Estimation of Hourly Global Solar Radiation in Egypt Using Mathematical Model

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Abstract **- The purpose of this paper is to develop a computer mathematical model which produces estimates of the total amount of hourly solar radiation that reaches the earth's surface in a day called hourly global solar irradiance for climate of Delta, Egypt. Predictors for solar radiation have been developed because there is often a lack of representative solar radiation data in most countries. Cloudiness, atmospheric transmissivity, latitude and orientation of the Earth relative to the Sun, time of day, slope and aspect of the surface determine the spatial and temporal distribution of irradiance incident on a surface. Experimental data were measured in the Solar-Meteorological stations of Agricultural Engineering Department at El-menoufiya University, El-Mansoura university and Belbees. To evaluate the present model a comparison between measured and predicted data has been carried out based on the main bias error and correlation coefficient. It can be concluded that the present model can be used to estimate the values of hourly solar radiation for El-menoufiya El-Mansoura and Belbees.**

Keywords: *Global radiation models; solar radiation; Mathematical Model.*

1. Introduction

Renewable energy is accepted as a key source for the future, not only for Egypt but also for the world. This is primarily due to fact that renewable energy resources have some advantages when compared to fossil fuels. However, environmental concerns and limited energy sources make renewable energy technology a good candidate for fossil fuels. While Egypt has adequate solar energy potential to support its energy demand, it is therefore important to harness that resource in view to find solution to energy shortage and environmental degradation the country is being faced to. Solar energy is now considered to be the most effective and economic alternative resource (El-Metwally, 2005).

In developing countries, such as Egypt, interest in solar energy applications has been growing in providing electricity and water supply in different areas. Understanding solar radiation data is essential for modeling solar energy systems. Solar radiation is used directly to produce electricity for photovoltaic (PV) systems and solar thermal systems. Therefore, precise knowledge of historical global solar radiation at a location of study is required for the design and estimation of the performance of any solar energy system. Knowledge of solar radiation incident on the earth's surface is essential to architects and engineers for energy-efficient building designs and solar energy applications (Duffie and Beckman 2006; Sen, 2008).

The solar radiation has temporal and spatial variations. To collect this information, a network of solar monitoring stations equipped with pyranometers and data acquisition systems are generally established in the desired locations. However, the number of such stations in the network is usually not sufficient to provide solar radiation data of the desired areas, especially in developing countries. This is mainly due to because of not being able to afford the measuring equipments and techniques involved. Therefore, it is necessary to develop methods to estimate the solar radiation on the basis of the more readily available meteorological data.

An alternative solution to this problem is to estimate solar radiation by using a modeling approach (Dorvlo et al., 2002; Ibrahim et al.,1985)

Modeling of solar radiation also provides an understanding of dynamics of solar radiation and it is clearly of great value in the design of solar energy conversion systems. Most locations in Egypt receive abundant solar radiation and hence solar energy technology can be beneficially applied to these regions. The solar radiation data are either obtained from In Egypt, quite few stations have been measuring the daily solar radiation on a consistent basis. In the absence and shortage of reliable solar radiation data, hence, it is necessary to approximate solar radiation by the use of mathematical model in order to estimate and predict global solar radiation. These models use meteorological data of the location under study. Knowledge of hourly solar radiation (direct and diffuse) on horizontal surface is essential to design solar energy devices. Hourly values of solar radiation enable us to derive very precise information about the performance of solar energy systems (Gopinathan, 1992).

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Solar exposure estimates are important for a wide range of applications, mainly in the agricultural and to a lesser extent engineering sector, and in research. Examples of use include: monitoring plant growth and disease control; evaporation and irrigation; architecture and building design e.g. power station condenser cooling systems; power generation; calculation of water requirements for crops; solar heating system design and use; skin cancer research; research into coral growth; weather and climate prediction models; solar powered car races. It is very common to design solar energy systems based on the hourly average of global solar radiation and other climatic data. Also, it is rather important to determine the beam and diffuse components of total radiation incident on a horizontal surface. Once, these components are determined, they can be transposed over tilted surfaces, and hence, the short as well as the long-term performances of tilted flat plate collectors, photovoltaic modules and other solar devices can be estimated. Many models have been developed to estimate the amount of global solar radiation on horizontal surfaces using various climatic parameters ,such as sunshine duration, cloud cover, humidity, maximum and mini- mum ambient temperatures, wind speed, etc.(Chegaar and Chibani, 2001; El-Sebaii and Trabea, 2005; Gopinathan, 1988; Halouani et al., 1993; Jacovides et al., 2006).

