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An Irradiation Prediction Model for Photovoltaic Power Generations Under Limited Weather Information

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Abstract: The customer side operation is getting more complex and difficult in a smart grid environment because of the adoption of renewable resources, such as photovoltaic, wind turbine, geothermal and fuel cell and the use of energy storage systems. In performing energy management planning or scheduling, it is essential to forecast non-controllable resources accurately and robustly. Photovoltaic is one of the common renewable energy resources in customer side. The output of photovoltaic is directly related to insolation and temperature at the installed location for a specific time. Therefore, obtaining precise weather information is critical for accurate estimation. However, the weather forecast information that customers can access is usually not precise and even not quantitative. In this paper, an irradiation prediction model for photovoltaic power generations based on limited weather forecast information is proposed. It is assumed that customers can obtain only ordinary daily weather forecast that usually provides the qualitative prediction of 3 hours unit for the next 24 or 48 hours. Some existing insolation estimation methods are combined and power conditioning system characteristics are considered. The model is applied to a field test site, and verified with historic data.

Keywords: Photovoltaic, Prediction model, Weather forecasting.

1. INTRODUCTION

Due to the emergence of smart grid environment, active adoption of the diverse distributed resources such as photovoltaic, wind power, energy storage system and others are expected. Accordingly, forecast on the distributed resources on time and weather is needed in order to develop effective energy management and operation plans. Photovoltaic which is one of the distributed resources is influenced considerably by weather. Thus, irradiance information following weather change is needed in order to forecast amount of generation. However, weather forecast usually does not include enough irradiance information. Thus, an irradiance forecast technique that suits weather phenomenon is required. In general, irradiance forecast conducts analysis for the data of past tens of years to calculate the irradiance of the interested region. The data from a region with similar weather condition can be used when the irradiance measurement data of the region is not available. When none of them are available, atmospheric penetration based irradiance forecasting method can be also used.

This research proposes an irradiance forecast model that combines existing meteorological radiation and cloud cover radiation models together. Forecast model's reliability is verified by conducting comparative analysis on the proposed forecast model with the past irradiance observation data.

2. SYSTEM MODELING

2.1 Irradiance modelling

In order to forecast Photovoltaic output, it is necessary to carry out the forecast of irradiance that expresses the strength level of solar radiation energy. Representative existing researches conducted on the irradiance estimation include direct/diffuse decomposition model (Liu and Jordan, 1960), and cloud cover radiation model (Kasten and Czeplak, 1980), meteorological radiation model (Sherry and Justus, 1983). Based on those early works, the transmittance of cloud can be additionally applied using albedo obtained from current satellite data. The transmittance can also be obtained from the regression analysis of the region's data history. In this work, meteorological radiation model and the Cloud-cover Radiation Model (CRM) are combined together considering the weather characteristics and cloud forecast information to predict the irradiance of the target region.

2.2 Irradiance modelling on a clear day

Irradiance that reaches the ground surface can be manifested as the direct beam irradiance that is transmitted directly from solar radiation, I_n, and the diffuse irradiance, I_d, that is transmitted by getting distracted at the atmosphere and ground surface. The total horizontal solar irradiance radiates on the horizontal plane can be expressed as the sum of those two irradiances.

First, directly radiated irradiance can be expressed as follows by using the solar constant (1367W/m^2) and transmittance of the decay components:

$$I_n = 0.9751\, I_{sc}\, (\overline{r^*} / r^*)^2 \tau_r \tau_0 \tau_g \tau_w \tau_a \quad (1)$$

Here, I_{sc} is the solar constant while $(\overline{r^*} / r^*)^2$ is eccentricity. τ_r means the Rayleigh distraction's transmittance, and it can be expressed as follows when the formula proposed by Bird & Hulstrom (1981) is utilized:

$$\tau_r = \exp[-0.0903\, m_r^{0.84} (1.0 + m_r - m_r^{1.01})] \quad (2)$$

Here, m_r is the optical air mass which represents the amount of attenuation components in the air while sunlight passes. It can be expressed using the following formula:

$$m_r = [35 / (1224 \cos \theta_z + 1)^{1/2}] \cdot (P / P_0) \quad (3)$$

Here, θ_Z is zenith angle, P is atmospheric pressure at the location of observation and P_0 means atmospheric pressure on the surface of the sea.

