Measured Data of Hourly Global Solar Irradiation Using Two Curve-Fitting Methods

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Abstract - *Solar energy has an important role to achieve the goal of replacing fossil fuels and significant potential to reduce green house gas emissions. Accurate information on solar radiation is very essential for engineers, architects and agriculturist to design the energy systems based on the solar source. The radiation data is highly useful for the designing of solar energy related electricity generation systems. The data was filtered by using polynomial fitting method. This paper studies the use of polynomial fitting to the global solar radiation that was measured by using Pyranometer model no. CMP11 at Kolayat, located in Rajasthan, India. Measured hourly global solar radiation data of Kolayat in May 2015 were analyzed in this work. The two curve –fitting methods that were found to be suitable to be applied to the filtered solar radiation data is the polynomial fit and the sinusoidal fit. Author have been taken solar radiation data every five minute during 6:00-20:00 . The polynomial data fitting method was used for data smoothing and was tested by using different degrees of polynomial curve fittings. The error measurement was calculated by using the root mean square error (RMSE) and by determining the R^2 value. The polynomial fittings were carried out by using MATLAB.*

Key Words: Curve-fitting; polynomial fit and sinusoidal fit; Global solar radiation data; Matlab

1. INTRODUCTION

The demand for energy is increasing exponentially as the human population increases dynamically [1-2].The solar radiation is an instantaneous power density measured in units of kW/m^2. In providing alternative energy sources and in electricity generation solar radiation prediction and forecasting plays a vital role [3]. In Karim et al. [4] the best polynomial fitting degree for solar radiation data is calculated using RMSE (root mean square error) and r^2 value. The curve fitting methodology requires the interpolation or approximation of the given data sets which are subjected to certain constraints such as continuity, error measurement, etc. Karim and Piah [5] and Karim et al. [6] have discussed the applications of curve fitting methods (interpolating and approximating method) in font designing and shape preserving interpolation which can be considered as important in certain applications. The rest of this paper is structured as follows. In section II solar radiation data collection and solar radiation Data using Polynomial fitting is discussed. Section III presents the Data fitting model frame work. Results are discussed and summarized In Section IV. Finally, In Section V conclusions are drawn.

2. SOLAR RADIATION DATA COLLECTION

The emitted solar radiation is the electromagnetic Radiation that is emitted by the sun in the wavelength Region of 280 nm to 4000 nm [1]. The instantaneous global solar radiation value at STP is estimated to be 1000 W/m^2, while the value of power density outside the earth's atmosphere is 1353W/m^2 [7]. At Kolayat, the data is measured by using Pyranometer model no. CMP11 as shown in Figure1. Data is captured by using computerized data acquisition system.10MW solar power plant as shown in Figure 2.

Fig-1(a): Pyrnometer CMP11

Fig-1(b): Pyranometer CMP11

Fig-2: 10 MW Solar Power Plant, Kolayat, Rajasthan

2.1 Polynomial data fitting

Polynomial data fitting is used for filtering and smoothening of global solar radiation data received in the stations. It was tested by various degrees of solar radiation data. The literature for doing curve fitting is well established and can be found in [8–12]. The solar radiation data is obtained shown in Table 1 and it is represented graphically in Fig3. There are various degrees of polynomial curve fitting such as linear polynomial, quadratic polynomial, cubic polynomial, 4^{th} degree polynomial, 5^{th} degree polynomial, 6^{th} degree, 7^{th} degree, 8^{th} degree, 9^{th} degree polynomial and so on. These polynomials are applied on the received solar radiation data for a perfect fitting. . Table 3 shows all the polynomial fitting results. Rmse which gives an error value and r^2 (coefficient of distribution) gives the goodness of fitting of data.

