Neural Network Estimation of Microgrid Maximum Solar Power

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***Abstract*—The integration of photovoltaic (PV) generating stations in the power grids requires the amount of power available from the PV to be estimated for power systems planning on yearly basis and operation control on daily basis. To determine the PV station maximum output power, the PV panels must be placed at an optimal tilt angle to absorb maximum energy from the sun. This optimal tilt angle is a nonlinear function of the location, time of year, ground reflectivity and the clearness index of the atmosphere. This paper proposes a neural network (NN) to estimate the optimal tilt angle at a given location and thus an estimate of the amount of energy available from the PV in a microgrid.**

***Index Terms*—Irradiation, neural network, photovoltaic systems, power estimation, tilt angle.**

I. Introduction

PHOTOVOLTAIC (PV) energy is obtained from the conversion of photo energy absorbed by series and parallel connected PV cells to electrical energy [1], [2]. For power system planning, the output power of PV stations is needed for power flow analysis and grid design. For operation control, the PV station output power must be forecasted for daily power grid scheduling. The scheduling problem of smart power grid, where millions of PV stations are installed in the form of distributed generation, needs forecasted output power of PV stations.

Although, for operation control, the measurement system for irradiance can be installed, however, for microgrid of distributed generation system, they are expensive. The expensive servo tracking can be avoided, by determining the expected irradiance on a seasonal basis and to rotate the PV panels to track the sun [3].

The rotation of earth along its axis and its revolution around the sun over a year causes the position of the sun to change over a day and a year, respectively. The mean angle that the sun makes with the horizontal surface at a location on the earth's surface changes on a daily basis and depends on the latitudinal location. This causes a change in the amount of solar energy received at that location to change every day. In addition to the angle of the sun, weather conditions like cloud cover and general clarity of the atmosphere determines the amount of solar energy that reaches the earth's surface. For the PV panels to receive maximum energy, they must be continuously rotated to face the direction of maximum irradiance. Ideally, the panels should be capable of being rotated along two axes on a real time basis. To avoid the cost and complexity involved in adjusting the panels in real time, the panels can be installed at fixed optimum angles [3]. These adjustments can be made at plausible time intervals. It has been shown in [4] that adjusting the tilt angle on a monthly basis achieves marginal improvement of the gain in energy received over quarterly adjustments.

With the data of the location available, the amount of solar energy received on a tilted panel can be calculated. For power systems planning, it is important to estimate the amount of energy that will be available from a new microgrid PV installation. In [5], an analytical method is presented which uses empirical formula to estimate the optimum tilt angle however, the diffusion and reflection factors have not been considered. Autoregressive moving average method is used in [3] to estimate the irradiation and the optimum tilt angle. However, this method is site specific and takes into account only the radiation values at the location for estimation and recommends use of intelligent networks to estimate the optimum tilt angle.

In this paper, the estimation of the amount of irradiation energy received from the sun on the PV panel, calculated based on the optimal tilt angle of microgrid PV panels on a quarterly basis using NN nonlinear mapping, is proposed considering the ground reflectivity and diffusion irradiance. This estimated energy/power is used for load flow studies and the grid design.

The estimated energy or power is extremely important for load flow studies performed on the grid. To reduce cost, a mapping model of the optimum tilt angle of PV panels of microgrid can be computed, as shown in (1) by mapping it as a function of irradiation, G, latitude, ϕ, and ground reflectivity, ρ, so that microgrid receives maximum energy from the sun over a year, on daily, weekly, monthly, and seasonal basis. This mapping model can be programmed in controller of inverter for operation control:

$$\beta^{\mathrm{opt}} = \mathrm{f}(\mathrm{G}, \phi, \rho). \tag{1}$$

II. Problem Description

The sun is a source of radiation energy. The flux of radiation energy received on a unit area at a point outside the earth's atmosphere is designated as solar constant and it is estimated to be equal to 1367 W/m^2 [6]. Irradiation is defined as total energy received from radiation on a unit area over a given period of time.

The solar energy received at a location on earth depends on astronomical and geographical factors. The angle which the sun

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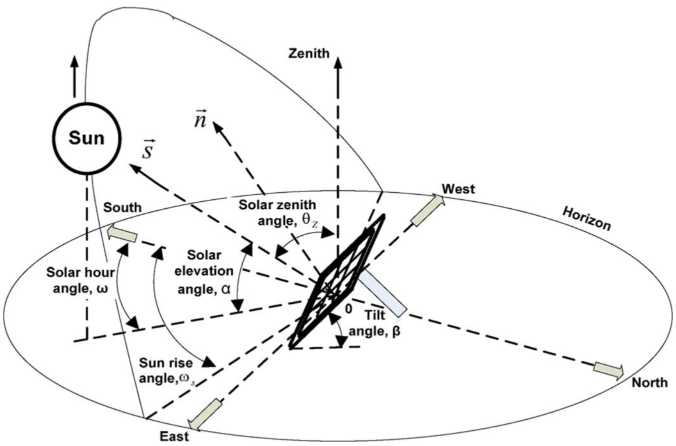

