Deterministic Modelling of Solar Radiation for Natural Resource Management in Udaipur Region

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Abstract - *Increasing use of various kinds of energy sources in rural as well as in urban areas highlights the necessity of using the more solar energy for sustainable use of precious natural resources and their management. The major electrical energy utilization in the region of Udaipur are for domestic lighting but a significant amount of energy is also utilized for pumping of water for irrigation and other on-farm activities. Knowledge of solar radiation over time plays very important role in planning, design, installation, operation and maintenance of solar energy harvesting units/ systems. In Udaipur region, where the solar energy is in abundance throughout the year, installation of such systems may prove to be very cost effective and energy efficient, if designed, with the help of precise and accurately fitted models predicting the values of solar radiations over time. In the present study the past data of thirty-two years (1983-2014) were used. The data of maximum, minimum and average values of total global and diffused solar radiation over time were assumed as the time series consisting of finite numbers of equally spaced data points. The periodic variations in the radiations were assumed to be the superposition of several sinusoidal harmonics. In this context, the Fourier Series Transformation has been fitted to the data of solar radiations available in Udaipur region. The models, thus developed, have been tested for the variance test analysis. The predicted values were compared with the historical values obtained from subtraction of respective predicted values of historical data series and were found random around zero mean. The models developed may well be adopted for prediction of solar radiations in Udaipur region. Similar models can also be made for different regions for utilization in generation of data and the spatial comparisons. The developed Fourier transformation models can also be employed for the prediction of such values which could be efficiently used for the optimisation of design parameters and thus, the cost effectiveness while designing solar radiation harnessing units such as solar photovoltaic array for successful electric generation in the region, solar cookers, dryers, solar ponds etc.*

***Key Words*: Fourier transformation, Modelling, Solar radiation, Udaipur Region, Natural Resources Management**

1. INTRODUCTION

Food and water would be among the top few challenges before the world in the second quarter of the 21st century. The world population may grow beyond 9 billion by the year 2050. Studies have indicated that the production of food in the world would increase by 50% by 2030 and 100% by 2050 from its current levels to feed the growing population (Kaledhonkar et al., 2013; Waghaye et al., 2018). Continuously increasing use of energy in rural as well as in urban areas highlights the necessity of using the solar energy. The energy utilization activities in Udaipur region are mainly for domestic activities in lighting in the rural dwellings. Besides this, a significant amount of energy is also needed for pumping water for irrigation and other on-farm activities including post- harvest operations (Kishore et al, 2016; Saxena et al, 2017). A major challenge before the country particularly in the agricultural sector has been to convert it into a commercial proposition by reducing the cost of cultivation by improved input use efficiency and by higher returns to the farmers through quality production (Saxena and Gupta, 2004; Saxena and Gupta, 2006 a & b; Saxena et al., 2013; Saxena et al., 2015). Although the available land and water resources has been decreased over time. On the other hand, the cultivated land has reduced to 0.12 ha in 2015 from 0.31 in 1961 (Pandey et al, 2010; Saxena et al., 2018). The agricultural sector consumes about 83% of the total water used, is the most lavish user of the resource (Bajpai and Saxena, 2017). The availability of water was above 5300 m^3 in 1951 which got reduced to 1588 m^3 in 2010, and likely to be lesser than 1500 m^3 in the year 2025 (Saxena et al., 2019). On-farm water management, therefore, should receive greater importance to save water in this sector and thus, more dependency on the use of alternative resources like that of solar radiations. The region faces bright sunshine for more than nine months in a year. Keeping this in view the availability of solar energy in terms of global and diffused solar radiations assures to be the only and freely available energy source for the ever increasing need.

Knowledge of solar radiation is must over time and space in design, planning, operation and installation of solar energy operated units in rural and urban sectors. Optimal size of solar photovoltaic solar array, flat plate collector or the other solar energy harnessing units may well be suggested to greater cost effectiveness if one possesses the idea of availability of solar radiation over time for a region. The potential of solar energy may be judged by studying the availability of global and diffused solar radiations and clearness index. The accurate predictions of the solar radiations for a region on monthly basis using various models and transformations may be of some use for such purposes. The Fourier transformation of radiations over the year fits to a fairly good extent that the predicted values through this transformation may well be adopted for computation of design value of solar radiation. In this context, the data of maximum, minimum and average values of total global and diffused solar radiations have been analyzed to develop the Fourier transformation model which may be used to predict the values of radiations for months from January to December. The observed and predicted monthly values have also been compared to strengthen the validity of the developed models.