In (1), τ_0 is ozone's transmittance and the formula proposed by Lacis and Hansen (1974) is utilized. Ozone's transmittance is determined by the attenuations from the absorption and reflection of visible rays and ultraviolet rays:

$$\tau_0^{via} = 0.02118\, X_0 / (1 + 0.042\, X_0 + 0.000323\, X_0^2) \quad (4)$$

$$\tau_0^{UV} = [1.0824\, X_0 / (1 + 138.6 X_0)^{0.805}] + [0.0658\, X_0 / 1 + (103.6 X_0)^3] \quad (5)$$

$$\tau_0 = 1 - (\tau_0^{vis} + \tau_0^{uv}) \quad (6)$$

$$X_0 = \varepsilon_0 m_r \quad (7)$$

Here, ε_0 uses 3.5mm, which is the average value of the total amount of ozone.

In (1), τ_g can be expressed as shown on the following formula since it is the transmittance of the gas in the atmosphere.

$$\tau_g = \exp(-0.0127\, m_r^{0.26}) \quad (8)$$

In (1), τ_w is the vapor's transmittance, and can be expressed as shown on the following, while ε_w expresses daily rainfall:

$$\tau_w = 1 - 2.9 X_2 / [(1 + 141.5 X_w)^{0.635} + 5.925\, X_w] \quad (9)$$

$$X_w = \varepsilon_w m_r \quad (10)$$

In (1), τ_a is the aerosol's transmittance, and uses the formula proposed by Machel (1983). Aerosol's transmittance can be expressed as shown in the following formula:

$$\tau_a = (0.12445\, \alpha - 0.0162) + (1.003 - 0.125\, \alpha) \times \exp[-\beta m_r (1.089\, \alpha + 0.5123)] \quad (11)$$

$$\tau_a = [0.97 - 1.25 (Vis)^{0.66}]^{mt^{0.9}} \quad (12)$$

Here, *Vis* is the visibility, and the range lies between 5 and 340km, and α and β utilize the value in Table 1.

Table 1. Parameters for various degrees of atmospheric cleanliness

Parameter / cleanliness	α	β	Visibility (km)
Clean	1.30	0.0	340
Clear	1.30	0.10	28
Turbid	1.30	0.20	11
Very turbid	1.30	0.40	<5

Diffuse irradiance uses the formula proposed by Paltridge and Platt (1976), and it can be expressed as follows:

$$I_d = I_{dr} + I_{da} + I_{dm} \quad (13)$$

Here, I_{dr} expresses Rayleigh's ground surface diffuse, and I_{da} is distraction by aerosol and I_{dm} means the ground surface distraction at the time of multiple reflections between atmosphere and ground, and it can be expressed as shown on the following formula:

$$I_{dr} = I_{sc} \cos \theta_z \tau_0 [0.5(1 - \tau_r)] \tau_a \quad (14)$$

$$I_{da} = I_{sc} \cos \theta_z (\tau_0 \tau_r - a_w) [B_{aa} w_0 (1 - \tau_a)] \quad (15)$$

$$I_{dm} = (I_{sc} \cos \theta_z + I_{dr} + I_{da}) A_{cs} A_c / (1 - A_{cs} A_c) \quad (16)$$

Here, A_{CS} is atmosphere reflexibility, and the value of 0.2 proposed by Davies and McKay (1989) is utilized, and A_C is ground surface reflexibility given by

$$A_C = 0.0685 + (1 - B_{aa})(1 - \tau_a) w_0 \quad (17)$$

where B_{aa} is total scattering by aerosol(Davies and Hay, 1980) and w_0 is single-scattering albedo. Finally, it is possible to obtain the total *horizontal* solar irradiance with the above obtained direct beam irradiance and diffuse irradiance as follows:

$$I_T = I_n \cos \theta_z + I_d \quad (18)$$

2.3 Irradiance model considering the effect of clouds

This paper applied the Cloud-cover Radiation Model (CRM) technique that calculates irradiance forecast based on the cloud cover. The CRM technique is the method for calculating irradiance by distinguishing cloud cover into 0 through 8 at the sun's altitude and forecasting points, which was developed into a formula by Kasten and Czeplak (1980). Later, Muneer and Gul (2000) developed the formula further to suit the conditions of a given region and it can be expressed using the following formulae:

$$I_{GC} = A \sin \alpha - B \tag{19}$$

$$I_G = I_{GC}[1 - C(N/8)^D] \tag{20}$$

Here, I_{GC} expresses the total horizontal solar irradiance on a clear day, I_G expresses the horizontal solar irradiance that factored in the effect of cloud, N expresses the cloud cover, α is solar altitude, and A, B, C, D show the CRM constants.

