Optimal PV Panel Tilt Angle Based on Solar Radiation Prediction

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***Abstract*—One of the most important parameters that affects Photovoltaic (PV) panel performance of both grid connected system and off grid system is solar radiation received. The position and angle of a PV panel are two very important factors in PV system design. This paper investigates the optimal tilt angle of PV panels using mathematical method. Both short term and long term analysis were carried out to calculate the optimum tilt angle. Using daily optimal tilt angle can increase the energy received than using optimal monthly tilt angle. However, trade-off needs to be made since changing the panel angle daily costs more effort. The solar energy prediction is based on a typical daily distribution. Two methods of solar radiation prediction were proposed and compared to give average daily radiation distribution prediction.**

I. Introduction

Utilization of renewable energy in electric power generation has being increased due to environmental concern and the dwindling of traditional fossil fuel. Among various renewable sources, solar energy is most commonly used due to its abundance and accessibility. Power generation using Photovoltaic cells is most commonly used technique. Stand-alone PV farms are usually applicable in rural and remote areas. In urban cities like Singapore, building integrated photovoltaic (BIPV) system is more feasible [1]. In order to increase efficiency of a BIPV system, the factors that affect the performance of a PV panel should be analyzed.

The tilt angle of a PV panel is a major factor that affects the solar radiation received and will eventually determines the electric energy output. In PV systems installed in building facades or on roof, the best way to extract maximum amount of daily solar energy is using tracking system. The benefit of installing tracking system depends on a trade-off between the cost of tracking system and the savings of using less PV panels to get a certain amount of power. Solar trackers are often expensive. Therefore, it is of considerable importance for studying the performance of a PV panel under different tilt angles and orientations for design purpose [2]. The optimum tilt angle at which a PV panel receives the maximum amount of solar radiation is denoted asΣ_{opt}. For a completely transparent atmosphere, Σ_{opt} is equal to the latitude of the collector location which is a rule of thumb according to [3]. As the sun's rays need to pass through thick atmosphere to arrive at the surface of the earth, attenuation will occur in this process. Furthermore, the position of the sun with respect to earth is not constant all year long. The analysis of actual optimum tilt angle for PV panel at specific location and different time of the year is necessary before installation.

The prediction of solar radiation is quite important for many solar applications. Although the radiant energy emitted by the sun to earth is enormous and almost constant on totally clear day, the energy that can be received in specific area is influenced by the climatological condition in long term as well as clouds density and rainfall in short period. As solar radiation data is one of the most important requirements for the design of a PV system, it is meaningful to develop a model to predict the solar radiation to optimize the system operation and planning. The radiation is a site-specific value since the main factor influencing it is the location of the installation and the time of the year. The orbit that earth moves around the sun is fixed, so given the time and the position information, the radiation that can be received at the site can be calculated using a series of empirical formulas[4]. Singapore, located near the equator, has quite a great solar radiation potential. The main features of the climate of Singapore are relatively uniform temperature, high humidity and abundant rainfall due to maritime influence. There are no large temperature changes throughout the year and the mean monthly temperature does not vary by more than 1.0°C from the mean annual value of 26.7 °C. There is no big seasonal change of the climate in Singapore since it locates near the equator.

In this paper, based on measurement from Singapore, the weather effects that result in the solar radiation deviating from ideal clear day value is analyzed in monthly pattern. Two indexes are used to represent the effects, first one is the radiation loss, second is the amended clearness index. The method of autoregressive and moving average (ARMA) is used to model the two indexes in order to make radiation prediction.

II. Methodology

A. Determination of optimum tilt angle

For the optimum operation of a PV system, one of the most important requirements is to harness the maximum electric energy received. To catch the maximum sunlight, the PV panel should be positioned at the angle that the solar rays of the sun arrive at the panel surface perpendicularly. A number of factors will affect the value of Σ_{opt}, such as the distribution

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and density of the clouds and the regional albedo and etc. However, it is not practical to account for the effects of all the factors. Furthermore, in most area, measurement data of these factors are unavailable. Compared with the ideal radiation data, the measurement data reflect the influence of these factors. Calculation using measurement data can include the combined effects of uncertain variables.