Fig. 1. Passage of the sun in the sky over a day.

makes with the horizontal plane is the solar elevation angle, α, which determines the amount of energy reaching the PV panel on the surface of the earth as depicted by Fig. 1. The plane tangential to the earth's surface at the location of the module is the *horizontal plane*. A line perpendicular to the horizontal plane, at the location of the module, is called the *zenith line*. The angle which the sun's rays make with the zenith line called *zenith angle*, θ_z. The complementary angle to it, *solar elevation angle*, α, is the angle between the horizontal plane and the sun. Due to the rotation of the earth, the sun appears to move from east to west and its position in the sky changes with time over a day. The angle measured from the line joining the module and the southern direction to the projection of the sun on the horizontal plane as shown in Fig. 1 is called *solar azimuthal angle* or *hour angle*, ω. The hour angle of the sun at sun rise is shown in Fig. 1 as ω_s. Instead of installing the modules horizontally, for capturing the maximum energy from the sun, the panels are tilted towards the equator (south for northern hemisphere). The angle which the plane of the module makes with the horizontal is called *tilt angle*, β, as shown in Fig. 1.

As the rays of the sun pass through the atmosphere, some of the energy gets absorbed in it. The amount of energy absorbed by the atmosphere depends on the distance the rays travel through the atmosphere. A factor called *air mass* (AM) is defined as the ratio of the distance the rays travel when the sun is at an angle to the distance travelled by the rays when the sun is perpendicularly overhead at the location. This factor determines how much irradiance is diffused into the atmosphere.

Fig. 2 shows orbit of the earth around the sun over one year. As the earth revolves around the sun, the angle of the sun at a location on earth appears to shift daily. This change is due to the variation in *declination angle*, δ which is the angle between the line joining the centers of the sun and the earth, and the equatorial plane [7] as shown in Fig. 2(a).

A location on the surface of the earth is specified by *latitude* and *longitude* at that location. The *latitude* of the location, ϕ, is the angle subtended at the center of the earth by the location and the equatorial plane. *Longitudes* are imaginary lines running from north-pole to south-pole on the surface of the earth.

The angles on the surface of the earth are detailed in Fig. 3. The *declination angle*, δ, is the angle which the sun makes with

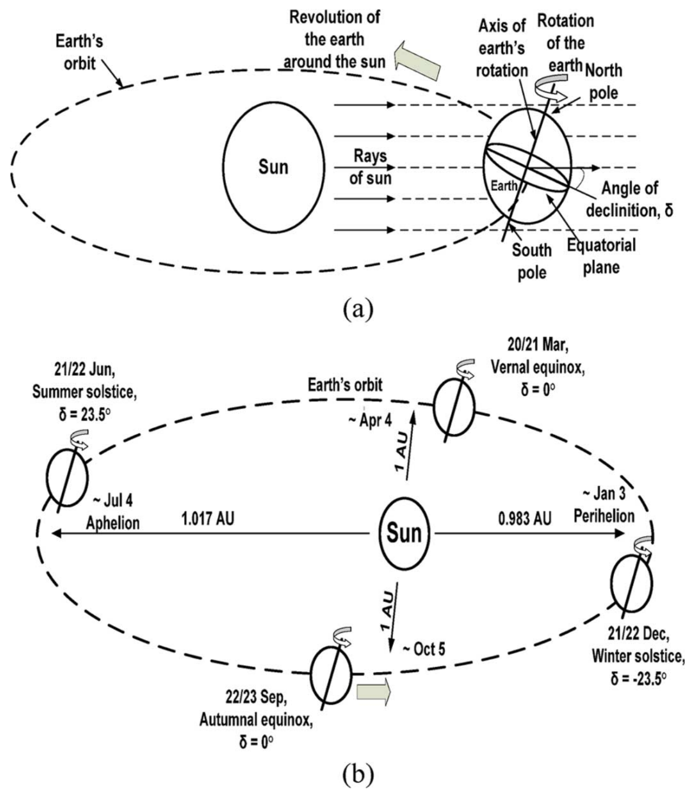

Fig. 2. Orbit of the earth around the sun over a year (a) defining the angles (b) detailing the orbit of the earth [8].

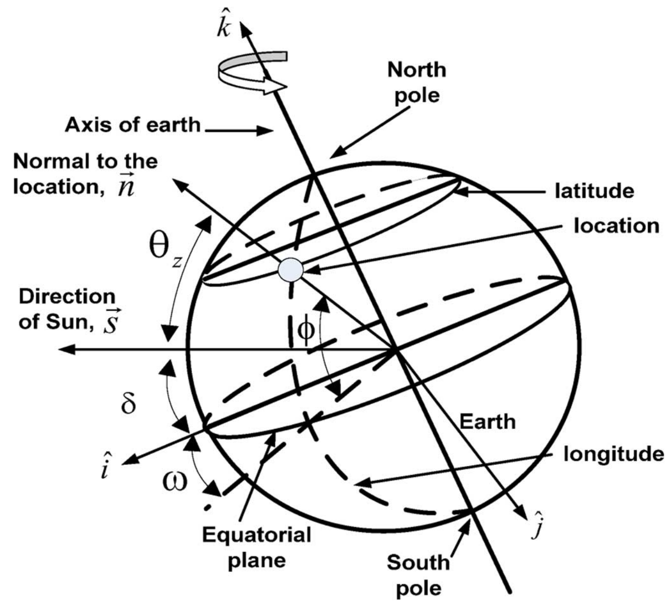

Fig. 3. Location of the panel on the globe showing the angles.

the plane of the equator. The *hour angle*, ω, is the angle which the longitude of the location makes with the sun at a particular time of the day. The *zenith angle*, θ_z, is the angle which the sun makes with the normal, $\vec{n}$ (the zenith line) at the location.

