Fuzzy logic based modeling and estimation of global solar energy using meteorological parameters

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Abstract: Global solar energy data is considered as the most important parameter in smart grid applications, particularly for sizing the photovoltaic system and demand driven supply. However the data of global solar energy is rarely available on hourly basis, even for those stations where measurement has already been done. Due to lack of such measured data, the estimation of global solar energy at the earth's surface is an important study in the present scenario to meet the energy requirement from green energy sources. This paper is based on fuzzy logic approach for modeling and estimating the global solar energy using mean duration sunshine per hour, temperature, latitude, longitude, altitude and months of the year as input parameters. Fortunately, these important for accurate parameters estimation of solar energy are commonly available. Results obtained from fuzzy logic approach are used for the prediction of SPV system output for smart grid application.

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1. Introduction

The rapid depletion of fossil fuel reserves and large greenhouse emissions are becoming the major challenge for the today's power sector. Due to increasing population and urbanization, the demand of electricity is increasing exponentially. Under such circumstances it is highly desirable to adopt the environment friendly energy sources for power generation. In order to achieve the target, renewable energy sources particularly solar and wind sources can play the important role. In addition, solar energy is one of the most promising and more predictable than other renewable energy sources. Therefore, high penetration of solar technologies into electric power system can meet the desired goals. It is well known fact that, India is located on the equatorial sun belt of the earth has great potential of solar energy with an average of about 300 solar days per year. Further, the government is also providing the in- centives and other benefits for installing the power plants based on solar energy. Hence, to exploit the environment friendly source of energy, analysis and estimation of solar energy at different stations of the country is utmost important [1e3]. Keeping in view of the aforesaid, a thorough literature review is carried out and it is found that number of mathematical models for the estimation of global solar energy under cloudless skies is available in the literature [4e5]. Regression models and stochastic models for estimating the solar energy are also presented by researchers [6e11]. The results obtained using these models were satisfactory, but applicable only for clear sky weather condition. In India around 300 days in a year are clear sky and remaining days are cloudy, so it is very difficult to estimate the accurately using mathematical/regression/stochastic models. Therefore, due to uncertainty in weather conditions, fuzzy logic based models are proposed by researchers to estimate the solar energy at a given location using different meteorological pa- rameters [12e18]. The uncertainty in atmosphere may occur due to the existence of the following: dust, moisture, aerosols, clouds, or temperature differences in the lower atmosphere. Among these factors, clouds can cause the maximum losses in the extraterrestrial solar energy reaching at earth's surface. The atmosphere causes a reduction of the extraterrestrial solar input by about 30% on a very clear day to nearly 100% on a very cloudy day [13]. Further, the use of solar energy estimation in smart grid application is rarely available in the literature. Keeping in view of aforesaid fuzzy logic based model for the estimation of global solar energy has been developed considering latitude, longitude, altitude of the location, months of the year, mean duration sunshine per hour (it is the ratio of average daily actual sunshine duration at the location to the theoretical sunshine duration), and temperature as input parame- ters. Obtained results are further simulated for smart grid appli- cations using fuzzy logic approach/toolbox.

Nomenclature

D day of the year

H monthly mean daily irradiance on horizontal surface

H0 mean clear sky daily irradiance

H/Ho clearness index

Hmeasured measured value of monthly mean daily irradiance on horizontal surface

Hestimated predicted value of monthly mean daily irradiance on horizontal surface

Is short circuit current of PV module at STC (A)

Isc solar constant ¼ 1367 W/m2

Pmax maximum power of module at MPP

S monthly mean daily hours of bright sunshine

So monthly mean of maximum possible daily hours of bright sunshine

S/So mean fraction possible sunshine hours

T monthly mean hourly temperature (C)

To monthly mean hourly maximum possible temperature

(C)

T/To ratio of monthly mean hourly temperature to monthly mean hourly maximum possible temperature

Ta ambient temperature (C)

Tcell cell temperature (C)

Tstc temperature of PV module at STC

Voc open circuit voltage of PV module at STC

Greek symbols

u hour angle

us hour angle at sunset

f latitude of the location

d declination angle

hc efficiency of the PV module

This paper is organized as follows: Section 2 presents the basics of smart grid operation. Section 3 describes the fuzzy logic based model for solar energy estimation. Fuzzy model for the prediction of SPV system output for smart grid application is presented in Section 4. Results and discussions are presented in Section 5. A Conclusion followed by the references is discussed in Section 6.

2. Smart grid

The global electricity sector and its customers are faced with a number of challenges that are unparalleled since the advent of widespread electrification. Challenges including climate change, escalating energy prices, energy security and energy efficiency are converging to drive fundamental change in the way of energy produced, delivered and utilized. Keeping in view of aforesaid the future electricity system must produce and distribute electricity which should be reliable, affordable and clean. To achieve the same, both the electricity grid and the existing regulatory system must be smarter. Hence there arises a need of grid that should be smart i.e. smart grid. Further, world is venturing into renewable energy re- sources like wind and solar. With such unpredictable energy sources, feeding the grid must be highly adaptive in terms of supply and demand. A good electric supply is one of the key infrastructure requirements to support overall development, hence the opportu- nities for building smart grid is immense [3,19e20].

