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Forecasting of photovoltaic power generation and model optimization: A review

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ABSTRACT

To mitigate the impact of climate change and global warming, the use of renewable energies is increasing day by day significantly. A considerable amount of electricity is generated from renewable energy sources since the last decade. Among the potential renewable energies, photovoltaic (PV) has experienced enormous growth in electricity generation. A large number of PV systems have been installed in on-grid and off-grid systems in the last few years. The number of PV systems will increase rapidly in the future due to the policies of the government and international organizations, and the advantages of PV technology. However, the variability of PV power generation creates different negative impacts on the electric grid system, such as the stability, reliability, and planning of the operation, aside from the economic benefits. Therefore, accurate forecasting of PV power generation is significantly important to stabilize and secure grid operation and promote large-scale PV power integration. A good number of research has been conducted to forecast PV power generation in different perspectives. This paper made a comprehensive and systematic review of the direct forecasting of PV power generation. The importance of the correlation of the input-output data and the preprocessing of model input data are discussed. This review covers the performance analysis of several PV power forecasting models based on different classifications. The critical analysis of recent works, including statistical and machine-learning models based on historical data, is also presented. Moreover, the strengths and weaknesses of the different forecasting models, including hybrid models, and performance matrices in evaluating the forecasting model, are considered in this research. In addition, the potential benefits of model optimization are also discussed.

1. Introduction

Energy is a prime mover of economic growth and a key factor for the development of a country. Over the years, the demand for energy, especially electrical energy, has been increasing due to industrialization, modernization, and population growth, aside from people's increasing living standard. In the last century, electrical energy was generated mainly from fossil fuels (namely, oil, coal and natural gas) and currently still relies on them significantly. However, this issue has created environmental concerns about greenhouse gas (GHG) emissions, global warming, and climate change. The burning of fossil fuels releases carbon dioxide and some other toxic gases into the atmosphere, which contributes to global warming, as well as environmental pollution. Therefore, the modern world wants to increase the penetration of renewable energy aside from minimizing the use of fossil fuel in this sector.

During the United Nations Climate Change Conference (COP21) in 2015, also known as the Paris agreement, most of the countries agreed to make an effort to limit the global warming to ensure a livable world for the next generation. A joint presidential statement of the USA and

Abbreviations: PV, photovoltaic; NWP, numerical weather prediction; AI, artificial intelligence; AR, auto regressive; MA, moving average; ARMA, auto regressive moving average; ARIMA, AR integrated MA; ARMAX, ARMA exogenous; ANN, artificial neural network; SVM, support vector machine; SVR, support vector regression; HS, hybrid system; FS, fuzzy system; ANFIS, adaptive neuro fuzzy inference system; GA, genetic algorithm; GHG, greenhouse gas; IEA, international energy agency; MSE, mean square error; RMSE, root mean square error; nRMSE, normalized root mean square error; MAE, mean absolute error; MAPE, mean absolute percentage error; MRE, mean relative error; MBE, mean bias error

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China on climate change highlights the new domestic policy commitments involving renewable energy and energy efficiency [1]. The European Union sets the production target of renewable energy to the domestic reduction of GHG emissions at least 40% by 2030 and 80% by 2050 (from a 1990 baseline). By 2030, 30% of the total energy will be produced from renewable energy sources and will achieve 100% by 2050 [2]. Similarly, most of the countries are committed to increase the use of renewable energy. Therefore, renewable energy has obtained the special attention of power production companies, energy policy makers, and governments.

Among the renewable energy resources, wind and solar energy are the more acceptable and promising sources due to their potential and availability. They have higher rate of success to penetration into the energy market. The sun, which is the source of solar energy, acts like a black body radiator with a surface temperature of 5800 K, which provides 1367 W/m^2 solar energy over the atmosphere [3–5]. A research study highlights that the earth receives approximately 1.8×10^{11} MW power from solar radiation at an instant [6]. However, the present world energy consumption requirement is less than the amount of energy received from the sun [7]. Therefore, solar energy has been obtaining much attention from energy players, investors, government, and international organizations in the last decade because of its several benefits including environmental and economic benefit.

Photovoltaic (PV) system has been achieving worldwide acceptance and is playing a significant role in providing clean and sustainable energy [8]. Therefore, PV power installation has experienced enormous growth over the last few years. Fig. 1 shows the installed worldwide capacity of solar PV power in the last decade. An exponential growth can be observed in the global PV power installed capacity from 2005 to 2015. The global capacity of PV power installation increased from 5.1 to 16.0 GW in 3 years (2005–2008) and continued to increase from 16.0 to 100.0 GW in the next 4 years (2008–2012). Overall, the global capacity of installed PV power has increased from 5.1 to 227.0 GW in the last 10 years. This growth will continue at a similar or higher rate in the future due to its technological benefit. Thus, the decrease of price (as low as $1.5/Wp for fixed-tilt systems) and the increase of the efficiency of the PV module will increase installations [9,10]. The high penetration of PV in electric systems has many economic benefits. The solar share has been reached annually in the electricity market, which is 7.8% in Italy and close to 6.5% in Germany and Greece; moreover, 22 countries have a percentage greater than 1% (IEA, 2016). According to IEA's highest projection, the installation of global solar PV power capacity could exceed 1700 GW by 2030 [11].

