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Estimation of Hourly Solar Radiation Based on Improved GISTEL Model

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***Abstract*—in this paper, we present a new satellite image approach for estimating solar radiation data. The estimation of the hourly global horizontal solar radiation data has been evaluated by using the GISTEL (Gisement solaire par télédetection: Solar Radiation by Teledectection) model improved by the fuzzy logic technique. Thus, the results were compared with the ground solar radiation measurements. The results showed a good accuracy and the simple implementation of the proposed approach.**

***Keywords*—Estimation of solar radiation, GISTEL model, satellite images, PV systems.**

I. INTRODUCTION

Solar energy is one of the most important renewable energies for generating electricity and meeting our daily needs. Hence, the methods for estimating the amount of the solar radiation and monitoring of the PV systems become very important tasks [1]. To ensure a proper monitoring of photovoltaic plants, it is necessary to adopt specific techniques related with the type and accuracy of the information provided as well as their prices [2]. The measurement of the solar irradiation is one of those techniques. To this end, different ways were proposed in the literature to estimate the solar radiation data; such as ground models [3]-[5] and satellite image processing models [6]-[8]. The results from these models showed that the optimal determination of the solar radiation estimation models lead to an efficient PV system.

The GISTEL (Gisement Solaire par Télé detection) proposed by [9] was used. It consists of the processing of the Meteosat second generation images MSG-2. An algorithm based on a relationship between the clearness indexes determined from the Meteosat images and the global solar irradiation received on the ground under clear sky was used. Moreover, a hybrid model was proposed in this paper that combined the basic method of GISTEL and the fuzzy logic approach in order to obtain more precise results. The evaluation of the proposed method was reached using the root mean square error RMSE and normalized root mean square NRMSE errors.

The remaining part of this paper is organized as follows. Section 2 presented the methodology used in this work and background of the GISTEL model has been viewed. In Section 3, we had simulated the results obtained from the GISTEL model and compared them to the measured solar radiation data. The last section is devoted to the conclusion and discussion of future works.

II. METHODOLOGY

In this work, a proposed simulation method based on the Matlab / Simulink environment has been used for estimating the solar radiation. This method consists of the GISTEL model was applied to estimate the hourly horizontal global solar radiation time series, and then the obtained results were compared to the measured ones.

A. GISTEL model

GISTEL is a satellite methodology based on a simple physical model. It is used to estimate global solar irradiance from METEOSAT data. The adopted methodology has several steps that we have summarized by the diagram of Fig. 1.

1) For estimating the global solar radiation (Gc) under a clear sky, the world organization of meteorology (W.M.O.) model given by Eq. (1) is used; this model depends on the solar height (*hs*) and the Linked turbidity factor (*TL*) used to quantify the effect of atmospheric components of solar radiation, the *TL* values generally vary from 2 (very pure and dry sky) to 6 (polluted and humid sky).

$$G_c = cor\left[1300 - 57T_L\right]\left(\sin(h_s)\right)^{(36+T_L)/33} \quad (1)$$

where *cor* is the correction factor of the earth-sun distance given by Eq.(2) and *nj* is the number of the days of the year.

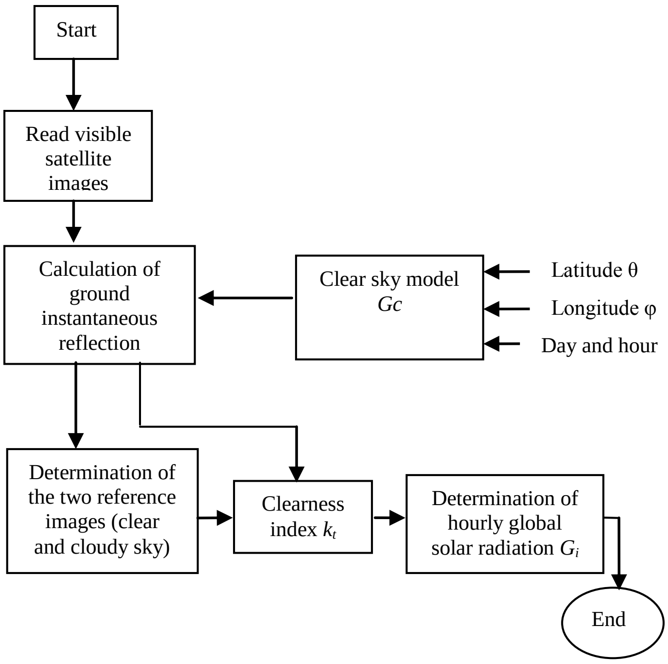

Fig. 1 The different steps of the GISTEL model [10].

$$cor = 1 + 0.034\cos(0.986(nj - 3)) \quad (2)$$

2) The ground instantaneous reflection coefficients *Rib(x, y, d, h)* for each pixel *(x,y)* of the visible MSG image of the day *d* and the hour *h* are given by Eq. (3). Those coefficients represent the reflection of solar radiation on the surface.