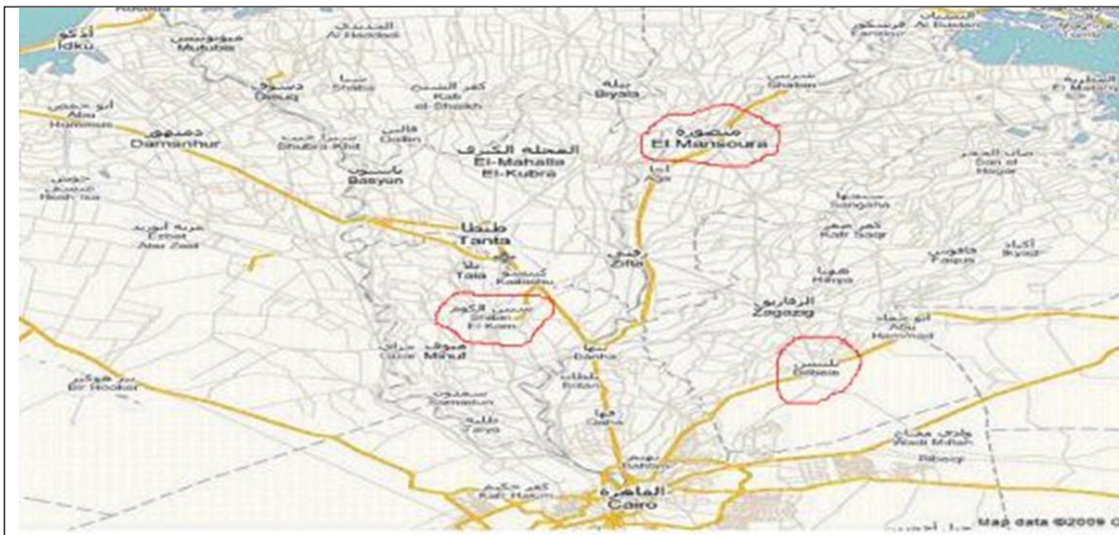

Figure 1 - solar radiation stations in the study.

Few papers have appeared concerning estimation of solar radiation over Egypt (Tadros, 2000 ;El-Sebaii and Trabea, 2005) estimated the daily global solar radiation for various places in Egypt.

Mansoura, Shebin El-Kom and Belbees are Egyptian cities Fig.(1) located 31.045, 30.54 and 30.22 N respectively (latitude) and they are one of the most solar energy abundant cities all days of the year . Therefore, solar energy devices can be operated with high performance.

The main purpose of this paper is to develop a mathematical model to estimate the hourly global solar radiation on horizontal surfaces in the cities using the available meteorological data, such as sunshine duration and cloud cover as well as maximum, minimum and daily mean of ambient temperature covering the year 2009.

2. Model for Computing Radiation on the Horizontal Surface

The total radiation received on the horizontal is a summation of the direct and diffuse radiation. (Parker, 1991; Duffie and Beckman, 2006).

Hottel (1976) has presented a technique for estimating the direct radiation transmitted through clear atmosphere as:

$$Q_{beam} = I_{on}\tau_{beam} Cos\theta_z \qquad [Wm^{-2}] \qquad (1)$$

Where:

I_{on} : the extraterrestrial radiation measured on the plane normal to the radiation on the n day of the year.

$$I_{on} = I_{sc}[1 + 0.034Cos(\frac{360n}{365.24})] \quad [Wm^{-2}] \quad (2)$$

Where:

I_{sc} : the solar constant 1353 W/m^2

n : the number of the day of the year starting from the first of January. (Parker, 1991 ; Duffie and Beckman, 2006) and according to Heindl and Koch, (1976) can be calculated as follows:

$$n = 30(M) + 0.6(M-3) - 30.5 + (N) \quad (3)$$

M : month number from 1 to 12
N : day number of the month
The atmospheric transmittance for beam radiation ,τbeam, is given in the form:

$$\tau_{beam} = A_0 + A_1.\exp(\frac{-k}{Cos\theta_z}) \quad (4)$$

The constants A_o, A1 and k are for the standard atmosphere with 23 km visibility and are found from:

A0=$r_0A^*_0$
A1=$r_1A^*_1$
K= r_k k*

The factors r_0, r_1 and rk are climate correlations which are presented in table (1):

Table (1): Beam radiation correction factors for climate types from ((Decarli et al., 1986; hotel 1976; Parker, 1991).