In (19), I_{GC} is the method that is generalized by adopting coefficients for a given region, and (18) is the meteorological radiation model, which was applied in this work. Accordingly, the irradiance forecasting formula that combines meteorological radiation model and the CRM together can be expressed as follows:

$$I_C = I_T[1 - C(N/8)^D]. \tag{21}$$

3. SIMULATION AND RESULTS

3.1 Simulation design and verification

To verify the irradiance forecast technique proposed in this paper, the forecast data were compared with the 2010 irradiance observation data of the Korea Institute of Energy Research (KIER) that is located in Daejeon, Korea. First, longitude and latitude of the area for measurement were set to 126.26° and 3.6°, respectively. Among the variables needed for the calculation of irradiance forecast, average monthly value for the years from 2000 to 2009 were utilized for the Daejeon area in order to factor into the characteristics of the region's weather when information are not given as weather forecast such as atmospheric pressure, rainfall and others. As for the cloud cover information, cloud cover measurement value of the Daejeon area in 2010 was utilized. The reason that the past data was utilized to compare was to verify forecast model's reliability. Here, because cloud cover information can be converted into weather information that is provided from the weather forecast, the actual forecasting system can use the weather information to carry out irradiance forecast. Actual cloud cover data are obtained by observing at a fixed time in intervals of every three hours. However, cloud cover data interpolation is needed in order to compare with the irradiance observation data of KIER that is collected every 15 minutes. This paper uses Lagrangian Interpolation to the subject data for interpolation in every 15 minutes. When cloud cover information of (n+1) units of time is given, Lagrangian interpolation becomes the n-th order polynomial expressed as follows:

$$y = \sum_{i=0}^{n} C_i L_i(x) \tag{22}$$

$$L_i(x) = \prod_{j=0, j\neq i}^{n} (x - x_j)/(x_i - x_j) \tag{23}$$

Here, C expresses the constant term, x expresses the input variable and y expresses the output variable.

To verify forecast model's reliability, this paper utilized the Root Mean Square Error (RMSE) and the Mean Bias Error (MBE), which are evaluation indices utilized for error analysis along with correlation analysis. They can be expressed as following:

$$RMSE = \sqrt{\sum_{i=1}^{N} (x_i - y_i)^2 / N} \tag{24}$$

$$MBE = \sum_{i=1}^{N} (x_i - y_i) / N \tag{25}$$

Here, x_i, y_i and N are measurement value, forecast value and the number of data, respectively.

3. 2 Simulation results and analysis

For simulation analysis, a day in which the cloud cover for observation was distributed between 0 and 1 was selected to carry out the comparison of the irradiance forecast on a clear day, first and foremost. Then, correlation analysis between observation irradiance and forecast irradiance was conducted. The result demonstrates that the correlation was very high with at least 0.98. When correlation analysis was conducted in every 15 minutes for all the days in 2010, high correlation of 0.904 was found although it had decreased slightly when compared to the clear days. Fig. 1 is the correlation diagram that compares observation and forecast values in every 15 minutes in 2010.

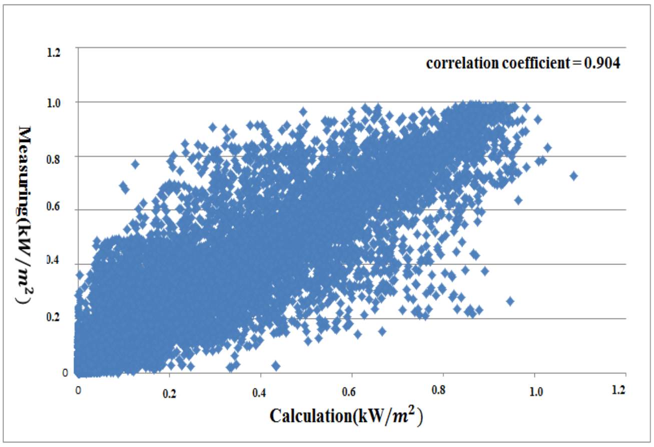

Fig. 1. Diagram on the correlation of observation and forecast values for all the days of 2010.

When a specific month was selected for each season to compare, for example, January, April and October which are the months in winter, spring and autumn, it is possible to see the correlation coefficients manifested high correlation with 0.915 ~ 0.93. Correlation coefficient during July which is during summer was relatively low with 0.84. As shown in Table 2, RMSE and MBE also show highest values during the summertime, which demonstrated that the forecast error was relatively high. This type of result is due to the effect of the cloud with severe changes taking place during the rainy reason in early summer. This may be because the effect of the cloud was limitedly considered due to the characteristics of the CRM technique that factors in only the cloud cover. Moreover, as the value of the MBE result is the negative numbers, it is possible to know that the results of the irradiance forecast is calculated slightly larger than the observation irradiance in overall.