For analysis, three orthogonal unit vectors $\hat{i}, \hat{j}, \hat{k}$ have been defined with the origin defined as the center of the earth as shown in Fig. 3. $\hat{i}$ lies on the equatorial plane, pointing towards the direction of the sun, $\hat{j}$ lies on the equatorial plane, perpendicular to $\widehat{i}$ and pointing towards east, while $\hat{k}$ is coincidental with the axis of the earth pointing towards the north-pole.

Two other unit vectors are shown in Fig. 3: the unit vector pointing towards the sun is $\vec{s}$ and the unit normal, towards the zenith, at the location of the module, $\vec{n}$. The angle between the two vectors is the zenith angle. To define these two unit vectors, they are resolved in the $\widehat{i}, \hat{j}, \hat{k}$ directions to give relations (3) and (4):

$$\vec{s} = \widehat{i}\ \cos\delta + \hat{k}\ \sin\delta \tag{3}$$

$$\vec{n} = \widehat{i}\ \cos\phi\cdot\cos\omega + \hat{j}\ \cos\phi\cdot\sin\omega + \hat{k}\ \sin\phi. \tag{4}$$

From the dot product of $\vec{s}$ and $\vec{n}$, the cosine of the angle between the two can be found as shown in (5):

$$\cos\theta_z = \cos\delta\cdot\cos\phi\cdot\cos\omega + \sin\delta\cdot\sin\phi. \tag{5}$$

III. Calculation of Irradiance

From Fig. 1, it can be seen that the zenith angle at sunset (also sunrise) is $\pi/2$. The hour angle ω at sunset is called *sunset angle* and is designated as $\omega_{\rm s}$ in Fig. 1. From (5) [8]

$$\cos(\pi/2) = \cos\delta\cdot\cos\phi\cdot\cos\omega_s + \sin\delta\cdot\sin\phi \tag{6a}$$

$$\begin{aligned}\omega_s &= \cos^{-1}[-\tan\delta\cdot\tan\phi] \quad \text{for } |\tan\delta\cdot\tan\phi| \le 1\\ &= \pi \quad |\tan\delta\cdot\tan\phi| > 1.\end{aligned} \tag{6b}$$

As the earth revolves around the sun in an elliptical orbit, its distance with sun changes. As seen in Fig. 2(b), the distance between the earth and the sun is maximum around July 4 and this position is called *aphelion*, while the distance is minimum around January 3 which is known as *perihelion*. The energy received from the sun obeys inverse square law which is represented by *eccentricity correction factor* of the earth's orbit, E_o [9]:

$$E_o = (r_o/r)^2 = 1 + 0.033\cos(2\pi d_n/365) \tag{7}$$

where r_o is the mean distance of the earth and sun =1 AU $= 1.496 \times 10^8$ km, r is the distance of earth and the sun, d_n is the day number of the year (1 for January 1 through 365 for December 31).

A constant called *solar constant*, S, is defined as rate of energy at all wavelengths received by a unit area outside the earth's atmosphere, perpendicular to the rays, at a distance of one astronomical unit. The value of the solar constant is 1367 W/m^2 (or 4921 kJ/m^2/hour) as suggested by [10]. *Irradiance* (rate of energy received) on a surface should be adjusted for the variation in the distance of the earth and the sun as shown in (8):

$$I_{dn} = S.E_o \tag{8}$$

where I_{dn} is the irradiance on the day d_n.

The irradiance on a horizontal surface is received at an angle θ_z. Therefore, the irradiance on the horizontal surface, $I_{\rm hor}$, is

$$I_{\rm hor} = I_{dn}\cos\theta_z. \tag{9}$$

Using (5) and (8) in (9)

$$I_{\rm hor} = S.E_o\cdot\{\cos\delta\cdot\cos\phi\cdot\cos\omega + \sin\delta\cdot\sin\phi\}. \tag{10}$$

The beam energy, or *irradiation*, B_o, received during the day, is found by integrating $I_{\rm hor}$ over time from sunrise to sunset as shown in (12). It takes the earth 24 hours to make a 2π rad rotation. Therefore

$$\frac{2\pi}{24}\,dt = d\omega \tag{11}$$

$$B_o = \int I_{\rm hor}\,dt = \int S.E_o \cdot\{\cos\delta\cdot\cos\phi\cdot\cos\omega + \sin\delta\cdot\sin\phi\}\,dt. \tag{12}$$