Climate types	r_0	r_1	r_k
Tropical	0.95	0.98	1.02
Mid-latitude summer	0.97	0.99	1.02
Mid-latitude winter	1.03	1.01	1.00
Subarctic summer	0.99	0.99	1.01

These values are obtained as follows:

$$A^*_0 = 0.4237 - 0.00831(6 - A)^2$$

$$A^*_1 = 0.5055 - 0.00595(6.5 - A)^2$$

$$k^* = 0.2711 - 0.01858(2.5 - A)^2$$

θ_z: the angle of incidence, θ_z, defines the angle between the incoming beam solar rays and the normal to the horizontal surface, that is, the angle of incidence of beam radiation on a horizontal surface. It can be calculated from the following equation.

$$\theta_z = Cos^{-1}[Cos\phi Sin\delta Cos\omega + Sin\phi Sin\delta] \quad [\,^\circ\,] \quad (5)$$

Φ: Latitude angle which is the angular location north or south of the equator, northern hemisphere of the earth is positive and southern is negative

(-90° < Ø > 90°).

ω : Solar hour angle Which is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour, morning negative and afternoon is positive.

$$\omega = (LAT - 12).15 \quad [\,^\circ\,] \quad (6)$$

Where, LAT. is the local apparent time (standard time).

Solar altitude angle (α) Which is the angle between the sun's rays and the horizontal plane or its the angle between the horizontal and the line to the sun, that is, the complement of the zenith angle.This angle can be estimated from the following equation:-

$$\alpha = Sin^{-1}[Cos\phi Cos\delta Cos\omega + Sin\phi Sin\delta] \quad [\,^\circ\,] \quad (7)$$

The equation for clear sky diffuse radiation is in the from:

$$Q_{diff} = I_{on}.\tau_{diff}Cos\theta_z \quad (8)$$

$$\tau_{diff} = 0.2710 - 0.2939 \times \tau_{beam} \quad (9)$$

These equation can be used to estimate the total standard clear sky radiation on a surface with incident angle,θz:

3. Model for Computing Radiation on an Inclined Surface

The total radiation received on an inclined can be calculated in a similar way as the sum of the direct(beam) ,diffuse and reflected radiation from the surroundings :

$$Q_{Gt} = Q_{bt} + Q_{dt} + Q_{rt} \text{ [Wm}^{-2}\text{]} \quad (10)$$

Where:

QGt: solar radiation absorbed at a tilted surface [Wm-2]

Qbt: beam solar radiation absorbed at a tilted surface [Wm-2]

Qdt : diffuse solar radiation absorbed at a tilted surface [Wm-2]

Qrt: reflected radiation from the surroundings [Wm-2]

The direct radiation can be calculated using the Lambert's law with the described geometric terms as follows:

$$Q_{bt} = (Q_{Gt} - Q_{dt}).Cos\theta \quad \text{[Wm}^{-2}\text{]} \quad (11)$$

Where:

Qbt: direct or beam solar radiation absorbed at collector surface.

QGt : solar radiation absorbed at collector tiled surface [Wm-2]

Qdt : diffuse solar radiation absorbed at wall surface [Wm-2]

θ: incidence angle [°]

Liu and Jordan (1960) used a simplified assumption that the diffuse radiation on the tilted surface, Qdt, was isotropic and could be calculated as follows:

$$Q_{dt} = Q_d[\frac{(1 + Cos\beta)}{2}] \quad \text{[Wm}^{-2}\text{]} \quad (12)$$

Where:

Qdt : diffuse solar radiation absorbed at tilt surface [Wm-2]

Qd: diffuse radiation [Wm-2]

β: tilt angle of the surface [°]

The amount of radiation that is reflected onto a tilted surface is a function of the amount of beam radiation , diffuse radiation and the reflectivity of the horizontal surface (Parker, 1991). According to (parker, 1991, & Elminir et al.,2006), the reflected radiation from the surroundings can be calculated as follows:

$$Q_{rt} = Q_d \xi[(1 - Cos\beta)/2) + Q_d \xi(1 + Sin^3(\beta/2))(1 - Cos\beta/2]. [1 + Sin^2(\theta_z/2)][|Cos\gamma|] \quad \text{[Wm}^{-2}\text{]} \quad (13)$$