The measurement data obtained from the weather station are usually global radiation on a horizontal surface. A procedure was adopted to separate the global horizontal radiation into direct and diffuse parts and then projected them onto tilted surface to get the radiation can be received by the tilt surface[5]. The tilt surface with optimum tilt angle receives maximum solar radiation. A lot of previous research work have been done on specific area using both analytical and mathematical methods [1,2,3,6-11]. Some researchers have given empirical formula for determining the optimum tilt angle. Lewis [3] suggested that $\Sigma_{opt} = \emptyset \pm 8^0$ based on examination of four locations in USA. Here $\emptyset$ is the latitude of the location of PV system. But solar radiation is a site specific value and Σ_{opt} cannot be represented accurately with fixed formula. Later investigation also shows that this formula is not applicable in Singapore. Most of the previous studies were done by analytical method at specific area. Authors of [6] investigated the optimal tilt angle in Cyprus while Tang [7] did research in China, Kacira [8-9] and Morcos [10] also made investigation at Turkey and Egypt respectively. These works were all done at specific location and came up with optimum value for a specific time period from one month or several months to a year. However, no similar work has ever done for Singapore. A mathematical procedure is proposed in this paper to determine the optimal PV panel tilt angle in Singapore.

B. Calculation of solar radiation

In order to determine the optimal tilt angle, the amount of solar radiation can be received at the location should be given. Given the detail location information and time of the year, the ideal solar radiation can be calculated using a series of empirical formulas [4].

The solar radiation strike the PV panel consists mainly of three parts: direct-beam part I_B which is the primary part, diffuse radiation I_D and reflected radiation I_R.

The direct-beam radiation passes in a straight line through the atmosphere to the receiver. Attenuation occurred during this period as some parts of the radiation were absorbed by the atmosphere or scattered by air molecules or particulate matter. A commonly used model is given by ASHRAE Clear Day Solar Flux Model. The formula for calculating I_B is

$$I_B = \left\{1160 + 75\sin\left[\frac{360}{365}(n - 275)\right]\right\} e^{-km} \quad (1)$$

where n is the Julian day number of a year ranges from 1of Jan 1^{st} to 365 of Dec 31^{st} ,except for leap years when it has a Julian day of 366 [11] , m and k are air mass ratio and optical depth respectively given by (2) and (3).

$$m = \frac{1}{\sin\beta} \quad (2)$$

where β is the altitude angle of the sun.

$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n - 100)\right] \quad (3)$$

Beam solar radiation fall on tilt surface with tilt angle of Σ, I_{BC} and horizontal surface I_{BH} are calculated by (4) and (5),

$$I_{BC} = I_B[\cos\beta\cos(\phi_s - \phi_c)\sin\Sigma + \sin\beta\cos\Sigma] \quad (4)$$

where ϕ_s and ϕ_c are azimuth angle of the sun and PV panel respectively.

$$I_{BH} = I_B\sin\beta \quad (5)$$

When considering the diffuse radiation, an isotropic sky model is used and a sky diffuse factor C given by ASHRAE is adopted. The diffuse radiation fall on the horizontal surface I_{DH} and on the tilt collector surface I_{DC} are calculated by (6) and (7) respectively.

$$I_{DH} = C\, I_B \quad (6)$$

$$I_{DC} = C\, I_B \left(\frac{1+\cos\Sigma}{2}\right) \quad (7)$$

C in above equation is given by

$$C = 0.095 + 0.04\sin\left[\frac{360}{365}(n - 100)\right] \quad (8)$$

Reflection radiation is the part that reflected by surfaces in front of the panel. In this text, a gross assumption of a large horizontal area in front of the panel is used. The reflection radiation on tilt panel surface I_{RC} is

$$I_{RC} = \rho I_B(\sin\beta + C)\left(\frac{1-\cos\Sigma}{2}\right) \quad (9)$$

where ρ is the ground reflectance of the horizontal surface.

For horizontal surface, reflection radiation is zero since Σ equals zero.