Table 2. RMSE and MBE results of the values observed and forecasted by each season

month / method	Winter (Jan)	Spring (Apr)	Summer (Jul)	Autumn (Oct)
RMSE	0.07104	0.116	0.157	0.093
MBE	-0.0232	-0.0508	-0.058	-0.0346

When average monthly irradiance is examined, it expresses an average error rate of 12%. As for the minimum error, high forecast result was shown with 7~8% for winter and autumn. Compared to this, however, error rate for the summer was close to 20%, demonstrating the need to correct irradiance forecast during summer. Fig. 2 shows average irradiance comparison by each month. Fig. 3 shows correlation diagram on the specific month by each season.

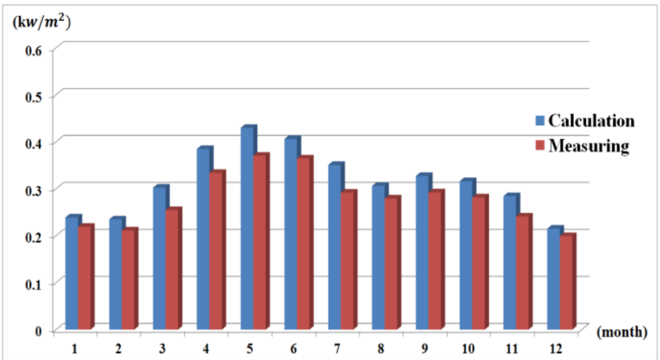

Fig. 2. Average monthly irradiance observation and forecast value trend for 2010.

To examine the daily pattern of a clear day and of the day when there is a change in the clouds, the cloud cover between 0~2 and 3~8 were respectively selected. The result demonstrated that the correlation coefficient of the observation and forecast shows very high value of 0.98 or greater on clear days, while irradiance patterns were very similar.