2. FOURIER TRANSFORMATION

The Fourier transformation in its general and simplest form may be expressed as follows.

$$R_t = A_0 + \sum_{k=1}^{N/2}\left(A_k \cos\frac{2\pi kt}{P} + B_k \sin\frac{2\pi kt}{L}\right) \quad (1)$$

where, R_t is monthly solar radiation at time(month) t, kwh/m^2/day, P is periodicity of data (12 in present study), N is total number of equally spaced data points, t is time factor, t = 1,2,3......N, k is number of harmonics, $1 \leq k \leq p/2$ and A_o, A_k and B_k are the Fourier coefficients and half range amplitudes of k^{th} harmonic which are given by

$$A_o = \frac{1}{N}\sum_{t=1}^{N}(R_t) \quad (2)$$

$$A_k = \frac{2}{N}\sum_{t=1}^{N}\left[R_t Cos\left(\frac{2\pi kt}{P}\right)\right] \quad (3)$$

$$B_k = \frac{2}{N}\sum_{t=1}^{N}\left[R_t Sin\left(\frac{2\pi kt}{P}\right)\right] \quad (4)$$

The numbers of significant harmonics (m) of original historic series were determined by variance test analysis (Box and Jenkins, 1976). For further analysis the periodic means (m_r) were computed and expressed in the Fourier transformation form as follows.

$$m_r = m_o + \sum_{k=1}^{P/2}\left[\alpha_k Cos\left(\frac{2\pi kt}{P}\right) + \beta_k Sin\left(\frac{2\pi kt}{P}\right)\right] \quad (5)$$

Where,

$$m_o = \frac{1}{P}\sum_{t=1}^{P}(m_t) \quad (6)$$

$$\alpha_k = \frac{2}{P}\sum_{r=1}^{P}\left[m_r Sin\left(\frac{2\pi kt}{P}\right)\right] \quad (7)$$

$$\beta_k = \frac{2}{P}\sum_{r=1}^{P}\left[m_r Cos\left(\frac{2\pi kt}{P}\right)\right] \quad (8)$$

Thus the numbers of significant harmonics obtained were computed for these harmonics only. The computed values of R_t *i.e.,* R_{tc} were subtracted from the observed series of solar radiation. The residual components, thus left, were analysed for the presence of randomness.

The periodic variations are the functions of solar radiations with time and may be expressed as a superposition of several sinusoidal variations (harmonics). Every individual harmonics have separate phase angle, amplitude and their contribution towards the total explained variance.

3. RESULTS AND DISCUSSION

The data of solar radiations for thirty two years (1983-2014) were collected from the Meteorological Observatory and Renewable Energy Centre, College of Technology and Agricultural Engineering, Udaipur, Rajasthan. The mean daily values were transformed into mean monthly values representing daily averages for that month. These values were assumed to be the time series consisting of a finite numbers (twelve in the study) for equally spaced data points for each maximum, minimum and average values of global and diffused solar radiations. Thus, the months starting from January to December were designated by the numbers 1 to 12 successively.

The arithmetic mean of monthly maximum, monthly minimum and monthly average global and diffused solar radiations are more than the annual mean values for four months in a year. Similarly, the maximum values of global and diffused solar radiations were found to be more than observed values for six months in a year for global and diffused solar radiations. The values of the mean and the standard deviation (population) for observed series are given in Table 1. Rathore and Vijay (1989) also suggested that the solar radiations available in Udaipur region having a clearness index with mean at 0.666 may be found in good harnessing range.