Based on above calculation, total radiation received by the PV panel is

$$I_C = I_{BC} + I_{DC} + I_{RC} \quad (10)$$

C. The solar radiation prediction

As mentioned in many previous research works, the intensity and availability of solar radiation is influenced by many parameters. It is difficult to employ analytical methods for prediction of solar radiation. Safi [12] proposed to use higher order statistics method to predict daily radiation. Garg [13] predicted the global solar radiation from bright sunshine hours and meteorological parameters. Sfetsos [14] and Mohandes [15] came up with a method of using artificial intelligence techniques to predict hourly radiation value. Since training of artificial intelligence network will need a lot of meteorological information which is not widely applicable in many places, the statistical method is usually adopted to model the solar radiation directly.

Autoregressive and moving average (ARMA) model is widely used in modeling and prediction of time series [16].

Let OI_t= the observed solar radiation at the t_{th} 5 mins interval.

I_t= the clear day solar radiation at the t_{th} 5 mins interval.

SI_t= the simulated solar radiation at the t_{th} 5 mins interval.

Different time series can be derived from the above data. Generally, let

$$y_t = f(OI_t, I_t) \quad (11)$$

The data series y_t can be used to build the ARMA(p,q) time series model:

$$y_t = \emptyset_1 y_{t-1} + \emptyset_2 y_{t-2} + \cdots + \emptyset_p y_{t-p} + a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \cdots - \theta_q a_{t-q} \quad (12)$$

where $\emptyset_i (i = 1,2, \dots, p)$ and $\theta_j (j = 1,2, \dots, q)$ are the auto-regressive and moving average parameters of the model respectively. at is a normal white noise process with zero mean and a variance of σ_a^2 (i.e. $a_t \in NID(0, \sigma_a^2)$), where NID denotes Normally Independently Distributed).

After establish proper time series model for y_t, the simulated solar radiation can be calculated by:

$$SI_t = f^{-1}(y_t, I_t) \quad (13)$$

where $f^{-1}(\cdot)$ is the inverse function of $f(\cdot)$.

The adequacy of the model is checked the fitness of the model which is calculated using the following equation:

$$\text{Fitness} = \left(1 - \frac{|y - \hat{y}|}{|y - \bar{y}|}\right) \times 100 \quad (14)$$

y is the measured output and $\hat{y}$ is the predicted output, $\hat{y}$ is the mean of y. It represents the percentage of the output that the model reproduces. While 100% indicates perfect fit, 0% indicates that the fit is no good than guessing the output to be a constant. In this text, fitness above 80% is perceived as acceptable. Another standard called Akaike's Information Criterion (AIC) which provides the way to measure the model quality by simulating the condition using a different data set. The smaller value indicates better estimation. In the following case study, ARMA models with different orders were fitted and the one with smallest AIC value is chose. Usually these two standards provide same results. Many work have been done using ARMA method to model hourly or sub-hourly solar radiation or clearness index. As the data available in Singapore is of 5 mins interval, an ARMA model will be established by using these data.

To build a solar radiation model that take into consideration of various factors' influence, the ideal radiation data can be used as a standard, then we can 'extract' the influence of the empirical fixed influence such as latitude and annual average value from the measured data. The seasonal trend can be separated in several different ways [12]: (1) the conventional method which can account for the influence of the latitude, is defined as the division of terrestrial solar radiation values by the corresponding extraterrestrial values, (2) subtraction of the annual harmonic which is the first harmonic of its Fourier analysis, (3)take the 'loss part' of the radiation which is calculated as the subtraction of the extraterrestrial radiation to its corresponding terrestrial value. These methods were used in previous work on prediction of daily total global radiation. In order to make short term prediction like 5 minutes in this text, the calculated clear day solar radiation value which was perceived as the ideal condition was used instead of the extraterrestrial radiation. Being different with the extraterrestrial solar radiation, the clear day solar radiation already accounts for the attenuation caused by various meteorological factors such as dust, air pollution, atmospheric water vapor, clouds, turbidity and so on[4]. Two methods which are derived from the above mentioned methods are used. First is "radiation loss" which is the subtraction of each value of the clear day radiation the corresponding value of measured radiation received on the horizontal surface. Second is the amended clearness index which is defined as the division of measured solar radiation values by the corresponding clear day values. The traditional clearness index is defined as the ratio of the average horizontal terrestrial radiation to the extraterrestrial radiation [4]. The ideal data is more close to real radiation value compared with extraterrestrial insolation. The adequacy of using both of the two methods is evaluated in next part.