Using the relation in (11) in (12)

$$\begin{aligned}\mathrm{B_o} &= \frac{24}{2\pi}\int_{-\omega_{\rm s}}^{\omega_{\rm s}} \mathrm{S.E}_o \cdot\{\cos\delta\cdot\cos\phi\cdot\cos\omega + \sin\delta\cdot\sin\phi\}\,\mathrm{d}\omega\\ &= \frac{24}{\pi}.\mathrm{S.E_o}[(\cos\delta\cdot\cos\phi\cdot\sin\omega_{\rm s}) + \omega_{\rm s}(\sin\delta\cdot\sin\phi)].\end{aligned} \tag{13}$$

In (13), B_o is in kJ/m^2/day if S is in kJ/m^2/hour or in kWh/m^2/day if S is in kW/m^2.

The angle of declination can be calculated from the empirical formula [11]:

$$\delta = 23.45\sin\left[\frac{360(d_n + 284)}{365}\right]. \tag{14}$$

For the modules to receive maximum energy, they are tilted towards the equator. For a tilt angle β, the angle made by the module to the equatorial plane is $\phi - \beta$. Hence the angle which the rays of sun make with the module, $\theta_{\rm tilt}$ is given by (15):

$$\cos\theta_{\rm tilt} = \cos\delta\cdot\cos(\phi-\beta)\cdot\cos\omega + \sin\delta\cdot\sin(\phi-\beta). \tag{15}$$

The sunset angle as seen by the module is now given by (16):

$$\begin{aligned}\omega_{s,\rm tilt} &= \cos^{-1}[-\tan\delta\cdot\tan(\phi-\beta)] \quad \text{for}|\tan\delta\cdot\tan\phi| \le 1\\ &= \pi \quad |\tan\delta\cdot\tan\phi| > 1.\end{aligned} \tag{16}$$

But in practice, $\omega_{s,\rm tilt}$ cannot be greater than ω_s. Therefore, the sunset angle is now the minimum of the two:

$$\omega_s' = \min(\omega_{s,\rm tilt}, \omega_s). \tag{17}$$

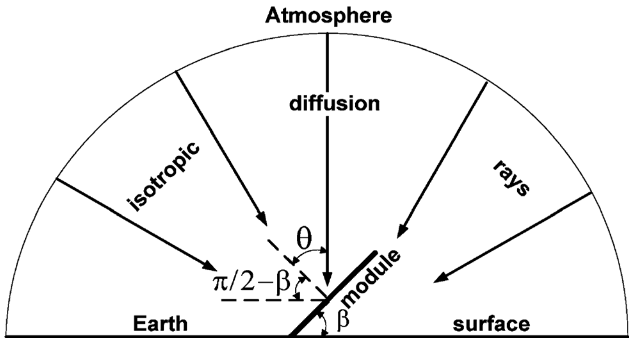

Fig. 4. Isotropic diffusion on the module.

Hence, (13) now get modified to (18) using (15) and (17):

$$B_\beta = \frac{24}{\pi} \cdot S.E_o \begin{bmatrix} \{\cos\delta \cdot \cos(\phi-\beta) \cdot \sin\omega_s'\} \\ +\omega_s'\{\sin\delta \cdot \sin(\phi-\beta)\} \end{bmatrix}. \tag{18}$$

As the rays from the sun pass through the atmosphere, they get scattered and a portion of it reaches the earth as diffused irradiance [12]. It is generally assumed that these diffused rays are isotropic, which means that they appear to come from all directions with equal intensity as shown in Fig. 4. The amount of diffused radiation the surface receives is directly proportional to the cosine of the angle of incidence, θ, shown in Fig. 4. The total diffused irradiance for tilt angle β is given by (19):

$$D(\beta) \propto \int_{-\pi/2}^{\pi/2-\beta} \cos\theta d\theta = (1+\cos\beta). \tag{19}$$

The amount of irradiance that reaches the surface of the earth is a function of the air mass and the clarity of the atmosphere. From the meteorological data recorded at the location, a fraction called clearness index, $\mathrm{K_T}$, is calculated:

$$\mathrm{K_T} = \mathrm{G/B_o} \tag{20}$$

where G is global daily irradiation for a typical day of the month.

Form the clearness index, the diffusion component, D, of the irradiation is calculated using the empirical formula [12]:

$$D/G = 1 - 1.13K_T. \tag{21}$$

The ratio of the diffusion irradiance for a tilted module to that of horizontal module is given by (22) using (19):

$$D(\beta) = \frac{1}{2}(1+\cos\beta) \cdot D. \tag{22}$$

Similarly, if ground reflection is considered isotropic, then we get (23):

$$R(\beta) \propto \int_{\pi/2-\beta}^{\pi/2} \cos\theta d\theta = (1-\cos\beta). \tag{23}$$