Table -1: Daily Average of Measured Global Solar Radiation Data (KOLAYAT 09 -MAY 2015)

Time	Lode	Solar Radiation Data (W/m^2)
6:00	0	8
7:00	774	71
8:00	2466	232
9:00	4704	442
10:00	6375	616
11:00	7263	733
12:00	7863	819
13:00	7878	824
14:00	7524	838
15:00	4203	425
16:00	4338	477
17:00	1137	122
18:00	1017	114
19:00	198	31
20:00	0	7

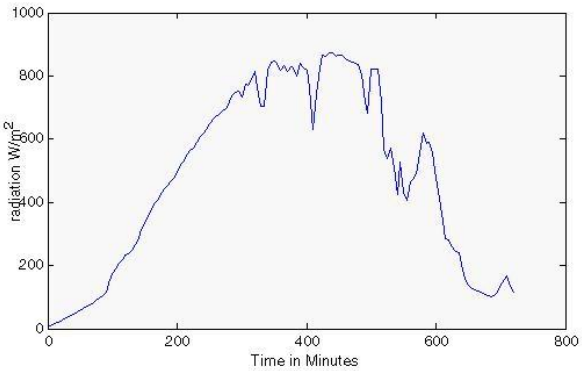


Fig- 3: Graphical Representation (09-MAY 2015)

The averaged measured data sets for the month of MAY 9, 2015 are as shown in Figure 3. The system has the ability to capture solar radiation data every minute. All the polynomial coefficients are obtained under 95% confidence interval. The rmse and r^2 value is calculated for every degrees of polynomial on analyzing, it can be clearly seen that for higher degrees of polynomial the fitting graphs will starts to wiggle thus higher degrees are omitted though they give a low rmse value and high r^2 value [4].Since higher degrees becomes unstable. Among the entire model 7^{th}, 8^{th}, and 9^{th} polynomial degree seems to give better results.

Table-2: Measured Peak Solar Radiation Data Every Five Minute (Kolayat 09-May 2015)

Time	Lode	Radiation Data (W/m^2)	Time	Lode	Radiation Data (W/m^2)
12:05	7965	833	13:05	8034	867
12:10	7782	815	13:10	8013	862
12:15	7887	829	13:15	8010	874
12:20	7860	825	13:20	8001	872
12:25	7743	798	13:25	7893	862
12:30	7983	841	13:30	7860	864
12:35	7836	824	13:35	7887	865
12:40	7752	817	13:40	7650	856
12:45	7266	763	13:45	7684	848
12:50	6177	630	13:50	7719	842
12:55	7242	743	13:55	7626	841

From Wu and Chan [3], we believe the best model for the fitting of solar radiation data is quadratic polynomial shown in Fig.5(b) Since it gives better indication to the solar radiation data compare with other polynomial fitting model. Polynomial of n^{th} degree

$$y = a_0 + a_1 x + a_2 x^2 + \dots + a_n x^n \tag{1}$$

This can be achieved by defining the error of fitting model:

$$e_i = y_i - f(x_i) = y_i - \left(a_0 + a_1 x_i + a_2 x_i^2 + \dots + a_n x_i^n\right) \tag{2}$$

Taking sum square of the error in (2) gives us

$$S = \sum_{i=0}^{N} e_i^2 = \sum_{i=0}^{N} \left[y_i - \left(a_0 + a_1 x_i + a_2 x_i^2 + \dots + a_n x_i^n\right)\right]^2 \tag{3}$$

To obtain least square fitting, the sum of error in (3) must be minimized. Hence,

$$\frac{\partial s}{\partial a_i} = 0, i = 0,1,\dots.n. \tag{4}$$

The values of $a_0, a_1, \dots, a_n$ which gives the best least square polynomial equation for the given data.

χ^2 = Chi Square
y_i = actual value
x_i = calculated Y fit value
σ_i = weight

$\bar{y}$ = mean of actual values
$\bar{x}$ = mean of calculated Y fit values

$$R = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}} \tag{5}$$

$$R = \sqrt{1 - \frac{\chi^2}{\sum_i \sigma_i (y_i - \bar{y})^2}} \tag{6}$$

$$\chi^2 = \sum_i \left(\frac{y_i - x_i}{\sigma_i}\right)^2 \tag{7}$$

3. DATA FITTING MODEL FRAMEWORK

This section will gives framework for solar radiation data fitting. Figure 4 shows the framework.