$$Rib(x, y, d, h) = \frac{Bi(x, y, d, h) - Bia(x, y, d, h)}{K.Gc(x, y, d, h).Ti(x, y, d, h)} \quad (3)$$

Where, *Bi (x, y, d, h)* represents the brightness of the *(x, y)* pixel, *Bia (x, y, d, h)* the atmospheric brightness recorded by the satellite above the sea by a clear sky. This brightness was considered constant, and it is equal to 12 [8]; *K* is the factor calibration of the visible channel sensor equal to 0.514. *Ti (x, y,d, h)* is the transmission coefficient of the direct irradiation from the ground to the satellite. It is given by the Eq. (4),

$$Ti = \frac{(1390 - 31T_L)}{1367}\exp\left[-\frac{T_L}{12.6\sin(h_v + 2)}\right] \quad (4)$$

where h_v is the height angle of the satellite, given by Eq. (5).

$$h_v = \arcsin\left(\frac{1.862\cos(\varphi)\cos(\theta) - 0.274}{\sqrt{3.41 - \cos(\varphi)\cos(\theta)}}\right) \quad (5)$$

θ and φ are respectively the latitude and the longitude.

3) For determining the two clear and cloudy reference images, a sequence of images was taken over long period at 12 h UTC. Taking the minimum values of the reflection coefficients obtained from those sequence images, the clear sky reference image can be obtained. On the other hand, the cloudy sky reference image is constructed by using the greatest values of the reflection coefficient obtained using the same sequence of images.

4) The clearness index k_t is calculated for each image by comparing pixel by pixel and hour by hour the instantaneous reflection coefficients *Rib* with the two clear sky R_c and the cloudy sky R_n reflection coefficients. According to this comparison three types of skies can be observed namely clear sky , partially covered sky and completely covered sky [8], as expressed in Eq. (6)

- Clear sky : $Rib \le Rc$: $k_t = 1$
- Partially covered sky: $Rc < Rib < Rn$:

$$k_t = 1 - (1 - K_0)\frac{(Rib - Rc)}{(Rn - Rc)} \quad (6)$$

- Completely covered sky: $Rib \ge Rn$: $k_t = K_0$

Where K_0 is the index by a cloudy sky equals to 0.2. However, for obtaining more precise results a fuzzy logic approach is proposed in this paper. Fuzzy logic methodology has the ability to translate human qualitative knowledge into formal algorithms; it deals with reasoning that is approximate rather than fixed. It consists of using expert rules that can sometimes produce a simple set of control for a dynamical system with less effort. Hence, three rules are introduced in this work to obtain logical values of the clearness index k_t as expressed in Fig. 2.

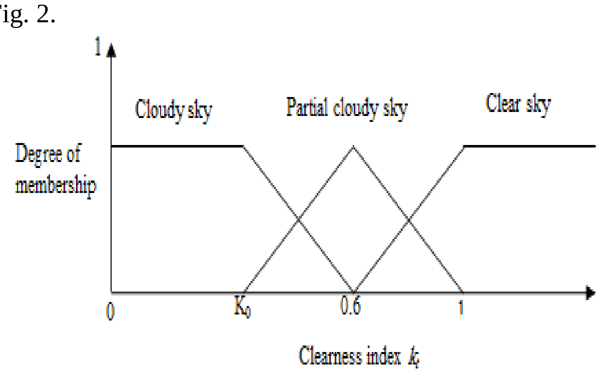

Fig. 2 Fuzzy logic membership functions.

5) Finally the instantaneous global solar radiation *Gi(x, y, d, h)* for each pixel is obtained by multiplying the clearness index k_t *by* the global solar radiation obtained under clear sky *Gc(x, y, d, h)*. As expressed in Eq. (7) as

$$Gi(x, y, d, h) = k_t \times Gc(x, y, d, h) \quad (7)$$

III. SIMULATION RESULTS

In our simulation we are interested by the estimation of hourly global solar radiation time series was determined using GISTEL model. In order to perform the GISTEL methodology, two different approaches with and without the fuzzy logic methods were used. We had chosen in our simulation three locations for validation purposes. First, two random days for the locations were selected, the first ones are from the site of Bouzareah in Algeria (36.78° N, 3° E) for the days of 3rd of February 2013 and the 26th of February 2013. The second location is Ghardaia in Algeria (32.48° N, 3.66° E) for the days of 22sd November 2012 and the 7th of December 2012. The data were collected from the National Meteorological Office (ONM) of Algeria. The third location is Almeria in Spain (36.84° N, 2.4 ° W) ; the data were collected from the GeoModel Solar S.R.O., M. Marecka 3, Bratislava, Slovakia for the days of 15th February 2011 and the 20th February 2011. Moreover, the satellite images for each hour were obtained from the Meteo Company B.V website: (http://www.sat24.com) for all locations of Bouzereah, Ghardaia and Almeria.