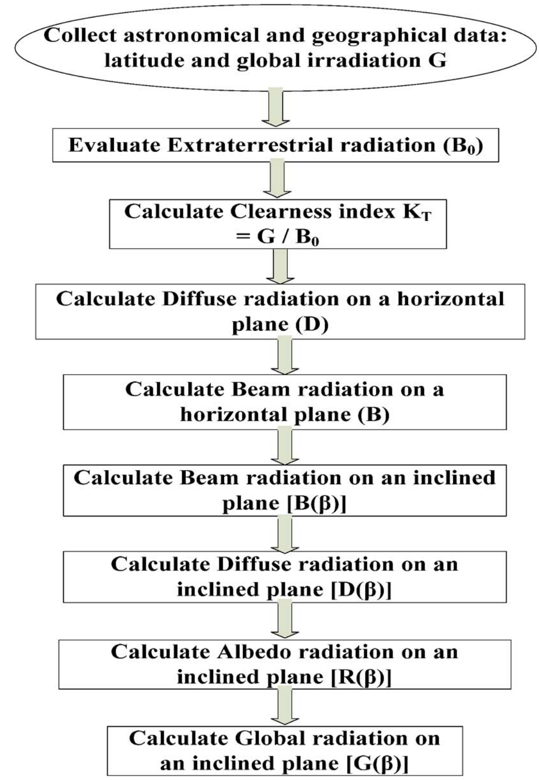

Fig. 5. Algorithm for calculation of global radiation on tilted PV panels.

The *reflected irradiation* or *albedo* on a tilted surface is given by

$$R(\beta) = \frac{1}{2}(1-\cos\beta) \cdot \rho \cdot D \tag{24}$$

where ρ is *reflection coefficient*

IV. Algorithm for Estimation of Output Power of PV Station

The algorithm to estimate the global irradiation and output power is given by Fig. 5. Although the problem of PV station output power can be formulated on daily, weekly, monthly, and quarterly basis, in this paper, the quarterly models of expected irradiation (kWh/m^2) are presented. Note that irradiation is computed in kWh/m^2. Thus the size of PV stations is a function of surface area of PV panels. The output power of PV stations is computed from location of stations and the irradiance. As seen from the above analysis, irradiation received on a tilted surface is a nonlinear function of the latitude of the location, the tilt angle, the ground reflectivity, clearness index, and the time of the year. The irradiation of a tilted surface at Columbus, Ohio, is plotted as a function of reflectivity and tilt angle for various times of the year in Fig. 6. In Fig. 7, the irradiation is plotted as a function of latitude and reflectivity. These plots illustrate the nonlinear relationship between the irradiation and tilt angle, latitude, and the ground reflectivity.

The reflected component from the ground that reaches the panel is a function of ground reflectivity. If the ground reflectivity is high, then more is the reflected component and the panels receive more irradiance as seen in Fig. 6(a) and (b). The

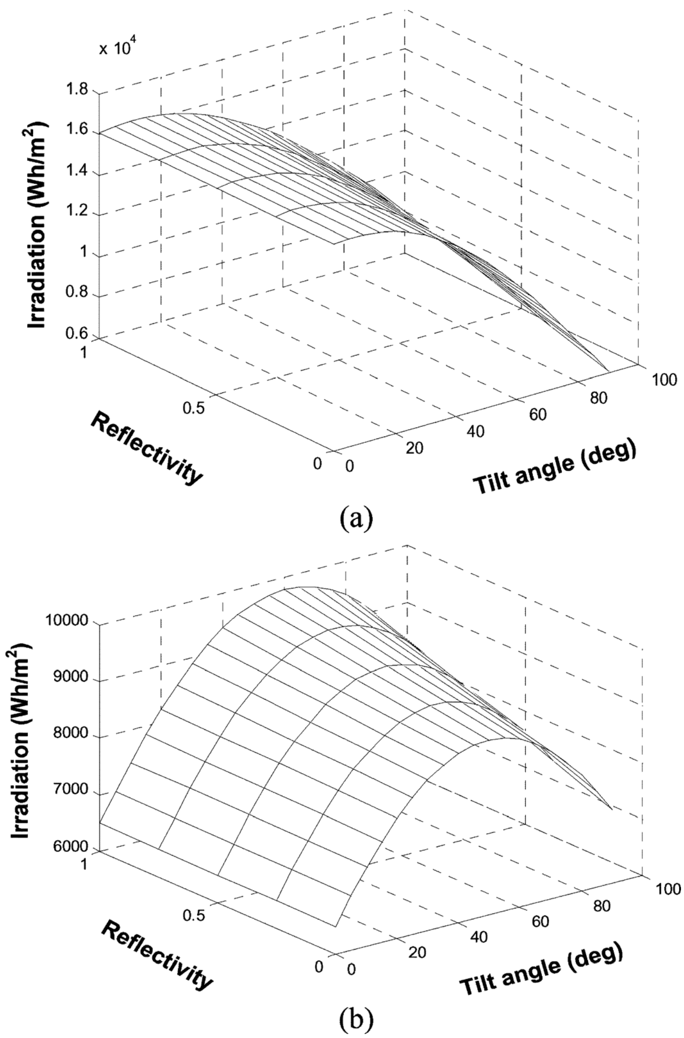

Fig. 6. Irradiation as a function of tilt angle and reflectivity for Columbus, Ohio from (a) April to June, and (b) October through December.