Table -1: Statistical parameters of observed, predicted and residual series

Solar Radiation Series	Observed Series		Computed Series		Residual Series	
	Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev.
Mean Global	5.76	1.01	5.76	1.01	0.00	0.07
Maximum Global	7.08	1.32	7.08	1.31	0.00	0.16
Minimum Global	1.66	1.12	4.66	0.95	0.00	0.58
Mean Diffused	1.98	0.91	1.98	0.91	0.00	0.08
Maximum Diffused	3.60	1.04	3.60	1.03	0.00	0.16
Minimum Diffused	0.68	0.36	0.68	0.31	0.00	0.18

The Fourier coefficients, A_k and B_k, are given in Table 2 up to N/2 = 6 harmonics for different series. Table 2 also includes the amplitude, phase angle in degrees and the percent explained variance with cumulative values for each harmonic for all series of radiations (average, maximum and minimum values of global and diffused solar radiation series). The data given with the table shows that the series consisting of mean and maximum values of global and diffused radiation explains more than 90 per cent variance by the first three harmonics cumulatively. Hence, from the prediction point of view the first three harmonics were considered in spite of the fact that the series of the minimum values of radiations could have more than 90 per cent of the variance in the 5th and 6th harmonics (Saxena et al., 2008). This was made a criterion to keep the similarity in the prediction models and the non-significant contribution made by the amplitudes from the fourth to sixth harmonics. Thus, the Fourier models for average, maximum and minimum values of global and diffused solar radiations respectively are given below.

$$R_{tc\,(Mean\ global)} = 5.76 - 1.23\,\text{Cos}\left(\frac{2\pi t}{12}\right) + 0.399\,\text{Sin}\left(\frac{2\pi t}{12}\right) - 0.27\,\text{Cos}\left(\frac{4\pi t}{12}\right) + 0.53\,\text{Sin}\left(\frac{4\pi t}{12}\right) - 0.21\,\text{Cos}\left(\frac{6\pi t}{12}\right) + 0.15\,\text{Sin}\left(\frac{6\pi t}{12}\right) \quad (9)$$

$$R_{tc\,(Max\ global)} = 7.08 - 1.69\,\text{Cos}\left(\frac{2\pi t}{12}\right) + 0.23\,\text{Sin}\left(\frac{2\pi t}{12}\right) - 0.44\,\text{Cos}\left(\frac{4\pi t}{12}\right) - 0.18\,\text{Sin}\left(\frac{4\pi t}{12}\right) - 0.18\,\text{Cos}\left(\frac{6\pi t}{12}\right) + 0.025\,\text{Sin}\left(\frac{6\pi t}{12}\right) \quad (10)$$

$$R_{tc\,(Min\ global)} = 1.66 - 0.45\,\text{Cos}\left(\frac{2\pi t}{12}\right) + 0.38\,\text{Sin}\left(\frac{2\pi t}{12}\right) - 0.48\,\text{Cos}\left(\frac{4\pi t}{12}\right) - 0.996\,\text{Sin}\left(\frac{4\pi t}{12}\right) - 0.03\,\text{Cos}\left(\frac{6\pi t}{12}\right) - 0.315\,\text{Sin}\left(\frac{6\pi t}{12}\right) \quad (11)$$

$$R_{tc\,(Mean\ diffused)} = 1.98 - 1.18\,\text{Cos}\left(\frac{2\pi t}{12}\right) + 0.16\,\text{Sin}\left(\frac{2\pi t}{12}\right) - 0.56\,\text{Cos}\left(\frac{4\pi t}{12}\right) + 0.28\,\text{Sin}\left(\frac{4\pi t}{12}\right) + 0.14\,\text{Cos}\left(\frac{6\pi t}{12}\right) - 0.06\,\text{Sin}\left(\frac{6\pi t}{12}\right) \quad (12)$$

Table -2: Fourier coefficients and other parameters for each harmonic for different radiation series