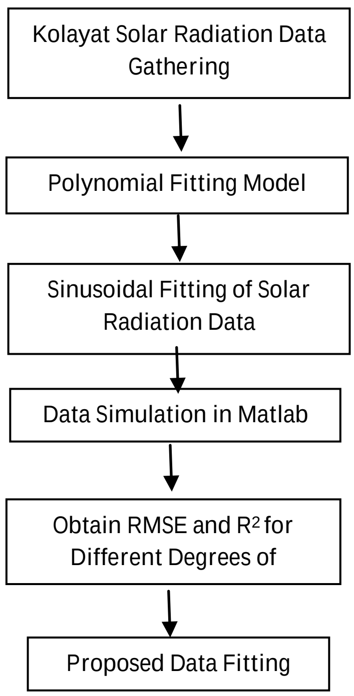


Fig-4: Data Fitting Frame work

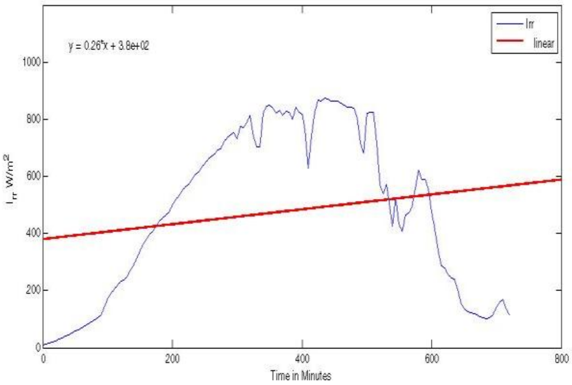
Figure 4 shows the basic block diagram which describes the flow of polynomial data fitting and sinusoidal fitting methods.

4. RESULTS AND DISCUSSION

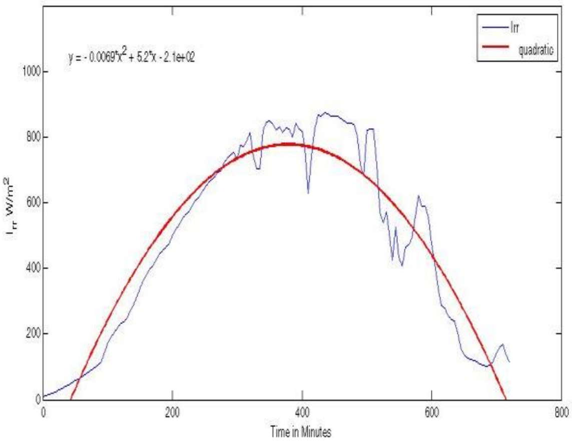
Author apply polynomial fitting (regression) starting with degree 1 (linear) until degree 9^{th}. All the polynomial coefficients are calculated based on 95% confidence interval. Table 3 summarized all the polynomial fitting results. Figs. 5 (a) until 5 (i) shows the polynomial fitting for solar radiation data.

