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Forecasting Models for an Intelligent Use of Renewable Energy Based on the Prediction of PV Energy

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Abstract

Renewable energy has many advantages, such as low environmental impact and endless resources. However, there are also some disadvantages. For example, such energy can be highly weather-bound and therefore not always available. This sometimes makes it necessary to store this time-dependent energy. On the other hand, it would be ideal to adjust the power consumption to the power generation. Forecasting the produced energy in order to plan its use in advance is thus highly advantageous. In photovoltaic technology (PV), forecast-based operation is very helpful to both electricity suppliers and plant operators. It prevents both the unwanted load peaks and the economic losses of the system. In this paper, a mathematical forecasting model is presented and validated. The main focus is on the forecast of energy production with PV systems. Electrical load forecasts are not examined here.

Keywords: *forecasting models, prediction, PV energy*

1. Introduction

Renewable energy has many advantages, such as low environmental impact and endless resources. However, there are also some disadvantages. For example, such energy can be highly weather-bound and therefore not always available. This sometimes makes it necessary to store this time-dependent energy. On the other hand, it would be ideal to adjust the power consumption to the power generation. Forecasting the produced energy in order to plan its use in advance is thus highly advantageous. In photovoltaic technology (PV), forecast-based operation is very helpful to both electricity suppliers and plant operators. Through the rapid expansion of PV and the fluctuating amount of electricity, the existing electricity network increasingly pushes its limits. To avoid damaging power peaks in the electricity network, various laws to limit the maximum feed-in capacity and to regulate the expansion of PV systems have been agreed upon in Germany. The operator of plants for generating electricity with PV are obliged to operate in accordance with feed-in management regulations or to limit the maximum active power feed to 70 percent of the installed capacity at the network transfer point. (EEG, 2014) Limiting the output means economic losses for the plant operator. This could be avoided by a forecast-based operating method of the PV system. Thus the energy consumption of the produced energy can be tracked by PV forecasts and suitable activation of electric loads. This prevents both the unwanted load peaks and the economic losses of the system. The basis for forecast-based operations are particular methods of predicting the PV production in order to plan the usage of the generated energy better. In this paper, a mathematical forecasting model is presented and validated. The main focus is on the forecast of energy production with PV systems. Electrical load forecasts are not examined here.

2. Forecasting methods

A forecast is defined as a statement about one or more events, conditions or developments in the future, based on information in the past (Theil, 1966). This information is usually in the form of time series, which are needed to calculate future values of the process (Schlittgen, 2001). Forecasts of load profiles of energy

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consumption and power generation are very important in the energy sector. Because the production and consumption of energy in the electricity grid have to be in balance at all times, forecasting methods are used to predict the energy consumption.

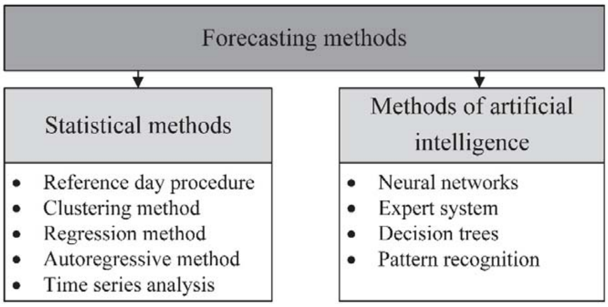

Fig. 1: Overview of typical forecasting methods

As shown in Figure 1, there are two typical types of forecasting methods. Statistical methods use mathematical combinations of historical data combined with information on the influencing variables to predict the behavior of consumers. However, if, due to the lack of information about influencing factors, no expedient prediction can be made, it could be helpful to use methods of artificial intelligence. Some artificial intelligence processes involve learning patterns of behavior with the help of historical data and project these patterns as a function of the expected operating conditions into the future. To select the optimal forecasting method for a particular application, it is also important to look for the required time horizon of the forecast. Short-term forecasts (forecast horizon of one day) can be created on the basis of measurements and current data. In contrast to long-term forecasts (forecast horizon of several months), mostly methods of artificial intelligence are used. These learn the different patterns of behavior based on historical data and project them into the future. Various forecasting methods can work differently depending on the influencing factors, such as climate or weather. Because of this, combined or cascaded models are increasingly used. Each of them operate for certain input variables and complement each other. A combination of different methods for a forecast can improve accuracy. (Prokhorova and Heimel, 2013)

3. Forecast of the PV capacity

The production of energy with a PV system is, in contrast to the electric load profile of a building, not affected by stochastic factors and can be described mathematically. A forecast of PV capacity can be done on the basis of weather forecasts and the characteristics of the PV system (type of assembly, module orientation, location, ...). The output of the generating PV system depends mainly on the available solar radiation at the place of installation, the installed modules and the efficiency of the inverter. The necessary basics for the calculation of the solar radiation range and the related performance calculation will be explained in the following sections with reference to Quaschning, 2015, Blank, 2005 and Schumacher, 2005.