Order of Harmonic	A_k	B_k	Amplitude	Phase Angle (Degrees)	Explained Variance	Cumulative Explained Variance
Mean Global Radiation						
1	-1.13	0.40	1.20	-19.49	70.30	70.30
2	-0.27	-0.53	0.60	63.15	17.53	87.83
3	-0.21	0.16	0.26	-36.38	3.37	91.20
4	0.09	0.03	0.09	16.26	0.44	91.64
5	0.00	-0.01	0.02	-89.45	0.02	91.66
6	-0.02	0.00	0.02	0.00	0.01	91.67
Maximum Global Radiation						
1	-1.69	0.23	1.70	-7.66	82.84	82.84
2	-0.44	-0.18	0.48	22.28	6.49	89.34
3	-0.18	-0.03	0.19	7.82	0.98	90.32
4	-0.14	-0.10	0.17	35.68	0.89	91.15
5	-0.06	0.01	0.06	-7.53	0.11	91.26
6	-0.17	0.00	0.17	0.00	0.81	92.07
Minimum Global Radiation						
1	-0.45	0.38	0.59	-40.69	13.82	13.82
2	-0.48	-1.00	1.11	64.19	48.97	62.80
3	-0.03	0.32	0.32	-84.86	4.00	66.80
4	-0.51	0.25	0.56	-26.10	12.74	79.54
5	0.50	-0.17	0.53	-18.45	11.30	90.84
6	0.20	0.00	0.20	0.00	1.65	92.49
Mean Diffused Radiation						
1	-1.18	-0.16	1.19	7.71	84.74	84.74
2	0.06	0.28	0.29	78.85	4.88	89.62
3	0.14	-0.06	0.15	-23.04	1.38	91.00
4	-0.08	-0.01	0.08	8.89	0.39	91.38
5	-0.02	0.05	0.05	-67.29	0.17	91.56
6	0.06	0.00	0.06	0.00	0.22	91.78
Maximum Diffused Radiation						
1	-1.36	0.04	1.36	-1.79	85.41	85.41
2	-0.15	0.12	0.19	-39.92	1.72	87.13
3	0.23	0.00	0.23	-0.84	2.40	89.52
4	-0.06	0.09	0.01	-58.42	0.51	90.03
5	0.07	0.14	0.16	63.80	1.13	91.16
6	-0.15	0.00	0.15	0.00	1.01	92.17
Minimum Diffused Radiation						
1	-0.39	0.10	0.41	-13.58	64.43	64.43
2	0.01	-0.06	0.06	-78.61	1.57	66.00
3	-0.04	-0.04	0.05	47.49	1.15	67.15
4	-0.19	0.05	0.20	-15.77	15.13	82.28
5	0.11	-0.02	0.11	-10.34	4.98	87.26
6	-0.15	0.00	0.15	0.00	8.81	96.07

$$R_{tc\,(Max\,diffused)} = 3.60 - 1.36\,\mathrm{Cos}\left(\frac{2\pi t}{12}\right) + 0.04\,\mathrm{Sin}\left(\frac{2\pi t}{12}\right) - 0.15\,\mathrm{Cos}\left(\frac{4\pi t}{12}\right) + 0.12\,\mathrm{Sin}\left(\frac{4\pi t}{12}\right) + 0.23\,\mathrm{Cos}\left(\frac{6\pi t}{12}\right) + 0.003\,\mathrm{Sin}\left(\frac{6\pi t}{12}\right) \quad (13)$$

$$R_{tc\,(Min\,diffused)} = 0.68 - 0.39\,\mathrm{Cos}\left(\frac{2\pi t}{12}\right) + 0.09\,\mathrm{Sin}\left(\frac{2\pi t}{12}\right) + 0.013\,\mathrm{Cos}\left(\frac{4\pi t}{12}\right) - 0.062\,\mathrm{Sin}\left(\frac{4\pi t}{12}\right) - 0.037\,\mathrm{Cos}\left(\frac{6\pi t}{12}\right) - 0.04\,\mathrm{Sin}\left(\frac{6\pi t}{12}\right) \quad (14)$$

The observed values of historical monthly average values and the corresponding computed values using equations 9 to 11 for mean, maximum and minimum values of global radiations for t = 1,2,3,....12 have shown in Fig.1.