Table-3: Polynomial fitting

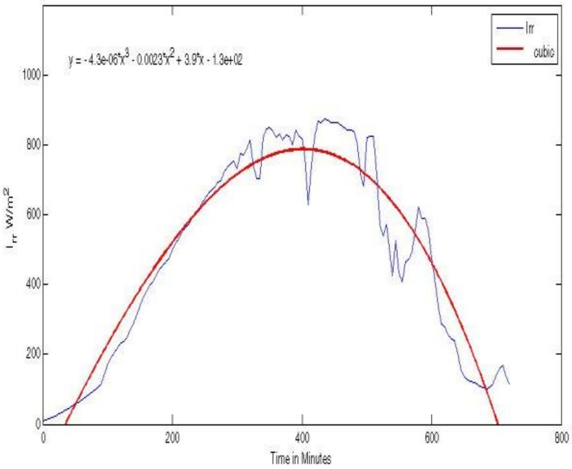
Polynomial Fitting	Statistics	
	RMSE	R^2
n=1 y=0.26*x+3.8e+02	297.7	0.009167
n=2 y = - 0.0069*x^{2} + 5.2*x - 2.1e+02	65.28	0.9568
n=3 Y=-4.3e-06*x^{3}-0.0023*x^{2}+3.9*x-1.3e+02	61.35	0.9657
n=4 y = 4.3e-08*x^{4} - 6.6e-05*x^{3} + 0.026*x^{2} - 0.61*x + 26	60.28	0.9759
n=5 y = 5.5e-11*x^{5} - 5.7e-08*x^{4}-2.1e-06*x^{3}+0.009*x^{2} + 1.1*x -13	48.84	0.9767
n=6 y = 3.9e-13*x^{6} - 7.8e-10*x^{5}+6.3e-07*x^{4}-0.00026*x^{3}+ 0.056*x^{2} - 2.2*x + 40	21.68	0.9962
n=7 y = 5.5e-16*x^{7} - 1e-12*x^{6} + 6e-10*x^{5}-6.3e-08*x^{4}-8.4e-05*x^{3}+ 0.033*x^{2} - 0.99*x +26	20.61	0.9994
n=8 y = - 1.9e-18*x^{8} +6.2e-15*x^{7} - 7.6e-12*x^{6} + 4.7e-09*x^{5}-1.5e-06*x^{4}+0.00018*x^{3} +0.0071*x^{2}+ 0.028*x + 17	20.09	0.9994
n=9 Y= 6e-23*x^{9} - 2.8e-19*x^{8} + 4e-16*x^{7} - 6.4e-15*x^{6} - 5.2e-10*x^{5} + 5e-07*x^{4} -0.00019*x^{3} + 0.031*x^{2} - 1.9*x + 29	10.09	0.9996


y = 0.26*x + 3.8e+02
Irr
linear
I_rr W/m^2
Time in Minutes

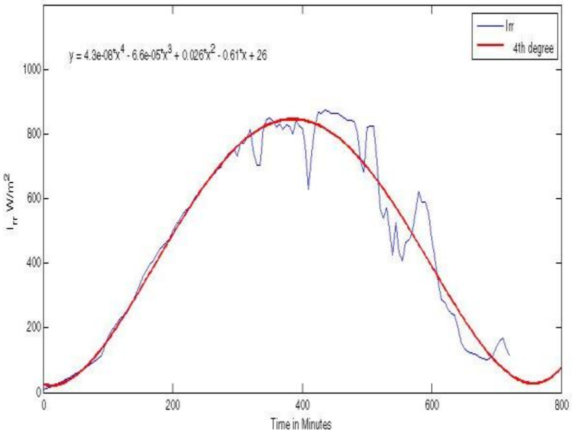
(a)


y = - 0.0069*x^2 + 5.2*x - 2.1e+02
Irr
quadratic
I_rr W/m^2
Time in Minutes

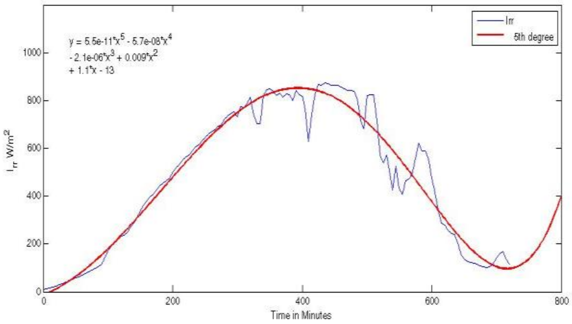
(b)


y = - 4.3e-06*x^3 - 0.0023*x^2 + 3.9*x - 1.3e+02
Irr
cubic
I_rr W/m^2
Time in Minutes

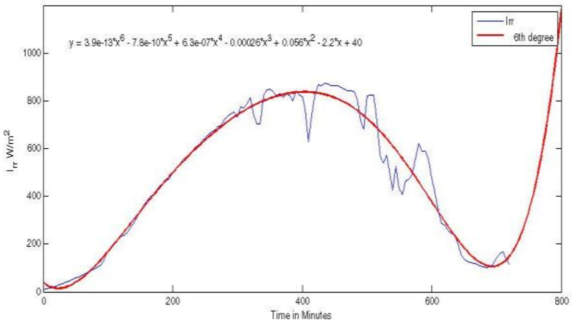
(c)


y = 4.3e-08*x^4 - 6.6e-05*x^3 + 0.026*x^2 - 0.61*x + 26
Irr
4th degree
I_rr W/m^2
Time in Minutes

