

Estimate and characterize PV power at demand-side hybrid system

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HIGHLIGHTS

- A new way is developed to directly perform the forecast of PV power at demand side.
- Effects of temperature, humidity, historical value on PV power forecast are explored.
- Estimation results are qualitatively investigated via data mining approaches.
- Experimental studies show that the new method could achieve more accurate prediction.

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ABSTRACT

Power forecasting, in a hybrid photovoltaic (PV) system, is an important issue regarding to the control and optimization of energy systems. In this work, multi-clustered echo state network (MCESN) models are proposed to directly perform the forecast of PV power generation. Furthermore, data characteristics of measured and estimated PV power are qualitatively investigated via data mining approaches. These characteristics include seasonality, stationarity (or non-stationarity) and complexity analysis. Simulation results indicate that the proposed MCESN model is able to precisely forecast PV power one-hour-ahead. The performance on the 24-h-ahead forecast is competitive with the correlation coefficient 99% for sunny days, and 91–98% for cloudy days. Results of data analysis unveil that critical characteristics between the measured and estimated PV power data are analogous. Comparison studies also show that MCESN could achieve more accurate prediction, compared with auto-regressive moving average (ARMA), back propagation (BP) neural networks.

1. Introduction

In recent years, due to globally increasing energy demand, renewable energy sources (e.g., wind and solar energy) have gained great attention, as they are freely available, omnipresent, and environmental friendly. Thanks to easy accessibility, government's support, and technical development, large-scale photovoltaic (PV) systems have been installed around the world. However, the power generation of PV system is a nonlinear and complex process, depending on time-varying factors, such as, temperature, humidity, wind speed and direction, and historical data of PV system. In order to ensure reliable and efficient operation of PV energy systems, it is essential and urgent to forecast PV power precisely [1,2].

There have been a large number of studies on PV power prediction, in which high accuracy and low computational complexity are two main concerns.

A common approach is to transform PV power prediction into solar

irradiance prediction, which consists of two steps. The first step is to forecast solar irradiance, and the second step is to calculate the PV power according to solar irradiance and system parameters. Different models of prediction have been developed by traditional techniques and linear methods, e.g., various clear-day models [3], auto-regressive moving average (ARMA) [4] and other econometric technologies. However, as many statistical assumptions and empirical parameters are involved in these models, it is rather difficult to precisely forecast the dynamic behavior of solar irradiance. Some improved models have been proposed based on advanced technologies in [5–7].

Artificial intelligence (AI) and neural network (NN) provide powerful tools of approximating nonlinear systems. Various AI and NN models have been successfully applied to forecasting solar irradiance in literature. A wavelet-coupled support vector machine (W-SVM) model was adopted to forecast global incident solar radiation [8]. A NN model is proposed to achieve a 24-h-ahead solar irradiance prediction for a PV system [9]. Based on recurrent neural networks (RNNs) and wavelet

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neural networks (WNNs), a new diagonal recurrent wavelet neural network (DRWNN) was established to perform the forecast of hourly and daily global solar irradiance [10]. Advanced approximation techniques based on wavelet analysis [11,12], fuzzy technique [13], and empirical analysis [14] can also be employed to enhance NN models. In addition, some other forecasting approaches have also been proposed, such as, peer-to-peer (P2P) solar forecasting [15], machine learning [16,17], probabilistic approach, and so forth. The predicted values of solar irradiance are used to obtain PV power output. On the one hand, canonical PV formula could be utilized to compute the power output of PV system. On the other hand, some commercial PV simulation softwares, such as HOMER and PVFORM, could be used to forecast PV power based on the forecasted solar irradiance and system parameters.

Echo state networks (ESNs) is an improved and simplified form of RNNs [18]. Unlike classical RNNs, ESNs adopt non-trainable sparse connections in the hidden layer (called dynamic reservoir), and only connections in the output layer need to be trained through linear regression. As a result, the high computational complexity is conquered, and ESNs is much faster than traditional RNNs. ESNs also show obvious advantages in dealing with nonlinear time series and dynamic prediction system due to its high prediction accuracy and efficiency. ESNs have been widely applied to various practical fields, including dynamic pattern classification and recognition [19,20], image processing [21], optimal energy management [22], and especially nonlinear time series prediction [23,24]. To our best knowledge, there exist few results in ESN-based prediction of solar irradiance and PV power.

For a PV hybrid system, one practical issue is the uncertainty of PV power. While considering the external environment and different demand-side features, the PV power cannot be directly calculated from a linear form of solar irradiance. Therefore, recent studies have focused on the direct prediction of PV power [25–28]. In this paper, the uncertain PV power at the demand side will be specifically modeled in a direct approach. In the application of PV hybrid system, few results are reported to evaluate inner rules and hidden patterns of the demand-side PV power. Influenced by many factors, such as seasons, geographic locations, weather and surroundings, the PV power profile presents its own data characteristics, which are closely related to the power generation process [29]. In order to unveil the inner dynamics, data features of measured and estimated PV power are quantitatively analyzed. In this paper, some main data characteristics between measured and forecasted PV power will be studied to check statistical similarity.