Where:

Qrt : reflected solar radiation absorbed at wall surface [Wm-2]

Qd: diffuse radiation [Wm-2]

ξ: surface reflectance value [-]

γ : Surface–solar azimuth angle [°]

4. Software Tools

The hourly solar radiation model was designed by using Simulink, which is an interactive tool for modeling, simulating and analyzing dynamic systems. Simulink provides a complete set of modeling tools that can be used to quickly develop detailed block diagrams of the systems. It integrates seamlessly with MATLAB, providing the user with immediate access to an extensive range of analysis. Simulink enables the building of graphical block diagrams, simulate dynamic systems, evaluate system performance and refine the designs (Palm, 1999).

5 Model Parameters

They are model inputs and can be divided into two groups. The first group includes parameters supplied by the user such as: the simulation time, latitude angle, surface azimuth, tilt angle for the inclined surface, day and month number which were used to calculate the solar radiation at the surface.The second group includes parameters taken from the literature such as: sea level, solar constant and the constants which are used to calculate the atmospheric transmittance for beam and diffuse radiation.

6 Results and Discussion

The simulation results obtained from this model are considered "blind", since they have not been yet compared with the measured results from the selected regions. The comparison between measured and simulated results is very important in order to check out how far the simulated results are from the measured ones. It gives an idea, if there are any obvious errors and prospects about the possibility of improvements that can be achieved by such model.

To investigate the model's ability to predict and describe the hourly solar radiation during different times, simulations were compared with measurements for the selected regions (Shebin El-Kom, Belbees and El-Mansoura).

