presented here, AI-techniques seem to offer an alternative method for sizing PV-systems in many regions of the world that lacks complete data, where this technique should not be under-estimated.

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