The contributions are in three folds. First, the ESN models are established to directly perform the one-hour-ahead and 24-h-ahead forecast in the PV hybrid system. The direct effects of measured temperature, humidity, historical 24-h-lag information are also explored in detail. Comparison between ARMA model, BP neural networks and MCESN have been conducted. Secondly, the estimation performance is evaluated with comprehensive criteria, such as normalized root mean square error (NRMSE), mean absolute error (MAE), root mean square error (RMSE), and correlation coefficient (r). Thirdly, the data characteristics are investigated with respect to descriptive statistics, seasonality, non-stationarity and complexity.

The rest of this paper is organized as follows. In Section 2, background is introduced. Section 3 describes the basic theory of ESN in terms of network structure, mathematical model, and training methods. The experimental design and numerical results are shown in Section 4. The data characteristics of measured and estimated PV power are qualitatively analyzed in Section 5. Finally, the conclusion is presented in Section 6.

2. Uncertainty in the PV hybrid system

The electricity consumption have been increasing in past decades, which could result in over exploration of traditional fossil fuel resources. Therefore, the exploration of renewable energy (RE) resources is necessary to control fossil fuel consumption and pollutant emission.

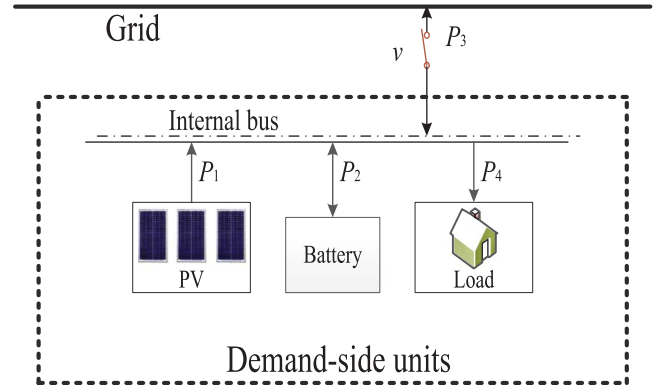


Fig. 1. Schematic of PV hybrid system.

Due to large potential and free availability, wind and solar energy are the popular choices among available RE resources. However, the storage components are required for renewable energy hybrid system due to the intermittent nature. A renewable energy hybrid system is composed of multiple power resources and storage components for stable power supply.

Hybrid renewable energy system (HRES), commonly used for remote power supply, is playing an important role in demand side management with the grid connection, such as, green building and smart community. The PV hybrid system is the most popular application due to easy accessibility, low cost, and high safety. The PV hybrid system consists of PV panel and battery bank that are both connected to the grid, as shown in Fig. 1. As the first priority, the PV power is used to feed the load demand. If the demand is less than the PV power, the surplus PV power will be charged into the battery. If the demand is larger than the PV power, the deficient amount will be then covered by the battery. For saving electricity cost, the battery can be charged by the grid when the electricity has a low price, and be discharged when the electricity has a high price. The grid takes part into the power supply when the load demand cannot be satisfied by the PV and the battery. Note that the PV hybrid system could work in the stand-alone mode and the grid-connected mode, depending on the on/off status of switch v , as shown in Fig. 1.

In the PV hybrid system, a critical problem arisen is the power flow control, which refers to scheduling the power flow between each component for satisfying requirements of cost saving and safety. Let P_1 denote the PV power generation, and P_2 denote the charging/discharging power of battery. Let P_3 denote the grid power flow, and P_4 denote the load demand. With respect to cost, the electricity cost can be expressed as

$$J = \int_{t=0}^T \rho(t) P_3(t), \quad (1)$$

where $\rho(t)$ is the real time price of electricity, and J is the electricity cost. With respect to safety, the power balance should be first satisfied as

$$P_1 + P_2 + P_3 = P_4, \quad (2)$$

Power flow control methods have significant effects on electricity cost and operational safety at demand side. In literature, rule-based and optimization-based methods are proposed to reduce the cost and enhance the safety. However, the uncertainty of PV power has presented several challenges on the power flow control. First, the uncertainty could violate the condition of power balance and risk the security of grid and demand-side units. Secondly, the uncertainty could influence actual energy consumption, so that the electricity cost might deviate from the reference one.

In this paper, the prediction of uncertain PV power is specifically studied at the demand side, as solar irradiation at a certain location (a weather station or solar farm) cannot be directly used in the PV power

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