III. CALCULATION PROCEDURE AND CASE STUDY

Examine the measurement data of solar radiation from weather station in Singapore with location information of latitude 1.3667 N, and longitude 103.8E. The daily total radiation behavior is shown in Fig. 1.

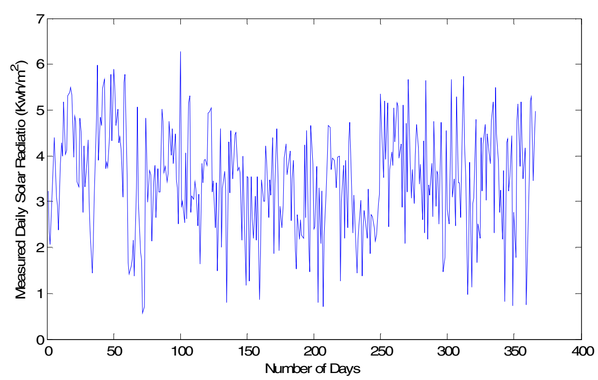

Figure 1. The distribution of measured daily solar radiation on horizontal surface for a whole year

From Fig.1, the total daily value falls mainly between 3-4 Kwh/m^2. The fluctuation reflects the influence of cloudiness, changing air mass and other meteorological factors.

The following case studies are conducted to examine the effects of weather condition on the determination of Σ_{opt}. Two prediction models are proposed to compare the real value with ideal value.

A. Optimal monthly angle determination

The monthly average optimum tilt angle of a PV panel has been determined for two conditions of clear day and real data with weather effect. An average daily total radiation value for a month was used to calculate the monthly optimal tilt angle. A program for calculating solar radiation at different tilt angles was developed respectively for the two conditions. The angle changes from 0^o to 90^oin step of 0.1^0. The results for the two conditions are shown in Fig. 2. It can be seen from Fig. 2 that the shapes of the two curves are quite similar. From April to September, Σ_{opt} of real value is 0^o and 0.1^0 for clear day. In Singapore, from April to September, it is the Southwest monsoon season which account for about 36% of annual rainfall. High frequency of rainy days may be the main cause of the angle difference for the above two conditions.

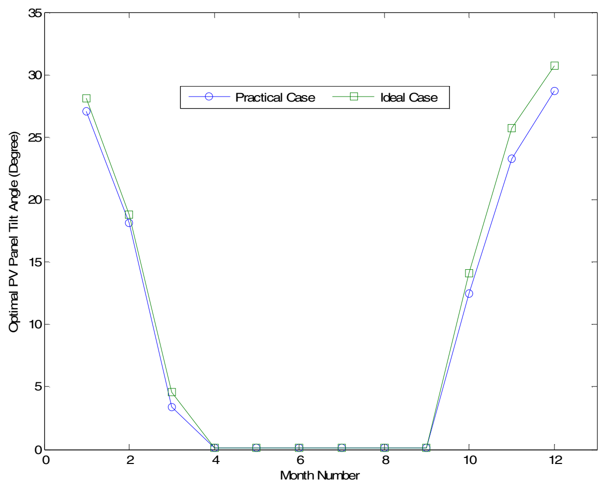

Figure 2. Optimal monthly tilt angles for clear day and real condition.

From November to March, it is the Northeast monsoon season which accounts for 48% of the annual rain fall. The angle difference is larger caused by higher rainy day frequency. It reflects that during these period, the effects of other meteorological effects are obvious, and the overall weather condition will influence the determination of Σ_{opt}. The results provide useful information for design and operation of the PV panel system. If the average monthly Σ_{opt} is used, angles for April to September are the same and changing the panel angle for 7 times per year is enough to get optimal operation.