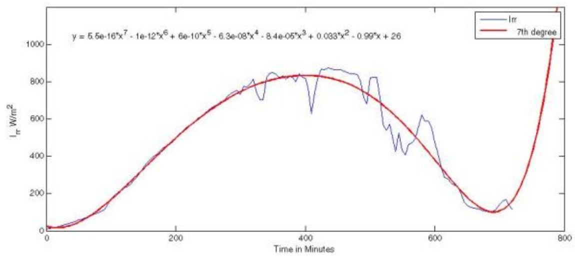
(d)


y = 5.5e-11*x^5 - 5.7e-08*x^4
- 2.1e-06*x^3 + 0.009*x^2
+ 1.1*x - 13
Irr
5th degree
I_rr W/m^2
Time in Minutes

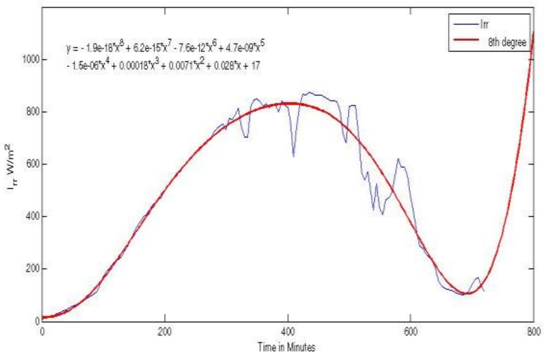
(e)


y = 3.9e-13*x^6 - 7.8e-10*x^5 + 6.3e-07*x^4 - 0.00026*x^3 + 0.056*x^2 - 2.2*x + 40
Irr
6th degree
I_rr W/m^2
Time in Minutes

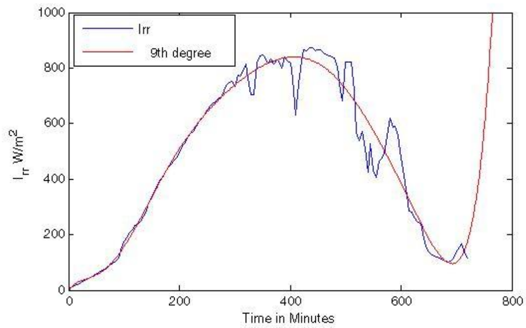
(f)



(g)



(h)



(i)

Fig-5: Various polynomial fitting (a) n=1 (b) n=2 (c) n=3 (d) n=4 (e) n=5 (f) n=6 (g) n = 7 (h) n = 8 (i) n = 9

From Figs. 5(a) until 5 (i), it can clearly be seen that once the degree of the polynomial is increasing, the fitting graphs will starting to wiggle. Among the entire fitting model, quadratic, cubic and quartic polynomials seem to give better results as compare with the other fitting model.For polynomial fitting with degree are quadratic, cubic and quartic, the value of RMSE and R^2 can be obtained in Table 3. From the table, Polynomial fitting with 9^{th} degree gives better R^2 (0.9996) and RMSE is 10.09.

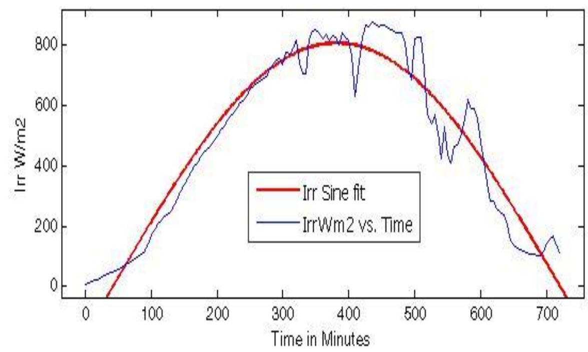


Fig.6: Sinusoidal fitting

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General model Sin1:
   f(x) = a1*sin(b1*x+c1)
Coefficients (with 95% confidence bounds):
     a1 =       804.9  (785.5, 824.2)
     b1 =    0.004636  (0.004549, 0.004722)
     c1 =     -0.1975  (-0.2337, -0.1614)

Goodness of fit:
  SSE: 7.983e+05
  R-square: 0.9337
  Adjusted R-square: 0.9328
  RMSE: 74.98
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There is trade-off between less RMSE and higher R^2 value. From figure6 Sinusoidal fitting gives better R^2 (0.9328) and RMSE is 74.98.