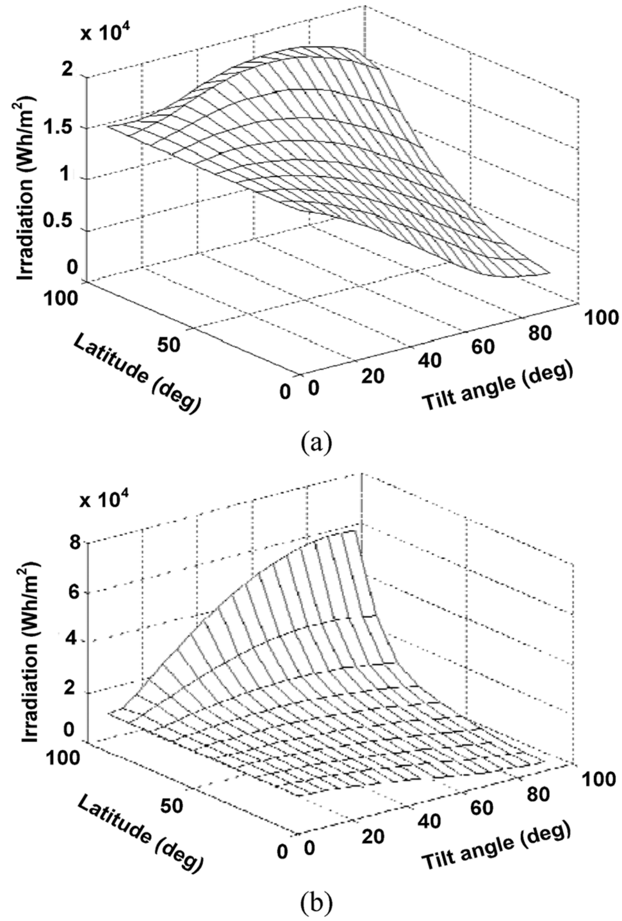

Fig. 7. Irradiation as a function of tilt angle and latitude of northern hemisphere for from (a) April to June, and (b) July through September.

sun makes a smaller zenith angle at Columbus, Ohio, which is located at 40° N during the months of April through June and hence the optimum tilt angle is closer to zero and the irradiation decreases as the tilt angle is increased [see Fig. 6(a)]. However, during autumn months, the sun is directly over the southern hemisphere and makes a larger zenith angle with Columbus. Therefore, to make the panels perpendicular with the sun, the panels must be given a larger tilt [see Fig. 6(b)].

Between April and September, when the sun is directly over the tropical latitudes of the northern hemisphere, the optimum tilt angle is close to zero in the tropics because the sun shines directly over the tropical latitudes. However, at locations far away from the tropics, with higher latitudes, the sun makes larger zenith angles and therefore, the optimum tilt angle increases at higher latitudes as seen in Fig. 7.

The nonlinear relationship between the tilt angle and the amount of irradiation received on the PV panels makes the computation of the optimal tilt angle and the irradiation difficult to estimate. Therefore, an NN is proposed for the estimation of the optimal tilt angle for each quarter of the year and the total amount of energy that will be available from the PVs when the PVs are installed at the respective optimal angles for each quarter.

V. Neural Network for Estimation of Optimal Angle and Irradiation

Neural network finds its application in various estimation problems including that of atmospheric sciences. In this paper, NN solution is proposed as it is successfully able to estimate the nonlinear relationship of tilt angle, latitude, ground reflectivity with the irradiation received without going through complicated analytical method. A multilayer perceptron is proposed to estimate the value of a nonlinear function. Multilayered perceptron has been chosen for its ability of function approximation [13]. Multiple layers are formed out of basic computational units called processing elements. A typical processing element accepts weighted sum of its inputs and transforms that through a nonlinear function to form the output [14]. The multilayer perceptron in this paper consists of perceptrons arranged in four distinct layers: input layer, two hidden layers, and output layer. The data presented at the input layer of the network is used to calculate the inputs for the hidden layer. The data from the inputs propagate to the hidden layers and then finally to the output layer. Training is a process in which known patterns of inputs and outputs are presented to the network and the weights between the layers are adjusted iteratively to match the output until

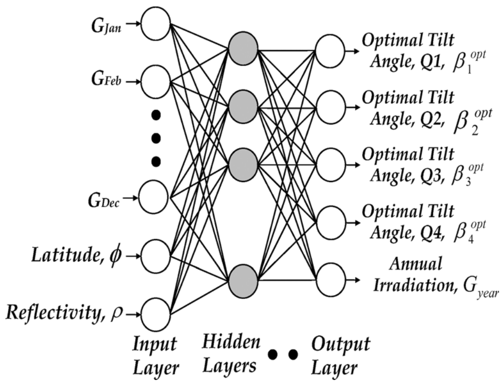

Fig. 8. Structure of NN for estimation of optimal tilt angle.

the error between the desired output and the output from the NN is below an acceptable value for all the training sets. In this work, the relationship between the input and output are as given by (25) and (26):

$$\beta_{\mathrm{i}}^{\mathrm{opt}} = \mathrm{f}_{1,\mathrm{i}}(\mathrm{G}_{\mathrm{month}}, \phi, \rho) \tag{25}$$

$$\mathrm{G}_{\mathrm{year}} = \mathrm{f}_2(\mathrm{G}_{\mathrm{month}}, \phi, \rho) \tag{26}$$

where $\beta_{\mathrm{i}}^{\mathrm{opt}}$ is the optimal tilt angle for the quarter i of the year and $\mathrm{G}_{\mathrm{year}}$ is the total irradiation that the panels receive over the year if the tilt angle is optimized for each quarter of the year.