B. Optimal daily angle determination

Since it might introduce errors by using only a typical daily value to calculate one tilt angle for the days within a month, Σ_{opt} for each day is determined. Both the ideal value and real value are used to conduct the daily Σ_{opt} calculation. The results are shown in Fig. 3.

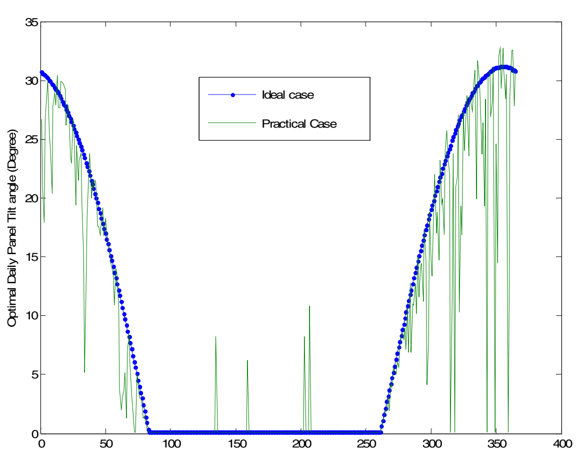

Figure 3. Optimum daily panel tilt angles for clear day and real condition

From the figure, the behavior of the distribution of ideal clear day condition is a smooth line with similar shape of monthly value in Fig 2. The line with fierce fluctuation is the practical condition which shows the influence of sudden rainfall or clouds density and etc. The optimum tilt angle from real data still coincides with ideal condition. During Southwest monsoon season, Σ_{opt} is around 0.1^0 . It is close to the value of rule-of-thumb of about 1.3^0. This shows during this period, the weather condition in Singapore has a big portion of cloudless day.

Compare the difference of using daily Σ_{opt} with monthly value. The result is shown in table 1 in which the daily Σ_{opt} is averaged for days within the same month.

TABLE 1. COMPARISON OF MONTHLY AVERAGE OPTIMAL TILT ANGLE (°)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daily average	25.9	17.0	2.6	0.1	0.4	0.3	0.7	0.1	1.3	11.5	21.2	25
Monthly value	27.1	18.1	3.4	0.1	0.1	0.1	0.1	0.1	0.1	12.5	23.3	28.7

From Table 1 we can see that the Σ_{opt} value calculated by using daily value deviate from using monthly value obviously. Furthermore, the difference of energy received is investigated.

As it will cost much more efforts to change the angle of PV panel every day than at a frequency of every month. The benefit of invest these effort should be examined with the cost. One standard is the additional energy it can bring to the PV panel system. Table 2 shows the comparison of energy received per year of using different panel angle.

TABLE 2. COMPARISON OF ENERGY RECEIVED FOR DIFFERENT METHODS

Conditions	Energy Received (Kwh/m^2-year)	Changing Tilt angle (times/yr)
No tilt angle	1264.78	0
Tilt with monthly optimal angle	1297.32	7
Tilt with daily optimal angle	1298.86	193

Figures in table 2 are just the value for one square meter, consider a building roof of hundreds of square meters, the difference of energy can be received will be quite big. It will bring an obvious energy increase of tilting the panel with a proper angle instead of just putting it horizontally. The increase of energy collection is only based on changing the panel angle a few times for a year without additional cost.

C. ARMA model of irradiation loss

The data from the weather station is in 5 minutes interval from 7 am to 6 pm for year 2008. In order to use ARMA model to predict the value, the property of the data should be examined first. Fig. 4 gives the basic shape of solar radiation distribution of average level in January as well as the calculated ideal value.