However, the generation of PV power fully depends on the uncertain and ungovernable meteorological factors, such as solar irradiance, atmospheric temperature, module temperature, wind pressure and direction, and humidity. The power output of a PV system dynamically changes with time due to the variability of environmental factors. Therefore, the accurate forecasting of PV power generation is considerably difficult. The unpredicted PV power output adversely affects the stability, reliability, and scheduling of the power system operation, aside from the economic benefit [12,13]. An accurate forecasting of the PV power generation can reduce the impact of PV power uncertainty on the grid, improve system reliability, maintain

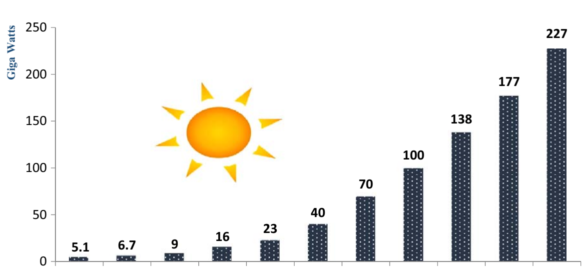

Fig. 1. Total installed PV power system from 2005 to 2015 worldwide [1].

power quality, and increase the penetration level of the PV systems. Therefore, accurate forecasting of PV power generation is a great challenge for the researchers at this moment.

A good number of research has been conducted to develop appropriate forecasting models in forecasting PV power generation with the targets of higher accuracy and minimum complexity with computational cost. These forecasting models are broadly classified into two categories: indirect and direct forecasting models. In the indirect forecasting model, the solar irradiance on different time scales have been forecasted by using various methods, including numerical weather prediction (NWP), image-based, statistical, and hybrid artificial neural network (ANN) based methods [14–21]. Therefore, the forecasted solar irradiance and others associated data are inputted in commercial PV simulation software, such as TRNSYSM, PVFORM, and HOMER [22], to forecast the PV power generation. However, in the direct forecasting model, PV power generation is forecasted directly using historical data samples, such as PV power output and associated meteorological data. Mitsuru *et al.* [23] have implemented direct and indirect methods to forecast the next-day power generation of a PV system, and showed that the direct method is better.

Several papers have reviewed the literature related to this field, focusing on different aspects. For example, in Ref. [24], the authors focused on wind speed/power forecasting and solar irradiance forecasting conducted by using ensemble methods. Gandomanin et al. [25] reviewed the literature on short-term forecasting of solar PV power output based on cloud cover influence. Antonanzas et al. [26] highlighted recent studies on solar power forecasting. However, PV power forecasting models were not extensively explored in their study. Wan et al. [27] analyzed different PV and solar forecasting techniques but did not review recent studies on PV power forecasting. On the other hand, Raza et al. [28] emphasized the PV power forecasting model beside the solar power forecasting model, which is insufficient. In addition, future studies should also consider the optimization of the PV power forecasting model.

Most of the recent studies in this field have focused on investigating direct PV power forecasting. Direct forecasting methods can achieve accurate forecasting of PV power generation. Therefore, a comprehensive literature review based on recent direct forecasting methods, including model development and optimization, should be conducted for new researchers in this field. This review will be helpful for the researchers in related fields, such as PV-integrated smart buildings, efficient energy management system, eclectic vehicle charging and smart grid.

The current work made a comprehensive and systematic review of the short-term direct forecasting models of PV power generation based on historical data. Section 2 of this paper presents a discussion on the importance of the correlation between input-output data and the preprocessing of input data to develop a PV power forecasting model. The classification of the forecasting models of PV power generation based on forecast horizon, historical data, and methodology is presented in Section 3. The strength and limitation of the different models, including statistical and artificial intelligence model based on historical data, are discussed in Section 4. The model optimization benefit is presented in Section 5. Section 6 introduces the performance matrices for evaluating the forecasting models. Section 7 presents an analysis of the recent works based on model performance and techniques. Finally, Section 8 summarizes and concludes the paper.

2. Input selection of the PV power forecasting model

Solar energy is one of most popular renewable energies, which comes from the sun in the form of solar irradiance. The solar cells made up of semiconductors in the PV module converts the solar irradiance to electricity through the photovoltaic effect. The PV power generation mainly depends on the amount of solar irradiance. In addition, other weather parameters, including atmospheric temperature, module tem-