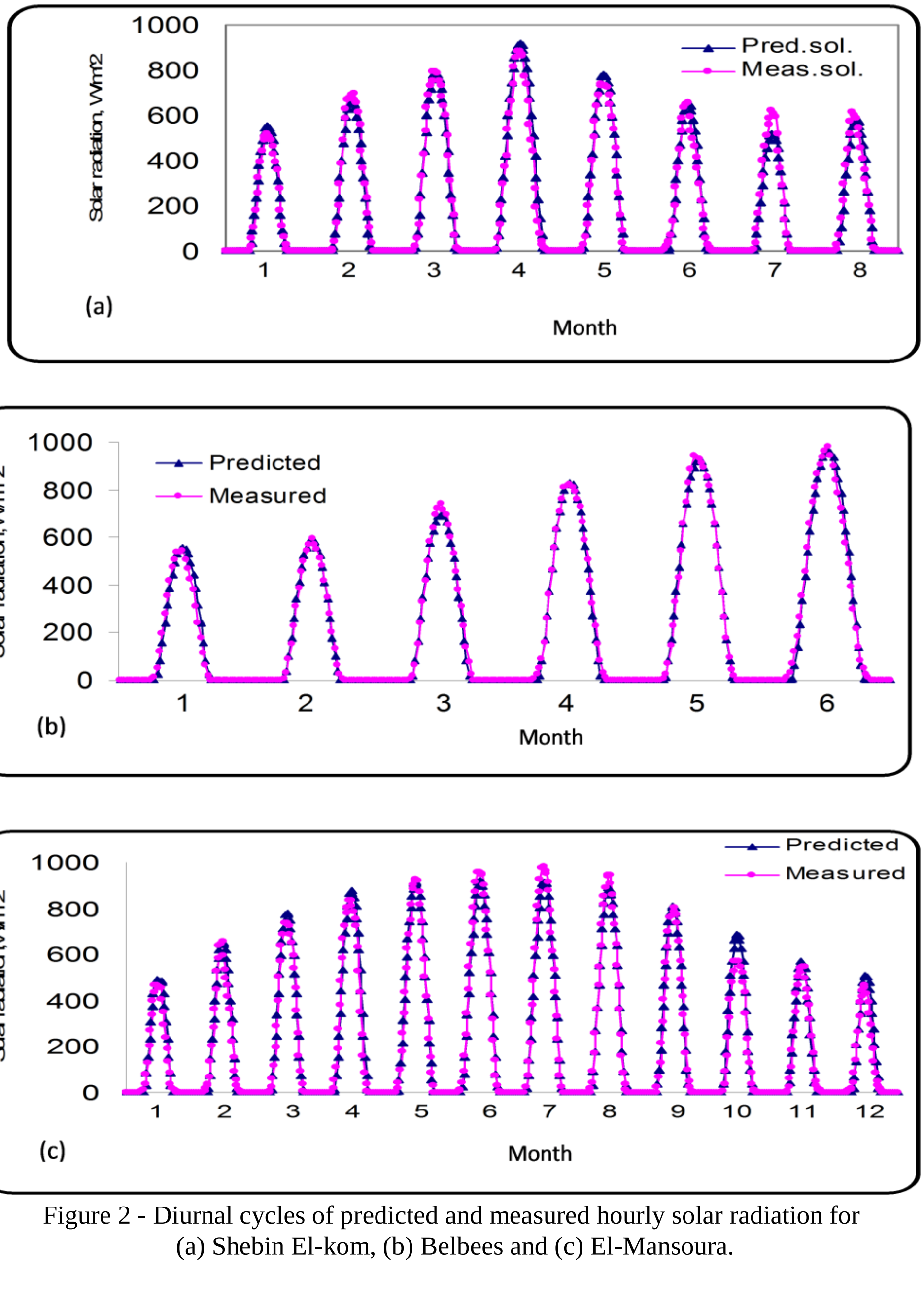

Figure 2 - Diurnal cycles of predicted and measured hourly solar radiation for (a) Shebin El-kom, (b) Belbees and (c) El-Mansoura.

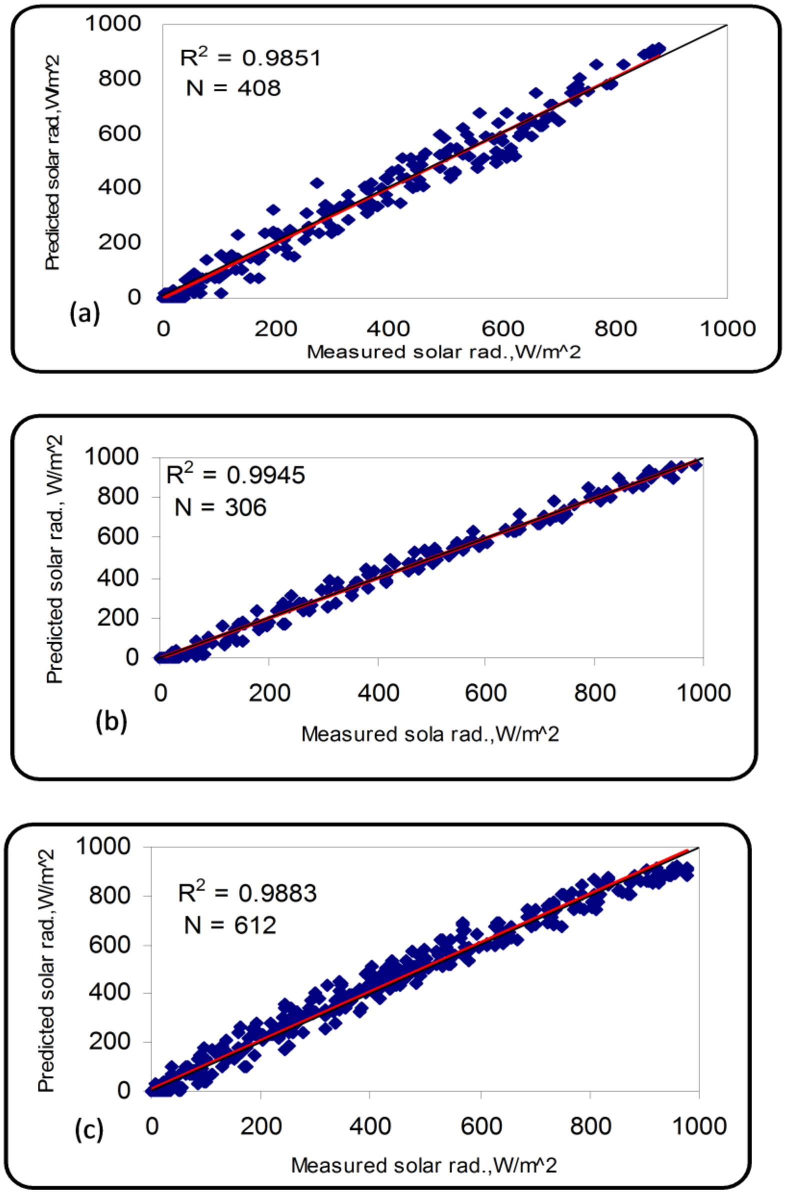

Fig.(3). Comparison between predicted and measured hourly solar radiation for (a) Shebin Elkom, (b) Belbees and (c) El-Mansoura, N the total number of the observation