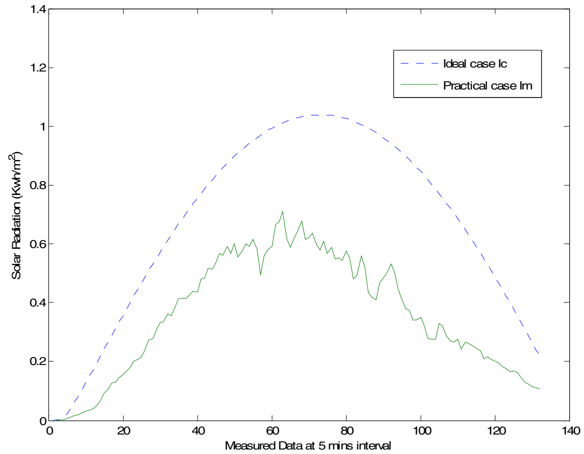

Figure 4. The average daily solar radiation distribution for January

The basic shape of the practical solar radiation has similar trend with the ideal value. The discrepancy is caused by meteorological influence. The radiation loss I_l is given by equation (15)

$$I_l(j) = I_c(j) - I_m(j) \qquad j=1, 2, 3, \ldots, 132 \qquad (15)$$

where I_c is the clear day value, and I_m is the measured solar radiation.

The ARMA models with different orders for each month are compared and the model with the smallest AIC value and highest fitness is selected. The data of each month was separated into two parts. The first part of data was used to build average daily solar radiation model. The remaining part was used to validate the adequacy of the model. For January, the model fitting result is shown in Fig 5.

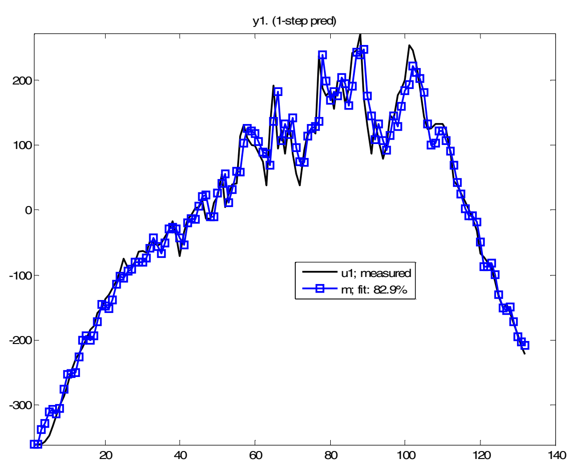

Figure 5. First step prediction fitness for Jan model

The fitness of the model is up to 82.9% from Fig.5. However, it is only useful for the modeling of the average level of solar radiation distribution. The reason is that although the clear daily solar radiation distribution is the main factors that determine the daily solar radiation distribution, there are a number of meteorological parameters that can affect the radiation like clouds distribution, rainfall and humidity condition and so on. These parameters cannot be predicted accurately using autoregressive and moving average process. The average daily solar radiation distribution of first half of the month was used to predict the average value for the remaining half of the month. The result is shown in Fig. 6.

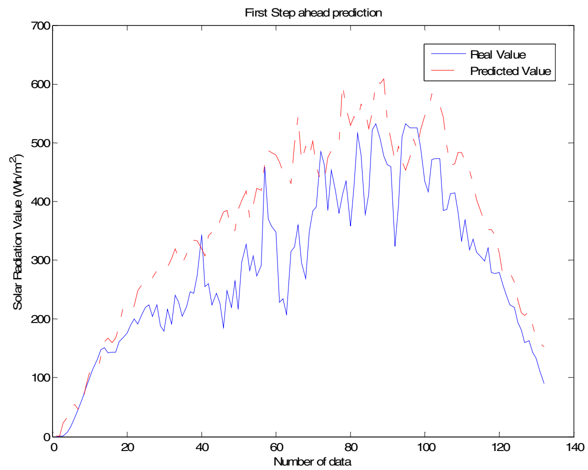

Figure 6. Comparison of the model prediction data with real measurement for Jan

From Fig. 6, the predicted radiation value was compared with the real measurement. The difference can be evaluated using the mean square error (MSE) which is defined by (16)

$$mse = \frac{1}{n}\sum_{j=1}^{n}\left(I_m(j) - \hat{I}(j)\right)^2 \qquad j=1,2,3\ldots\ldots 132 \qquad (16)$$

$\hat{I}(j)$ denotes the estimate value while $I_m(j)$ represents the actual measurement.