Smart grid is used to predict and intelligently respond to the behavior and actions of all users connected to it. Further, it is used to efficiently deliver the reliable, economic, and sustainable final customer. The main advantage of smart grid implementation in terms of utility benefits include reduced perturbations and outages; minimal power losses and blackout prospects; lower maintenance and operational cost; lower greenhouse gas emis- sions; increased energy efficiency; increased large scale renew- able energy and distributed generation integration; enabled micro-grid applications and energy management systems envi- ronmental benefits and economic growth through clean power markets [19].

In the present grid system generation is following the load, but in the smart grid system the load will follow the generation. For such a system, where load follows the generation the solar energy estimation at the site is the driving contributor to the power output calculations for these systems. If a system is able to predict solar energy with a good accuracy at a particular location then load scheduling, economic load dispatch, battery sizing, time of use and pricing can be done intelligently and optimally including the supply of critical loads for those times when the sufficient amount of po- wer is available. In addition to this when the power available from the solar energy based system is less then only critical loads can be supplied. With the correct data, solar collectors are fairly easy components to size, install, and begin generating power.

3. Fuzzy logic approach for global solar energy estimation

In the global solar energy estimation, geographical features like latitude, longitude, altitude and meteorological parameters like mean duration sunshine per hour and temperature play an important role. There are other meteorological parameters also which may affects the global solar energy such as relative humidity and wind speed. These parameters do not affect the global solar energy significantly. Therefore these parameters are not considered as input parameters in the proposed model.

Keeping in mind different climatic conditions, four stations such as New Delhi, Jodhpur, Kolkata and Shillong are chosen for the present study that cover the different climatic zones.

New and Renewable Energy [21].

The input parameters are latitude, altitude, longitude, months of the year, temperature ratio (T/T0) and mean duration sunshine per hour (S/S0). The output parameter is the clearness index (H/H0). The estimated global solar energy is obtained by multiplying the esti- mated clearness index by H0. Where H is the monthly mean global irradiance on horizontal surface, and H0 is the extraterrestrial solar irradiance on the 15th day of month, S is the monthly mean of the daily hours of bright sunshine; S0 is the maximum daily hours of sunshine or day length. The ratio of S/S0 is the fraction of maximum possible numbers of bright sunshine hours and H/H0 is the atmo- spheric transmission coefficient, commonly known as clearness index. The value of S0 can be computed from Cooper's formula.

Data of meteorological parameters like clearness index (H/H0), mean duration sunshine per hour (S/S0) and temperature ratio (T/T0) for New Delhi and Jodhpur stations .

Similarly, the data of meteorological parameters mentioned above for Kolkata.

The impact of mean duration sunshine per hour and tempera- ture is more significant as reported in the literature [11e12,15]. Therefore, it is necessary to select them as input parameters to get more accurate output. Hence, the sunshine duration and temper- ature have been selected as input meteorological parameters for the estimation of global solar energy. Further, we have also taken into consideration the effect of geographical parameters like lati- tude, longitude and altitude as inputs, though these parameters remain constant for a particular location. Hence these parameters have not been included in defining the rules.

The fuzzy system contains a set of rules which are developed from qualitative descriptions. In fuzzy systems, rules may be fired of the sources particularly wind and solar. This problem can be overcome by predicting the renewable energy sources intelligently. In addition, the generation and load forecasting can provide output consequent is the clearness index (H/H0). The consequents of the rules are shown in the shaded part of the matrix [22]. Ob- tained results are multiplied by the extraterrestrial solar irradiance (H0) to get the global solar energy. The rules are summarized in the fuzzy decision matrix.

The fuzzy variables, mean sunshine duration per hour (S/S0), temperature ratio (T/T0) and clearness index (H/H0) are described by the fuzzy terms high, highemedium/normal, medium/normal, lowemedium/normal or low. These fuzzy variables described by linguistic terms are represented by membership functions. The membership functions for sunshine duration, temperature ratio.

In this paper, prediction of SPV system output is done on the basis of data acquired from fuzzy model and cell temperature. This is done by predicting the output of PV module for a given insolation level and cell temperature. In this paper, 120 W PV module is selected and operated at maximum power point tracking.

Average power output of SPV system for smart grid application can be intelligently predicted using the fuzzy logic based model presented. Fuzzy rules for the prediction of SPV system output are presented. In the proposed model solar insolation and cell temperature are taken as input parameters and the output of the model is PV power generated by the given module. This data can then be used for variety of purposes which among others include reliability of supply, intelligent load management, optimized resource utilization, grid safety and grid stability.