Fig.(2). presents the simulation results obtained assuming that the solar radiation reached the maximal value of 958 Wm-2 in June. Comparing the results, we can see that all the used equations gave very good results. The model gave the best estimate and have the smallest errors for the hourly values. The figure shows also that the simulated hourly solar radiation followed the same trends as that measured one but with some variations in timing of the peak values. The simulated data sometimes higher, sometimes lower or almost equal the measured variable.

The measured hourly solar radiation was plotted versus the predicted from simulation model as shown in Fig.(3). High correlation coefficient between the predicted and measured values was observed. The model gave accurate prediction of the hourly solar radiation. Nevertheless, the points scattered above and below the regression line show a good agreement between the simulated versus measured hourly solar radiation and over a reasonably prolonged duration. The coefficient of determination during the simulation period were 0.9851, 0.9945 and 0.9883 for Shebin El-kom, Belbees and El-Mansoura respectively.

Fig.(4) represents the differences between the measured and the predicted values of the hourly solar radiation for during the simulation periods, where it can be seen that the higher difference occurred in the middle of the day and declined late afternoon and early morning. The maximum differences between measured and predicted hourly solar radiation profile are 145 Wm-2 in June for Shebin El-kom followed by El-Mansoura 120 Wm-2 in October while it is 75 Wm-2 in January for Belbees respectively. However, the errors obtained are similar to the common solar radiation modeling .

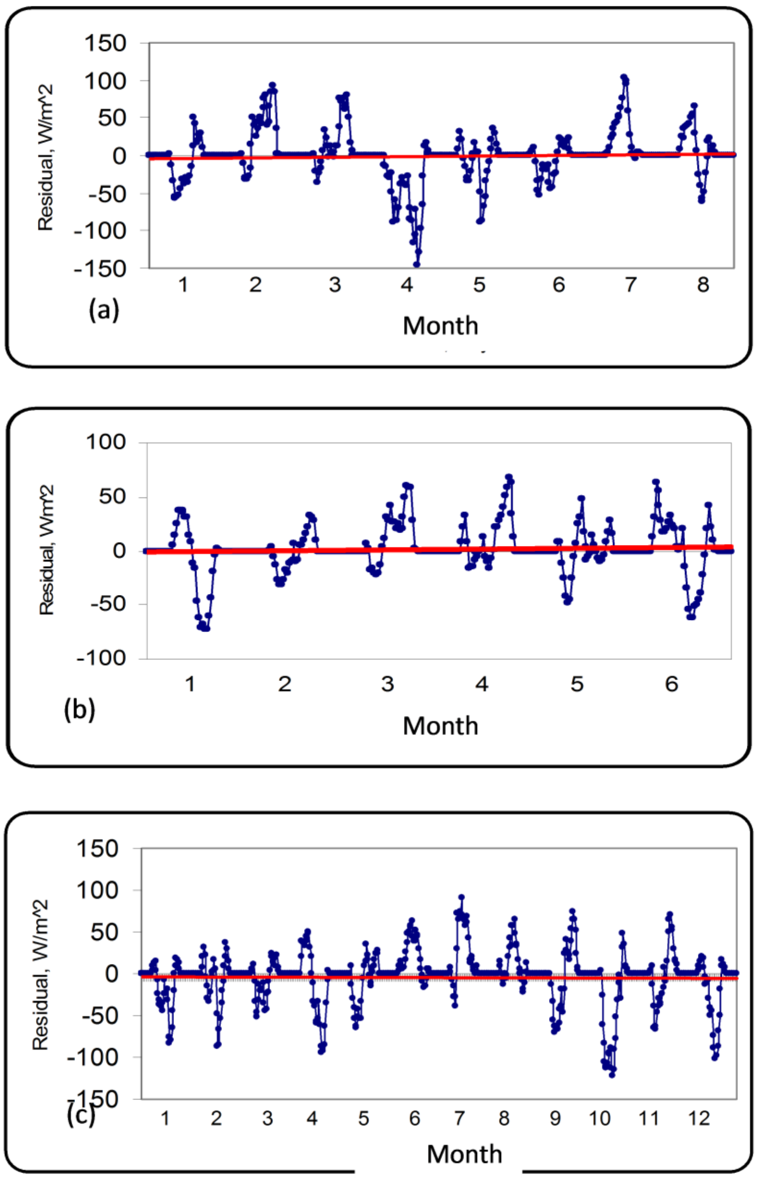

Fig.(4). Residuals of the measured and predicted hourly solar radiation for (a) Shebin Elkom, (b) Belbees and (c) El-Mansoura