3.1. Global radiation

The extra-terrestrial irradiance $E_e$varies due to the non-constant distance between sun and earth, which is between 1321 $\frac{W}{m^2}$ and 1412 $\frac{W}{m^2}$. Therefore, methods for the calculation must be chosen with care. An exact calculation of E_e is possible via the factor of eccentricity E_0, which can be determined by Duffie/Beckmann (Baehr and Stephan, 1994). The extraterrestrial irradiance is reduced by various influences as it passes through the earth's atmosphere. The horizontal extra-terrestrial irradiance $E_{e,hor}$ is reduced by the terrestrial atmosphere because of

- reduction by reflection at the atmosphere
- reduction by absorption of the atmosphere,
- reduction by Rayleigh scattering,
- reduction by Mie scattering.

All these influences can be analyzed though the transmittance τ. Determining the size of the influences is usually difficult, so it is possible to substitute the influences with a factor of the clearness index k_T. This is the ratio of the global irradiance $E_{G,hor}$ and the extra-terrestrial irradiance parallel to the surface of the earth $E_{E,hor}$.

The light on the surface of the earth is composed of a direct radiation component and a diffuse radiation component. Direct radiation $H_{dir,hor}$ comes directly from the sun and strikes in a certain point. The diffuse radiation $H_{diff,hor}$ is caused by scattering and reflection in the atmosphere and reaches a certain point indirectly. The sum of direct and diffuse radiation results the global radiation $H_{G,hor}$.

3.2. Calculation of the solar altitude

The current position of the sun, which is relevant for many calculations, can be determined for any place on earth. For this determination, two angles, the sun height γ_S and the solar azimuth α_S, are needed. According to DIN5043, the height of the sun is defined as the angle between the center of the sun and the horizon from the observer's perspective. The solar azimuth is the angle between geographic north direction and the vertical circle by the center of the sun (Fig. 2a).

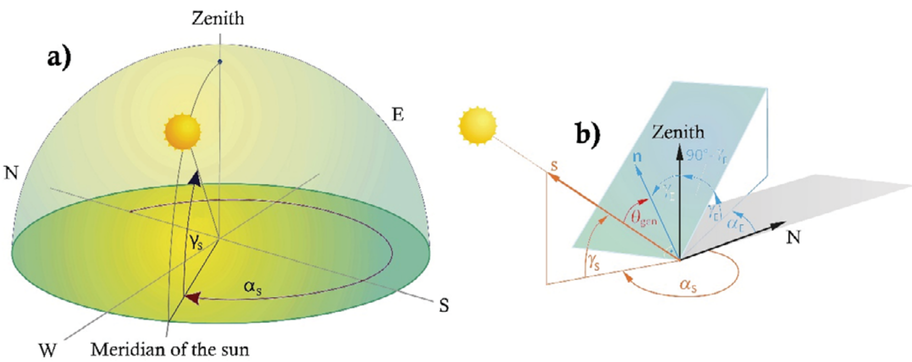

Fig. 2: Overview of typical forecasting methods (Figures based on Quaschning, 2011)

The height of the sun and the sun's azimuth also depend on date and time. The angle between the center of the sun and the celestial equator, also known as the solar declination *δ,* is an important variable. The position of the sun can be calculated with various algorithms. Some examples are SUNAE (Walraven, 1978), SOLPOS and SPA (Reda, 2008). In this paper, a method according to DIN 5034-2 is used to calculate the position of the sun. For each given point in time, it yields the height of the sun and the azimuth as a function of longitude λ and latitude φ.

To calculate the angle of incidence θ_{gen} at an oblique plane, the angle of inclination γ_E and the angle of rotation α_E is needed (Fig. 2b). Depending on the orientation of the generator surface and the angle of incidence of the sun, it is possible to calculate the direct radiation θ_{gen} on the PV modules. For this, the direction of irradiation $\vec{s}$ and the normal vector $\vec{n}$ of the surface are determined. The angle of incidence θ_{gen} can be calculated on the dot product of the two vectors $\vec{s}$ and $\vec{n}$. For detailed information, please refer to Fischer, 2016.