5. Results and discussions

Fuzzy logic based model is developed and presented for the estimation of global solar energy using the above mentioned data for New Delhi, Jodhpur, Kolkata and Shillong stations. The output of the model is clearness index (H/H0). Obtained results are multiplied by the extraterrestrial solar irradiance (H0) to get the global solar irradiance (H). Results of fuzzy logic based models are compared with the well established REST2 (Reference Evaluation of Solar Transmittance, 2 band) model [4] for validation. Further ANN based model considering the same input parameters is also developed and presented in Appendix. The estimated global solar energy us- ing the above mentioned models is compared with the measured data for New Delhi, Jodhpur, Kolkata and Shillong stations are presented respectively. The fuzzy logic and ANN based models are developed in MATLAB toolboxes. The perfor- mance of the models is evaluated on the basis of mean absolute relative error in percentage. The mean absolute relative error is calculated as very close to each other. It shows that the performance of the model is satisfactory. Obtained results of solar insolation are further simulated along with cell temperature as input parameters for the prediction of output power of the given SPV system. As the cell temperature of a PV module affects the output of the PV system. The predicted output of SPV system in comparison with the computed power for New Delhi is presented. Due to paucity of space the results of other stations are not presented in this paper. The predicted power of SPV system in comparison with computed power is quite accurate. The mean absolute relative error. The mean percentage error using fuzzy logic for New Delhi, Jodhpur, Kolkata and Shillong are 5.11%. 5.17%, 5.53% and 5.67% respectively whereas it is 4.87%, 4.89%, 4.81% and 5.97% respec- tively using ANN. The results obtained from REST2 model are 5.54%, 5.70%, 6.26% and 6.47% respectively. As REST2 model is a clear sky model and does not incorporate the uncertainties in the weather, therefore intelligent models for the estimation of solar energy are required. It is fact that the performance of REST2 model is better as compared to other models available in the literature. In addition, the data of transmittances is not available during monsoon month (July September). Therefore it is difficult to estimate the solar energy during above mentioned period. Further, the results ob- tained from ANN model are slightly better as compared to the proposed model but it can be compromised with other advantages of fuzzy logic like flexibility, tolerant of imprecise data, model for nonlinear functions of arbitrary complexity, blended with con- ventional control techniques, based on natural language apart from easy to develop and better understanding. In addition, the esti- mated values obtained from fuzzy logic based model as compared to measured data are also represented graphically for New Delhi, Jodhpur, Kolkata and Shillong respectively. It is clearly seen that the measured and estimated values are for New Delhi, Jodhpur, Kolkata and Shillong is 5.41%, 5.47%, 5.59% and 5.75% respectively. Therefore, the proposed models may be used for the prediction of solar energy and PV power generation. Further, the obtained results may be used for smart grid application.

6. Conclusions

In the proposed work, a fuzzy logic based model for esti- mating the global solar energy for a particular station is pre- sented. The meteorological parameters like mean duration sunshine per hour and temperature and the geographical pa- rameters of the particular location are considered as input pa- rameters. Since there is always ambiguity in climatic conditions and it is difficult to predict solar energy accurately by using mathematical formulas and regression techniques at a particular time and at a particular location that is utmost important in the design of solar based power station. However such problems are overcome by fuzzy logic based techniques. Based on the data generated, fuzzy logic is applied to estimate the solar energy at four Indian stations that covers different climatic as well as geographical conditions.

The results obtained from the proposed fuzzy logic based model are compared with reference data and it is found that the per- centage error is within permissible limits that are about 5% for all stations considered in this work.

By using proposed model other uncertainties may also be included easily in estimating solar energy more accurate for any location that are required to set up solar based power stations. Further, the estimation of solar energy and prediction of SPV output would be helpful in smart grid application.

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Appendix

For the estimation of global solar energy at New Delhi, Jodhpur, Kolkata and Shillong stations, an ANN based model has been developed and presented in Figure 1.

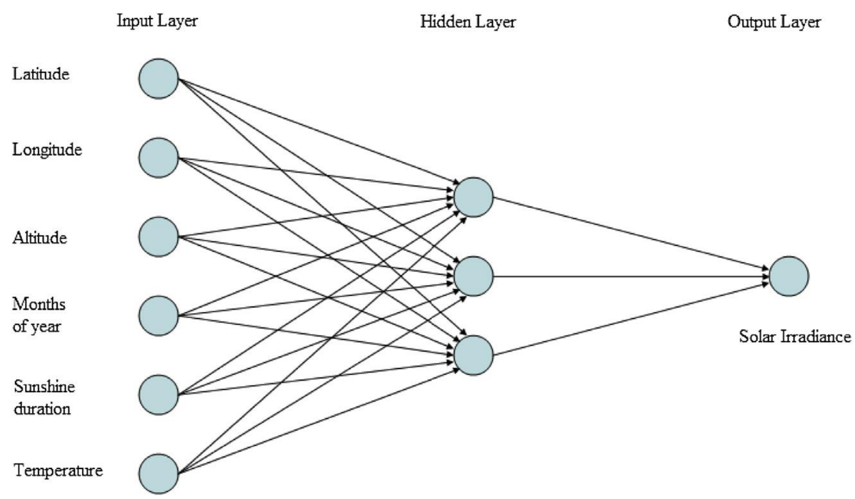

Figure. 1. ANN model for the estimation of global solar energy.

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