Fig. 8 shows the structure of the NN which is used to estimate the optimal tilt angle. The NN shown in Fig. 8 estimates the optimal tilt angle for each quarter of the year and also the total irradiation the location receives if the tilt angle is optimized on a quarterly basis over the year as given by (25) and (26). The multilayer perceptron used has 14 input processing elements corresponding to the irradiation of each month, the latitude and the ground reflectivity of the location as given by (25) and (26). There are five output processing elements corresponding to the optimum tilt angle for each quarter in the year and the energy that is available from the installed PV if optimal tilt angle is used. The number of hidden layers and the number of elements in each layer is chosen arbitrarily depending on the complexity of the mapping. The transfer functions at the hidden layers are hyperbolic tangents which introduce the nonlinearity whereas the transfer functions at the input and output layers have linear transfer functions. Levenberg-Marquardt [15] algorithm for training is used for training the NN so that the sum of error squares, E, between the actual outputs, O_{A}, and the desired outputs O_{D} is minimized for training over all patterns μ and is below acceptable level:

$$\mathrm{E} = \sum_{\mu} (\mathrm{O}_{\mathrm{D},\mu} - \mathrm{O}_{\mathrm{A},\mu})^2. \tag{27}$$

As seen in Fig. 8, the NN accepts the meteorological data in the form of irradiation on a horizontal surface for each month, the latitude of the location and the ground reflectivity of the location to estimate the optimal tilt angle at that location to receive maximum irradiation. The estimate of the nonlinear mappings $\mathrm{f}_{1,\mathrm{i}}$ and f_2 representing the optimal tilt angle for quarter i and the total irradiation received by the panel can be expressed using weight vectors W, bias vectors B, and the inputs:

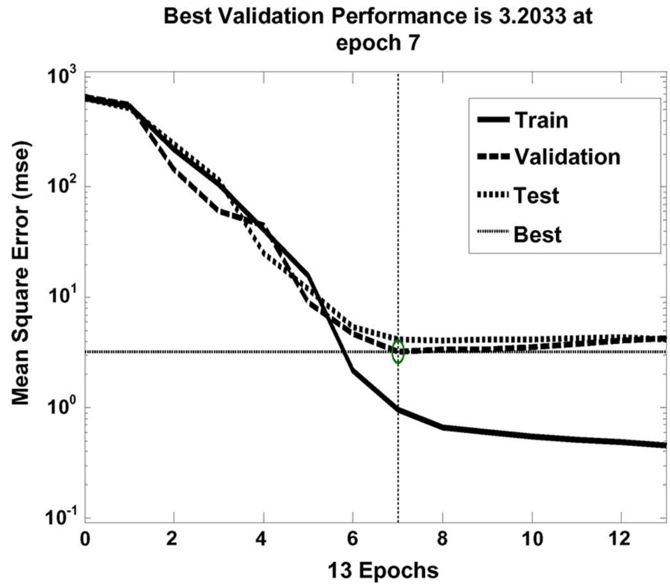

Fig. 9. Plot mean square error versus epoch during training.

$$\begin{bmatrix} \beta_{\mathrm{i}}^{\mathrm{opt}} \\ \mathrm{G}_{\mathrm{year}} \end{bmatrix} = \mathrm{W}_3 \tanh(\mathrm{W}_2 \cdot \tanh(\mathrm{W}_1 \cdot \mathrm{I} + \mathrm{B}_1) + \mathrm{B}_2) + \mathrm{B}_3 \tag{28}$$

where W_1 is 15×14 matrix connecting the 14 inputs, I, with the 15 layer first hidden layer, W_2 is 15×15 matrix connecting the first and second hidden layer, W_3 is a 5×15 matrix connecting the second hidden layer and the output layer. B_1, B_2, and B_3 are 15×1, 15×1, and 5×1 bias matrices for the first hidden layer, second hidden layer, and the output layer, respectively. The training patterns required to train the NN are obtained from the rigorous calculations shown in analytical section. The model presented by (28) has 15 perceptrons each in the two hidden layers and 14 inputs and 5 outputs.

VI. Neural Network Model Validation

The NN of Fig. 8 is trained from the available geographical and meteorological data [16], [17]. The NN has been trained with a best validation performance of 3.2033. The plot of mean square error has been shown in Fig. 9.

In the NN model [see (28)], the optimal tilt angle for each quarter and the total annual irradiance received at different locations with ground reflectivity of 0.5 have been estimated as shown in Table I. The results in Table I show that the estimated optimum tilt angle have small error from the actual values. The estimated optimum tilt angles by NN are within 3° of the analytical values. Hence it has been demonstrated that the NN can be effectively used to estimate the optimum tilt angle and the energy available which is required for power flow study and the solar energy available to the microgrid.