In context of studies of hourly solar radiation in this model, the distribution of the residuals of the hourly solar radiation as a function of measured data were plotted Fig.(5). It can be observed that, the points are scattered above and below the zero line, if all points are considered together, the residual was not increase with increasing of the solar radiation Fig.(4) for the all selected regions.

7. Conclusion

A simple model for simulating hourly solar-radiation was suggested in this study. The proposed model can be used for predicting accurately hourly solar-radiation, which helps in the estimation of the long-term performances of solar-energy systems.

The model is tested for 3 provinces of Egypt. It was seen that the statistical indicator for the model such as correlation coefficient are at acceptable levels. Comparison of the model with the measured data revealed that the model provides predictions in good agreement with the measured data. It is expected that the model developed for hourly solar-radiation will be useful to the engineers of solar-energy related systems as well as those who need to have fairly good estimates of yearly variations of daily global solar-radiation for specific location.

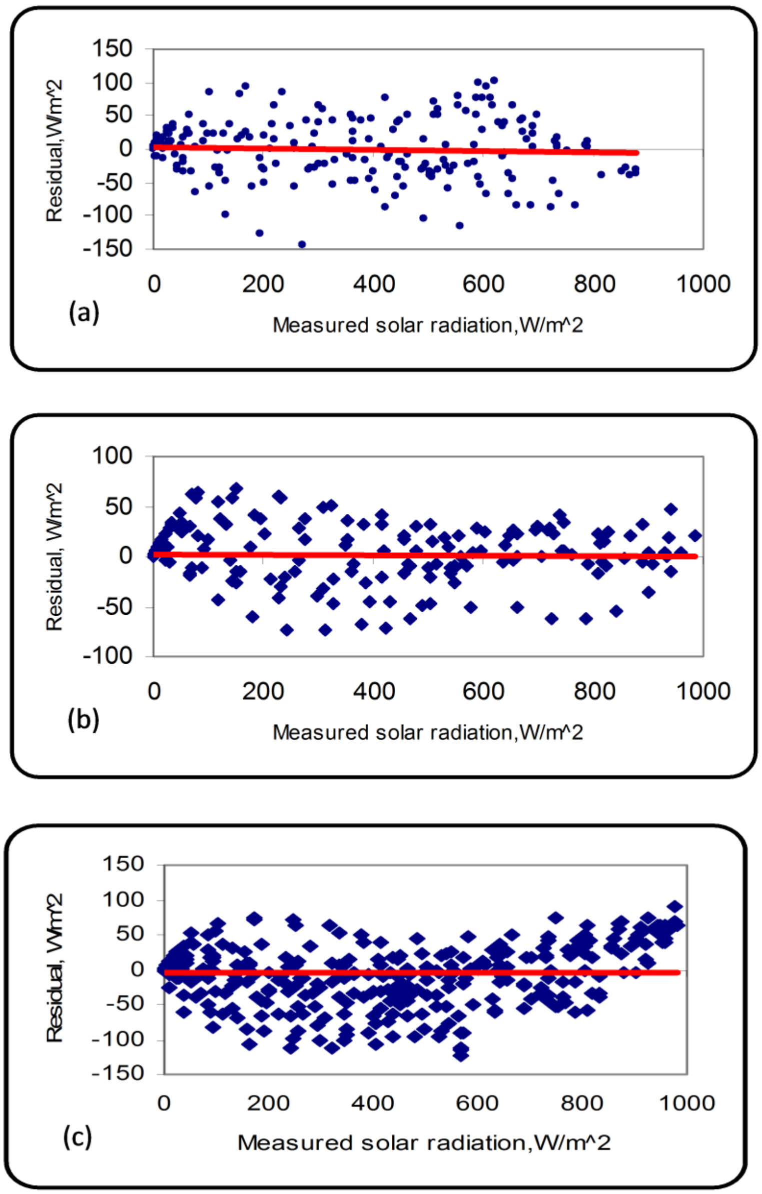

Fig.(5). Plot of residuals (predicted - measured) hourly solar radiation versus measured solar radiation for (a) Shebin Elkom, (b) Belbees and (c) El-Mansoura

References

[1] Chegaar, M. and A. Chibani, (2001). Global solar radiation estimation in Algeria. *Energy Conversion and Management* 42, 967–973.