3.3. Radiation on oblique and aligned surfaces

The global irradiance $E_{G,gen}$ on an oblique plane is composed of a direct, a diffuse and a reflective component:

$$E_{G,gen} = E_{dir,\mathrm{gen}} + E_{diff,gen} + E_{refl,gen} \qquad \text{(eq. 1)}$$

Because it is a geometric problem, the determination of the direct irradiance $E_{dir,gen}$ on the oblique plane can be solved mathematically based only on the sun. The direct irradiance can be determined on the geometric relationships below (Fig. 2b), where $E_{dir,\mathrm{hor}}$ is the direct horizontal irradiance:

$$E_{dir,\mathrm{gen}} = E_{dir,\mathrm{hor}} \cdot \frac{cos\theta_{gen}}{sin\gamma_S} \qquad \text{(eq. 2)}$$

The calculation of the diffuse irradiance $E_{diff,gen}$ on an oblique plane differentiates between an isotropic and anisotropic approach. The isotropic approach means that there is always the same proportion of sky radiation in all directions. The radiance is neglected. For an exact calculation, the anisotropic approach is needed, because the radiance, especially in a clear sky, is very different. For this, Temps and Coulson, 1977, Klucher 1979 and Perez, 1987 proposed some calculation models. Temps/Coulson's anisotropic radiation model for a clear sky was expanded by Kulcher, who introduced the weather factor F_K for general sky conditions. Several studies, such as Jakhrani, 2016, show that this model provides good results when calculating diffuse irradiation. Therefore, the calculation of the radiation components is based on the Temps/Coulson/Klucher model.

The reflected radiation $E_{refl,gen}$ of the ground depends on the reflectivity of the surface and can be determined by using the albedo value A. The albedo value describes the reflectivity of the surface, which depends on its texture. Blank, 2005 provides an overview of different albedo values.

3.4. Calculation of performance

The performance of PV modules is specified in watt peak (Wp). This is achieved under standard test conditions (STC) and corresponds to the rated output of a module. The STCs are defined by DIN EN 60904-3 and correspond to an irradiance of $1000\frac{W}{m^2}$ and a module temperature of 25°C. Under normal conditions, the specified power value is rarely achieved in Germany. Despite this, it can sometimes be exceeded. How high the power value depends on the method of installation, module temperature, season and ambient temperature. The influence of the spectral distribution of light and the reduction in performance by shadowing and pollution is neglected in the model.

Deviation of the temperature is a crucial factor. If it deviates from STC, the performance will vary. The temperature coefficient that describes the deviation of the STC is about $-0.43\frac{\%}{K}$ on current PV modules (Fischer, 2016).

The dimensions of a PV system a usually chosen so that the nominal DC output is higher than the nominal AC output. This is common because the theoretical generator power under (STC) is achieved only a few days of a year. In addition, system losses like cable resistances between modules and inverters have to be taken into account. Because of this, it is common to make the power of the inverter smaller than the power of the generator.

4. Verification of the forecast

In order to verify the forecasts of the PV simulation program, the comparison of the results with measurements of real systems is necessary. In this case, the measurements are from a conventional single-family house in the center of Germany. In the following, the results of the PV forecast are compared with the real measurements and the results achieved are evaluated.

The weather data "global radiation" and "temperature" required for the simulation are available at local weather stations that are provided by Weather Underground, 2016. In each case, a summer and a winter day are used to compare simulation and measurements of the PV system. A disadvantage is that there are no forecast data for global radiation and temperature for the periods in which measurements of PV systems are available. Instead of this, the actual weather data is used in each case.

The measurement (measuring station 1) of the global radiation takes place very close to the aforementioned building. This provides an optimum condition for the verification of the PV forecasting model. The data can be measured in the immediate vicinity of the generator field and thus represent the global radiation that exists near the generator field.