Fig. (3-8) shows the simulation results of the hourly global horizontal solar radiation time series of the above-mentioned locations; in all figures the blue line represents the measured data, the red dot line present the simulated data using the fuzzy logic approach and the green dot line presents the simulated data without fuzzy logic method.

In addition, for comparing the simulation of the hourly horizontal global solar radiation by the mentioned methods, the RMSE and NRMSE represented in Eq. (8) and Eq. (9) were used to judge the validity of the models.

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (I_{i,\text{predicted}} - I_{i,\text{measured}})^2 \right]^{\frac{1}{2}} \quad (8)$$

$$NRMSE = \left(\frac{\left[\frac{1}{n} \sum_{i=1}^{n} (I_{i,\text{predicted}} - I_{i,\text{measured}})^2 \right]^{\frac{1}{2}}}{\frac{1}{n} \sum_{i=1}^{n} (I_{i,\text{measured}})} \right) \quad (9)$$

We note that the simulated solar radiations are changed during the day; from low values in sunrise and sunset to high values at noon that leads to the fact that the results obtained from the GISTEL model were representing the real stat of a day. In addition, some fluctuations can be occurring due to the presence of clouds. The variation of the solar radiations depends on the clearness index k_t ; a clear day has a clearness index equal to 1, a cloudy day with k_t = 0.2 and a partially cloudy day between $0.2 < k_t < 1$.

For the validation of the simulation results of the estimation of hourly horizontal global solar radiation data with GISTEL model with the fuzzy logic model and without it, the RMSE and the NRMSE represented in Table 1 were used.

Table 1 The RMSE and NRMSE between actual data and simulated data with and without fuzzy logic method (FL) method

		Error (RMSE)		Error (NRMSE)	
	Date	With FL	Without FL	With FL	Without FL
Bouzereaha (Algeria)	26 Mar. 2013	52.87	69.80	0.21	0.28
	03 Apr. 2013	52.98	63.61	0.20	0.24
Ghardaia (Algeria)	22 Nov. 2012	53.84	69.99	0.22	0.29
	07 Dec. 2012	54.21	64.36	0.21	0.25
Almeria (Spain)	15 Feb. 2011	23.31	25.51	0.28	0.31
	20 Feb. 2011	36.95	49.08	0.24	0.31

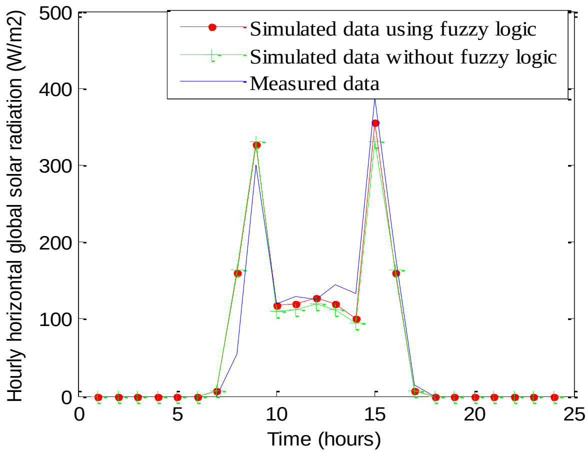

Fig. 3 Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 22sd November 2012 for the site of Ghardaia, Algeria.

From table 1, it is clearly shown that the simulated models with the fuzzy logic model are good enough, that represents an NRMSE error between 0.2 and 0.28 comparing to the measured solar radiation data for all locations. Moreover, from table 1, the NRMSE of the simulated hourly horizontal global solar radiation using the fuzzy logic method is lower than the simulated ones without use it, leads to a conclusion that the GISTEL model with the fuzzy logic method is good for such similar problems.

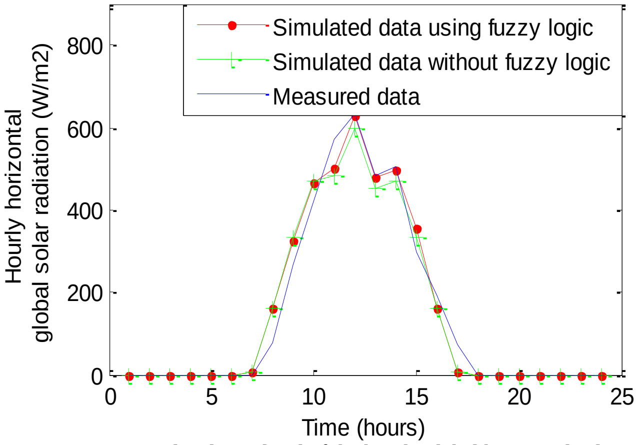

Fig. 4 Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 7th December 2012 for the site of Ghardaia, Algeria.