The comparison result is shown in table 3. In this case, the MSE is 0.0096 and 0.0094 respectively. Although this is not a significant improvement, the model uses in this case still gives better result. The model was also tested to other months.

TABLE 3. COMPARISON OF THE MSE RESULTS (LOSS PART)

Model	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ARMA	0.0094	0.0110	0.0193	0.0088	0.0058	0.0077	0.0038	0.0190	0.0045	0.0022	0.0041	0.0069
Average	0.0096	0.0114	0.0200	0.0094	0.0056	0.0075	0.0036	0.0195	0.0051	0.0030	0.0049	0.0072

From Table 3, it can be concluded that except for May, June and July, proposed method has a lower MSE value. In general, for a whole year calculation, proposed method can give more accurate prediction. Based on the prediction value, monthly optimal tilt angle was investigated and result was compared with using amended clearness index method in next part.

D. ARMA model of the amended clearness index

In order to predict the daily average solar radiation distribution, the second method is to model the distribution of amended clearness index K_{rc} and then derive the corresponding solar radiation.

$$K_{rc}(j) = I_m(j)/I_c(j) \qquad j=1, 2, 3, \ldots, 132 \tag{17}$$

This index reflects the percentage of the solar radiation that can be collected when the sky is not totally clear. The lower the value, the turbidity the sky is. The procedure of this case study is similar with last case except for modeling the revised clearness index instead of loss part of solar radiation.

Also compare the MSE of the results between proposed ARMA model and just using average value.

TABLE 4. COMPARISON OF THE MSE RESULTS (REVISED CLEARNESS INDEX)

Method	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ARMA Model	0.0154	0.0158	0.0282	0.0165	0.0105	0.0119	0.0085	0.0343	0.0078	0.0051	0.0205	0.0335
Average Value	0.0163	0.0169	0.0295	0.0186	0.0110	0.0117	0.0079	0.0373	0.0087	0.0052	0.0211	0.0334

It can be concluded from Table 4 that except for Jun, Jul and Dec, proposed ARMA model is more accurate than just using average value to make prediction.

After obtain the prediction value of amended clearness index value, corresponding solar radiation can be calculated, furthermore monthly optimal tilt angle can be calculated. Table 5 shows the predicted monthly average optimal tilt for above two methods.

TABLE 5. COMPARISON OF PREDICTED OPTIMUM TILT ANGLE

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Loss Radiation	23.8	14.2	0.5	0.1	0.1	0.1	0.1	0.1	1.8	15.4	24.1	27.5
Amended Clearness Index	23.8	14.2	0.5	0.1	0.1	0.1	0.1	0.1	1.8	15.5	24.2	27.5

The two ways of model solar radiation give almost same prediction of optimum tilt angle for every month and are close to actual value which demonstrates the effectiveness of both of the methods within acceptable error range. MSE value reflects the overall distribution error of the prediction. Comparing the results in table 2 with that in table 3, the first method has a smaller MSE value that proves it is more accurate than the second method.

IV. CONCLUSION

From analysis above, based on one year record of solar radiation, the importance of setting the angle of PV panel to an optimum angle was investigated and the value of the optimal angle was calculated. This paper provides simple methods which just make use of one year data to build the solar radiation prediction model. Two methods were adopted to derive the model. Since the only parameter used to build the model is the radiation value, the results cannot be as accurate as using other complicated method such as intelligent network which can incorporate many meteorological factors. In addition, solar radiation is quite a site-specific value, in order to develop more accurate model, long term data is needed.

The experiment results showed that by tilting the PV panel angle to a specific optimal value can increase the energy it can receive thus increase the output energy of the panel. However, from the results, the general weather condition of Singapore can also be derived which is useful in design of PV system parameters and make operation schedules.

The proposed prediction model also can be adopted to predict average distribution of solar radiation in a specific time period and can give acceptable results. More accurate prediction can be made if given more data. Investigation also showed that by modeling the corresponding loss part of the radiation value to predict corresponding radiation can give more accurate value than using the amended clearness index value.

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