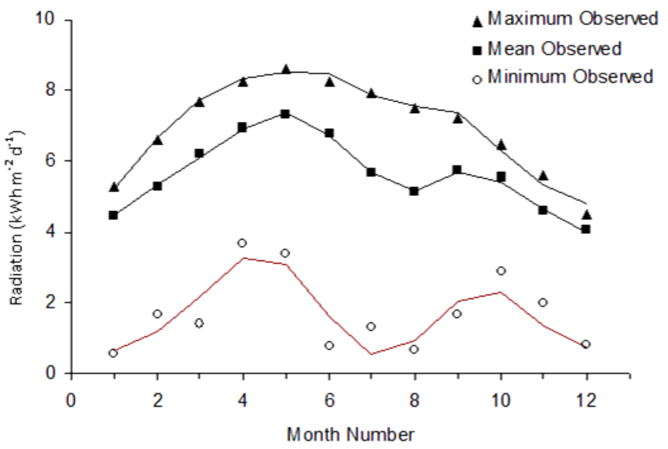

Fig -1: Historical and generated values of mean, maximum and minimum values of global radiation

Similarly, Fig.2 shows the observed and the computed values of mean, maximum and minimum values diffused radiations using equations 12 to 14. Fig.1 and 2 also reflect that the computed values using above models are thoroughly close to the observed historical data.

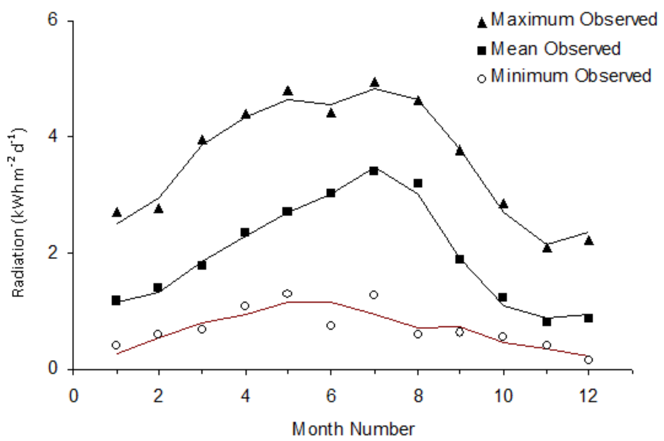

Fig -2: Historical and generated values of mean, maximum and minimum values of diffused radiation

The computed values of radiations (Eq.9 to 14) were compared and subtracted from observed values to get the residual component. The arithmetic mean and the standard deviation for both computed and residual series were worked out and are presented in Table 1. The closeness of the mean and the standard deviation of the observed and computed values is clearly visualised. The mean and the standard deviation of the residual component reflect that all the values are randomised with mean equals or very nearly equals to zero with a standard deviation less than 0.5821 among all the data sets. Thus, the residual component may be neglected as suggested by Kottagoda (1980).

3. CONCLUSIONS

On the basis of the above study the following conclusions may be drawn.

1. The general trend of variation of solar radiation is same for global and diffused radiations for mean, maximum and minimum values. In most of the months the availability of solar radiations in Udaipur region is within the good harnessing range.
2. The monthly average values of solar radiations may well be represented by the Fourier series deterministic models.
3. The developed Fourier transformation models may be employed for the prediction of such values which could be efficiently used for the optimisation of design parameters and thus, the cost effectiveness while designing solar radiation harnessing units such as solar cookers, dryers, solar ponds, and solar photovoltaic array for successful electric generation in the region.

ACKNOWLEDGEMENT

The authors are thankful to the Director, ICAR-Central Soil Salinity Research Institute, Karnal, India and for granting the study leave to the first author, as well to the Director, ICAR-Central Institute of Agricultural Engineering, Bhopal, India for other necessary permissions and the facilities.

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Prof. V.K. Vijay is actively engaged in research and worked for more than 40 sponsored research and consultancy projects and has about 150 publications in journals and conferences, 7 books to his credit. Prof. Vijay has developed and patented a technology on Biogas Enrichment and bottling for Vehicular Application and transferred it to the industries and field. He is fellow of Indian Society of Agricultural Engineers and Institution of Engineers (India) and Life Member of National Academy of Science in India, Indian Society of Technical Education, Solar Energy Society of India and other scientific and professional societies/ bodies. He is the Indian coordinator of Sustainable Energy and Environment Forum (SEE Forum) working in Asia with head quarter in Japan, General Secretary of Biogas Forum (India).