VII. Conclusion

In this paper, NN method to estimate the optimal tilt angle and the amount of energy available from the sun at the given lo-

TABLE I
ESTIMATED OPTIMUM TILT ANGLE FOR EACH QUARTER AND ANNUAL IRRADIATION

Location	Latitude (°)	Optimum tilt angle Quarter 1 (°)		Optimum tilt angle Quarter 2 (°)		Optimum tilt angle Quarter 3 (°)		Optimum tilt angle Quarter 4 (°)		Annual total irradiation (kWh/m^2)	
		Analytical	NN	Analytical	NN	Analytical	NN	Analytical	NN	Analytical	NN
Kolkata, India	22.00	35	35.54	0	0.95	0	0.98	40	41.43	58.65	58.24
Los Angeles, California	33.93	45	47.31	5	4.71	10	9.87	50	51.86	67.69	67.94
Columbus, Ohio	40.00	50	50.03	10	9.58	15	15.20	55	54.95	52.01	52.33
Barrow, Alaska	71.30	80	80.19	40	38.86	35	35.46	80	79.37	33.29	33.40
Daggett, California	34.87	50	48.86	5	4.73	10	12.65	55	54.04	81.65	81.64

cation has been presented. The nonlinear relationship between the irradiation, tilt angle, and the ground reflectivity is modeled by the proposed NN method. It is demonstrated that the NN is able to estimate the optimum tilt angle with an accuracy of 3° and the optimized irradiation at the microgrid with negligible error. The proposed neural network estimates the optimum tilt angle for online operation without additional instrumentation. For planning studies, the NN model can be used for accurate estimation of energy output of PV stations. For operation control and power flow studies, the NN model can be used for scheduling operation.

REFERENCES

[1] A. Keyhani, *Design of Smart Power Grid Renewable Energy Systems*. New York: Wiley, Jun. 2011.

[2] A. Keyhani, M. N. Marwali, and M. Dai, *Integration of Green and Renewable Energy in Electric Power Systems*. New York: Wiley, Jan. 2010.

[3] Q. Zhao, P. Wang, and L. Goel, "Optimal PV panel tilt angle based on solar radiation prediction," in *Proc. IEEE Conf. PMAPS*, Jul. 2010, pp. 425–430.

[4] R. Tang and X. Liu, "Installation design of solar panels with seasonal adjustment of tilt-angles," in *Proc. IEEE Conf. Power and Energy Engineering*, Apr. 2010, pp. 1–4.

[5] M. M. El-Kassaby, "Monthly and daily optimum tilt angle for south facing solar collectors; theoretical model, experimental and empirical correlations," *Solar Wind Technol.*, vol. 5, no. 6, pp. 589–596, 1988.

[6] E. Lorenzo, *Solar Electricity: Engineering of Photovoltaic Systems*. Madrid, Spain: Institute of Solar Energy, 1994, Polytechnic University of Madrid, ISBN 8486505550.

[7] T. Markvart, *Solar Electricity*. West Sussex, U.K.: Wiley, 1994, pp. 11–16.

[8] M. Iqbal, *An Introduction to Solar Radiation*. New York: Academic, 1983, pp. 1–84.

[9] J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*. New York: Wiley, 1980.

[10] C. Frohlich and R. W. Brusa, "Solar radiation and its variation in time," *Sol. Phys.*, vol. 74, pp. 209–215, 1981.

[11] P. I. Cooper, "The absorption of solar radiation in solar stills," *Sol. Energy*, vol. 12, no. 3, pp. 333–346, 1969.

[12] J. K. Page, "The estimation of monthly mean values of daily total short-wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40° N–40° S," in *Proc. United Nations on New Sources of Energy*, 1961, vol. 4, pp. 378–390.

[13] M. W. Garner and S. R. Dorling, "Artificial neural networks (the multilayer perceptron)—A review of applications in the atmospheric sciences," *Atmosph. Environ.*, vol. 32, no. 14/15, pp. 2627–2636, Aug. 1998.

[14] S. Pillutla and A. Keyhani, "Neural network based saturation model for round rotor synchronous generator," *IEEE Trans. Energy Convers.*, vol. 14, no. 4, pp. 1019–1025, Dec. 1999.

[15] L. S. H. Ngia and J. Sjoberg, "Efficient training of neural nets for nonlinear adaptive filtering using a recursive Levenberg-Marquardt algorithm," *IEEE Trans. Signal Process.*, vol. 48, no. 7, pp. 1915–1927, Jul. 2000.

[16] A Joint Project of Solar Energy Centre, MNRE Indian Metrological Department, Solar Radiation Handbook. [Online]. Available: http://www.indiaenvironmentportal.org.in/files/srd-sec.pdf.

[17] W. Marion and S. Wilcox, Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors, National Renewable Energy Laboratory. [Online]. Available: http://www.nrel.gov/docs/legosti/old/5607.pdf.

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