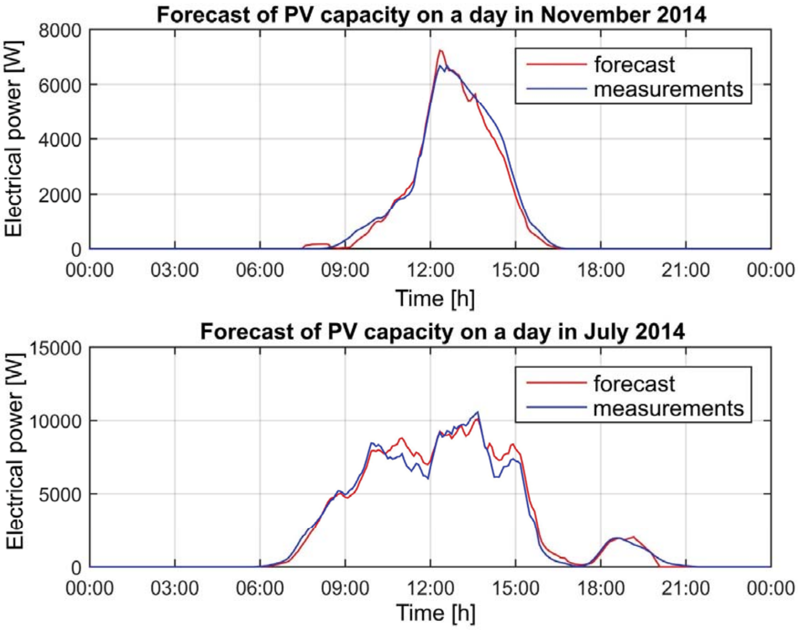

Fig. 3: Comparison between simulation and measurements on two days

Figure 3 shows the results of the forecast for a winter day (top) and a summer day (bottom) compared to the measured power values of the PV system. It can be seen that the calculated forecasts and the measured power curve correspond closely. The basic course of the calculated curve corresponds to the measured curve. Since the global radiation measurements were taken immediate vicinity of the PV system, it can be concluded that the existing minor forecast errors are caused by the calculation model or inaccurate measurements.

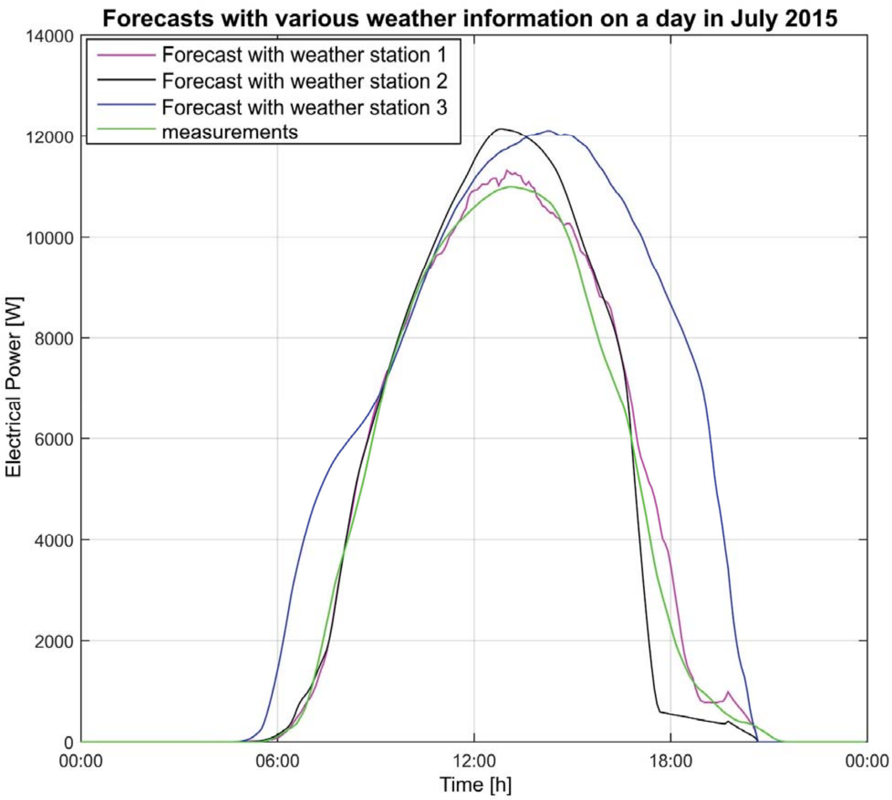

Fig. 4: Comparison between different forecasts depending on different weather stations

The above forecast with weather data from three different stations is useful for investigating the effects of the global radiation values on the forecast result. Figure 4 shows the measured curve of the power (green), and the forecasts based on the measurements of station 1 (magenta), station 2 (black) and station 3 (blue). It can be seen that the power curve of the forecast based on the measurements of station 1 is best predicted. The influence of the global radiation on the forecast results are clearly recognizable in the different weather stations. If the station is further away from the PV system, the differences between the measurements and the forecast are larger.

5. Conclusion and prospect

Due to the verification of the forecast model with data from the immediate vicinity of the PV system, it can be seen that the power curve of the PV system can be accurately predicted if the measurements and forecast data are of equivalent quality. The simulation program developed for the current paper makes it possible to predict the power of a PV system for a day with sufficient accuracy. In a near-optimal forecast, only negligible differences occur between forecast and real value. The simulations of a real pilot house at various summer and winter days clearly show that the forecasting model is highly dependent on the global radiation or temperature data.

Deviations between the forecast data and real measurement can be explained by simplifications in the calculation model, the neglect of shading losses and pollution and measurement inaccuracies. However, these deviations were not significant and the forecasting model is sufficient for the scope and requirements of this paper. Furthermore, since the input for and characteristics of a PV system are variable, a flexible and universal forecasting model such as the one developed for the current paper is also necessary and appropriate in other contexts and will be used in a further paper in conjunction with forecast data of global radiation and temperature.

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