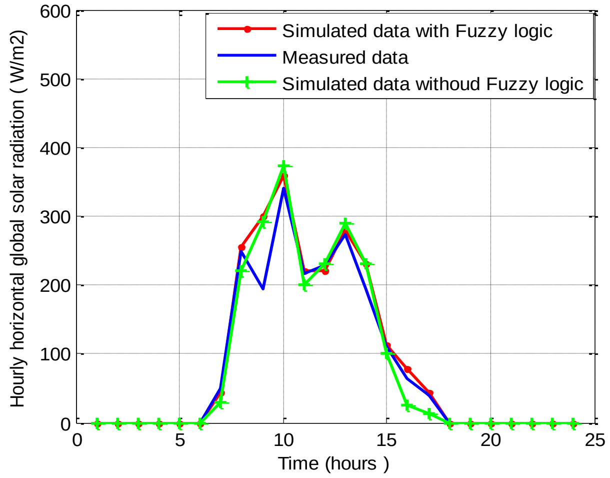

Fig. 5 Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 15th February 2011 for the site of Almeria, Spain.

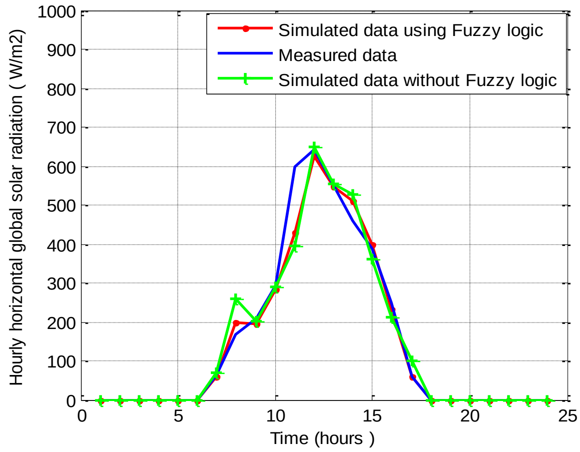

Fig. 6 Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 20th February 2011 for the site of Almeria, Spain.

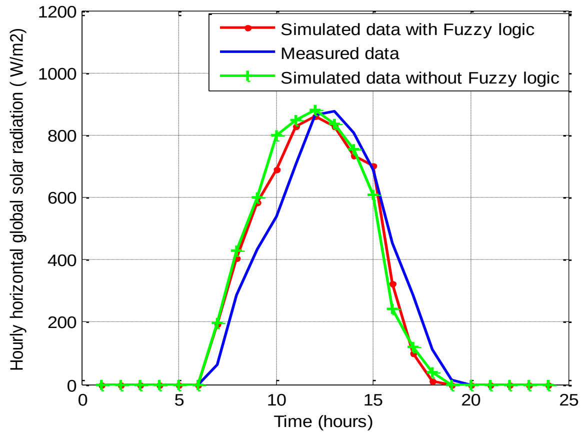

Fig. 7 Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 3rd March 2013 for the site of Bouzerah, Algeria.

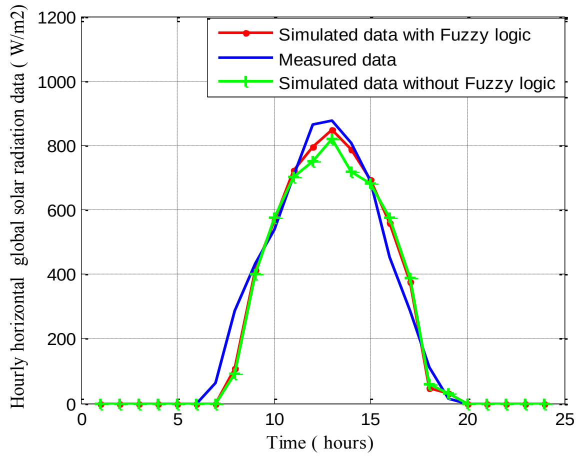

Fig. 8 Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 3rd March 2013 for the site of Bouzerah, Algeria

IV. CONCLUSIONS

In this paper, we proposed a new methodology for estimating the amount of the solar radiation. The methodology used in this work consists on the estimation of the hourly global horizontal solar radiation data using a modified GISTEL model. The objective of this approach is the processing of the visible satellite images by calculating the transmission coefficients for each pixel of the image. A comparison between those coefficients and the ones obtained from the clear, partial and totally cover sky have been reached, which allows determining the clearness index that used for the estimation of the hourly solar radiation. In addition, a combination of the base GISTEL model and a fuzzy logic approach was used in this model in order to obtain more precise results.

The obtained experimental results showed the accuracy of this approach. In addition, the proposed method does not need a complicate calculation and based only on few input parameters.

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