[2] Decarli, F., C. Groppi, R. Festa, and C. F. Ratto, (1986). Procedure to obtain global radiation maps from sunshine duration at isolated station in a region with complex orography . *Solar Energy* ,37 (2):91-108.

[3] Dorvlo, A. S. S. , J. A. Jervase and A. Al-Lawati (2002). Solar radiation estimation using artificial neural networks. *Appl Energy*;71:307–19

[4] Duffle, J.A. and W.R. Beckman, (2006). *Solar engineering for thermal processes*. 3rd ed., John Wiley and Sons. Inc., New York. NY.

[5] Elminir, H. k., A.E Ghitas, F. El-Hussainy, F. Hamid, M.M. Beheary, and K.M. Abdel-Moneim, (2006). Optimum solar flat-plate collector slope:Case study for Helwan. *Egypt Energy Conversion and Management*,47 :624–637

[6] El-Sebaii, A. A. and A. A. Trabea,(2003). Estimation of horizontal diffuse solar radiation in Egypt. *Energy Conversion and Management*; 44, 2471–2482.

[7] El-Sebaii, A. A. and A. A. Trabea,(2005). Estimating global solar radiation on horizontal surfaces over Egypt. *Egyptian Journal of Solids;* 28, 163–175.

[8] El-Metwally, M.(2005). Sunshine and global solar radiation estimation at different sites in Egypt. *Journal of Atmospheric and Solar-Terrestrial Physics*; 67 :1331–1342.

[9] Gopinathan, K. K.(1992). Estimation of hourly global and diffuse solar radiation from hourly sunshine duration. *Solar Energy*; 48(1):3.

[10] Gopinathan, K.K., (1988). A general formula for computing the coefficients of the correlation connecting global solar radiation to sunshine duration. *Solar Energy*, 41, 499–502.

[11] Halouani, N., C.T. Nguyen and D. Vo-Ngoc, (1993). Calculation of monthly average global solar radiation on horizontal surfaces using daily hours of bright sunshine. *Solar Energy*, 50, 247–258.

[12] Heindl, W. and H.A. Koch, (1976). Die Berchnung von Sonneneinstrahlungsintensitäten für wärmetechnische Untersuchungen im Bauwesen. Gesundheits -Ingenieur, 97 H.12,301-314.

[13] Hottel,H. C. (1976) . A simple model for eastimating the transmittance of direct solar radiaton through clear atmospheres. *Solar Energy* .18(2):129-134.

[14] Ibrahim, S. M. A.(1985). Predicted and measured global solar radiation in Egypt. *Solar Energy*;35(2):185-8.

[15] Jacovides, C.P., F.S. Tymvios, V.D. Assimakopoulos, and N.A. Kaltsounides, (2006).Comparative study of various correlations in estimating hourly diffuse fraction of global solar radiation. *Renewable Energy* ,31, 2492–2504.

[16] Liu, B. H. Y. and R. C. Jordan, (1960). The interrelationship and characteristic distribution of direct ,diffuse and total solar radiation. *Solar Energy*,4(3):1-19.

[17] Palm, W. J. (1999). *Matlab for engineering applications*. WCB, McGraw-Hill.

[18] Parker, B.F. (1991). *Energy in World Agriculture, Solar energy in Agriculture*. Elsevier Science Publishers, New York, 1-66.

[19] Sen, Z. (2008). *Solar Energy Fundamentals and Modeling Techniques, atmosphere, environment, climate change and renewable*. Springer-Verlag London Limited.

[20] Tadros, M. T. Y.(2000). Uses of sunshine duration to estimate the

[21] global solar radiation over eight meteorological stations in Egypt . *Renewable Energy*, 21 : 231-246.

[22] Trabea, A.A. and M. A. Mosalam Shaltout, (2000). Correlation of global solar radiation with meteorological parameters over Egypt. *Renewable Energy*, (21) :297-308.