5. CONCLUSIONS

In this paper the solar radiation data fitting by using the polynomial fit method has been discussed in detail. After the data has been smoothed, the model for solar radiation can be used to predict or forecast the received amount of solar radiation in Kolayat for a 9 May, 2015. One of the applications of the polynomial fit model can be to determine the optimum system sizing for the solar electricity generating system. Usually there is a need to do a proper system sizing in terms of the number of PV panels required and also the storage size. The curve fit that returned the highest correlation factor was the polynomial fit. From the numerical results, the fitting model with sinusoidal fitting has given better results without any wiggle at both end points of the graph and the value of RMSE is 74.98 and R^2 value is 0.9328 . Polynomial fitting 9^{th} degree has given better R^2 (0.9996) and RMSE is 10.09. Hourly global solar radiation showed that can predict the measured data with good accuracy.

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REFERENCES

[1] Karim, S.A.A., Singh, B.S.M, Karim, B.A., Hasan, M.K., Sulaiman, J., Josefina, B. Janier., and Ismail, M.T. (2012). Denoising Solar Radiation Data Using Meyer Wavelets. *AIP Conf.Proc.*1482:685-690. http://dx.doi.org/10.1063/1.4757559.

[2] Karim, S.A.A., Singh, B.S.M., Razali, R. and Yahya, N. Data Compression Technique for Modeling of Global Solar Radiation. In Proceeding of 2011 IEEE International Conference on Control System, Computing and Engineering (ICCSCE) 25-27 November 2011, Holiday Inn, Penang, pp. 448-35,(2011a).

[3] Wu, J. and Chan, C.K. Prediction of hourly solar radiation using a novel hybrid model of ARMA and TDNN. Solar Energy 85:808-817, 2011.

[4] Samsul Ariffin Abdul Karim and Balbir Singh Mahinder Singh," Global Solar Radiation Modeling Using Polynomial Fitting" Applied Mathematical Sciences, Vol. 8, 2014, no. 8, 367 – 378.2012.

[5] Karim, S.A.A and Piah, A.R.M (2009). Rational Generalized Ball Functions for Convex Interpolating Curves. JQMA 5(1): 65-74.

[6] Karim, S.A.A., Karim, B.A., Hasan, M.K. and Sulaiman, J. (2010d).Font Designing Using Generalized Ball Basis. In Proceedings of EnCon2010, 3rd Engineering Conference on Advancement in Mechanical and Manufacturing for Sustainable Environment April 14-16, 2010, Kuching, Sarawak, Malaysia, ISBN 978-967-5418-10-5.

[7] Thekaekara, M.P. (1973). Solar Energy Outside the Earth's Atmosphere. Solar Energy 14. p. 109.

[8] R.E. Childs, Donald G.S. Chuah, S.L. Lee, K.C. Tan. Analysis of solar radiation data using cubic splines. *Solar Energy,Volume32 ,Issue 5, 1984, Pages 643-653.*

[9] Donald G. S. Chuah, S. L. Lee. Solar radiation in peninsular Malaysia—Statistical presentations. *Energy Conversion and Management, Volume 22, Issue 1, 1982, Pages 71-8.*

[10] Genc, A., Kinaci, I., Oturanc, G., Kurnaz, A., Bilir, S. and Ozbalta, N. Statistical Analysis of Solar Radiation Data Using Cubic Spline Functions. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 24:12 1131-1138. (2002).

[11] De Boor, C. 2001. A Practical Guide to Splines. Springer-Verlag New York.

[12]Dr.P.M.BeulahDevamalar,Dr.V.ThulasiBai,D.Jahnavi, V.Vidhyawathy, Gap Filling of Solar Radiation Data using Polynomial Fitting and Wavelet Transform Comparison, International Journal for Scientific Research & Development, Vol. 2, Issue 12, 2015 | ISSN (online): 2321-0613 pp.no.268-270.

BIOGRAPHIES

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