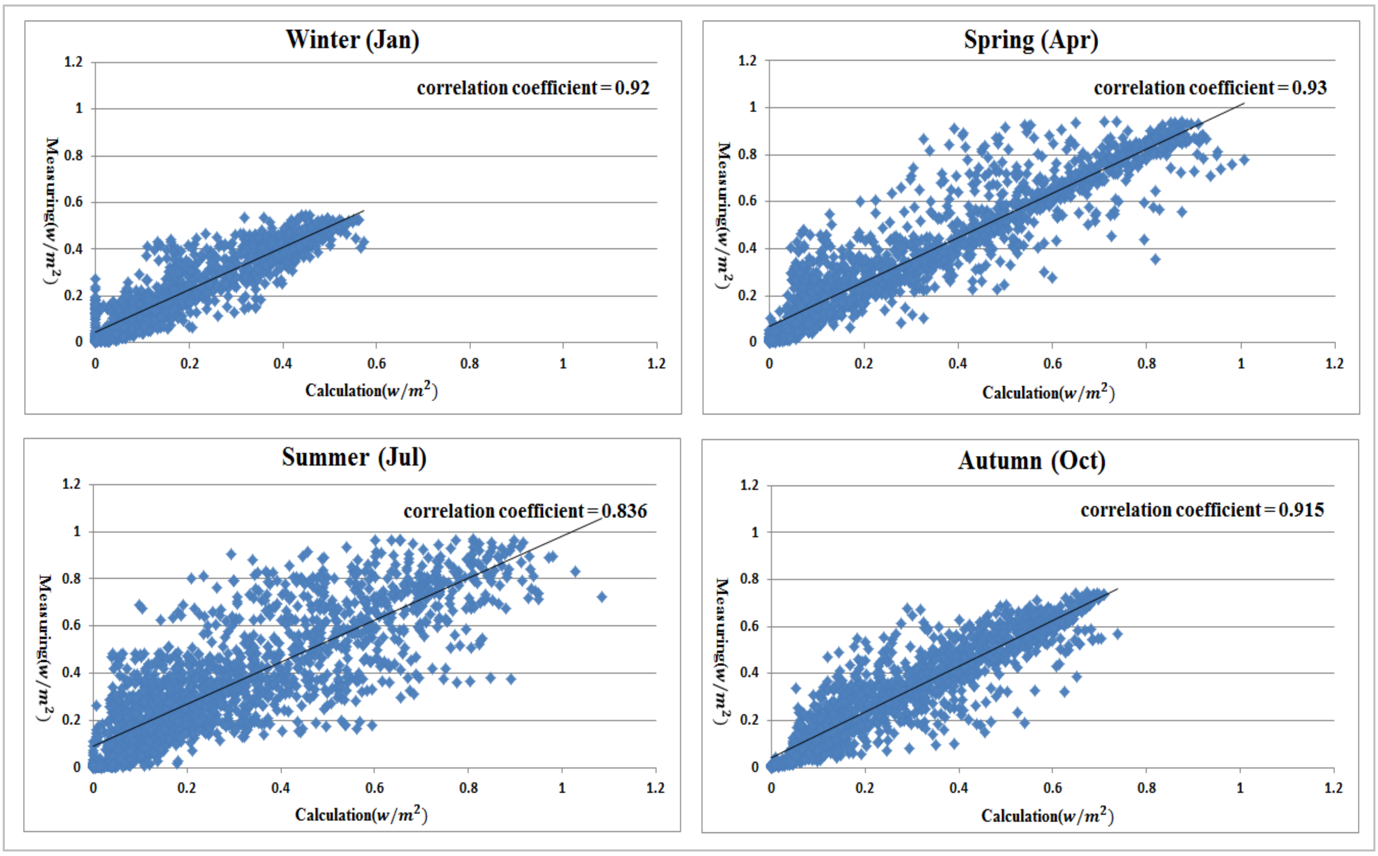

Fig. 3. Correlation between irradiance observation and forecast values by each season on specific days of 2010.

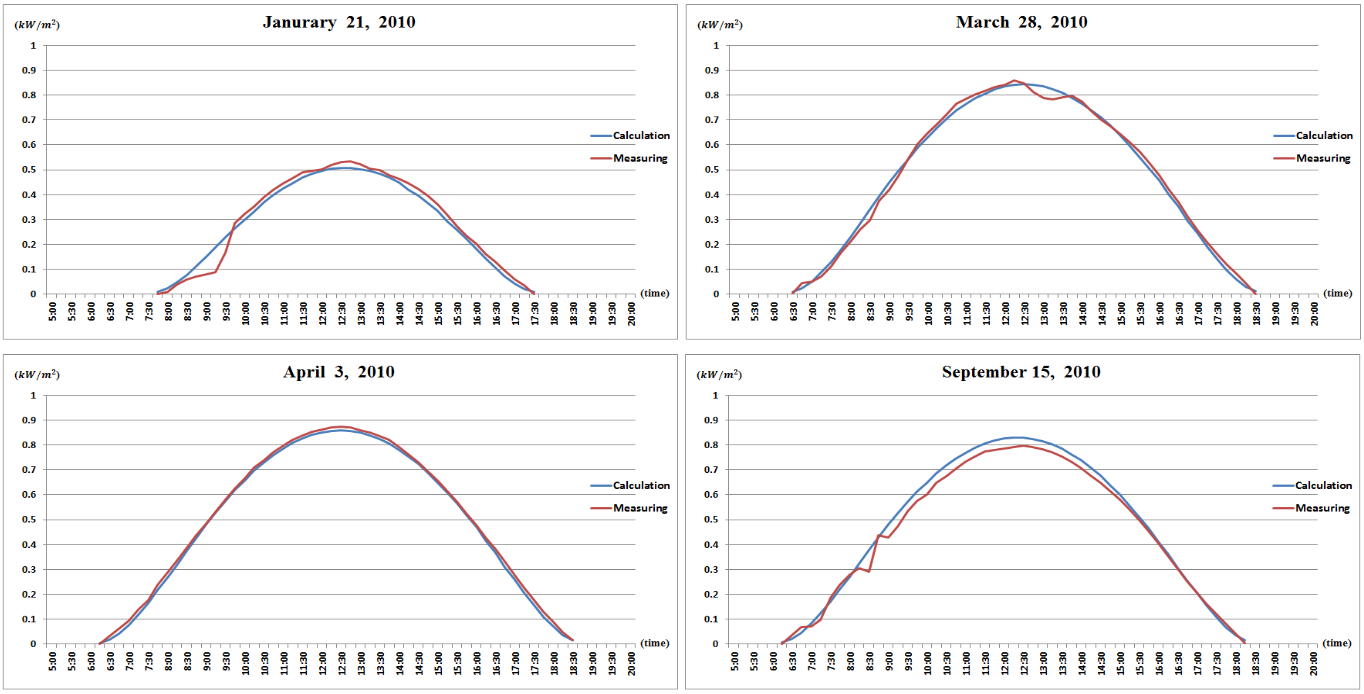

Fig. 4. Comparison of the observation value and irradiance pattern for 2010 (Clear days).

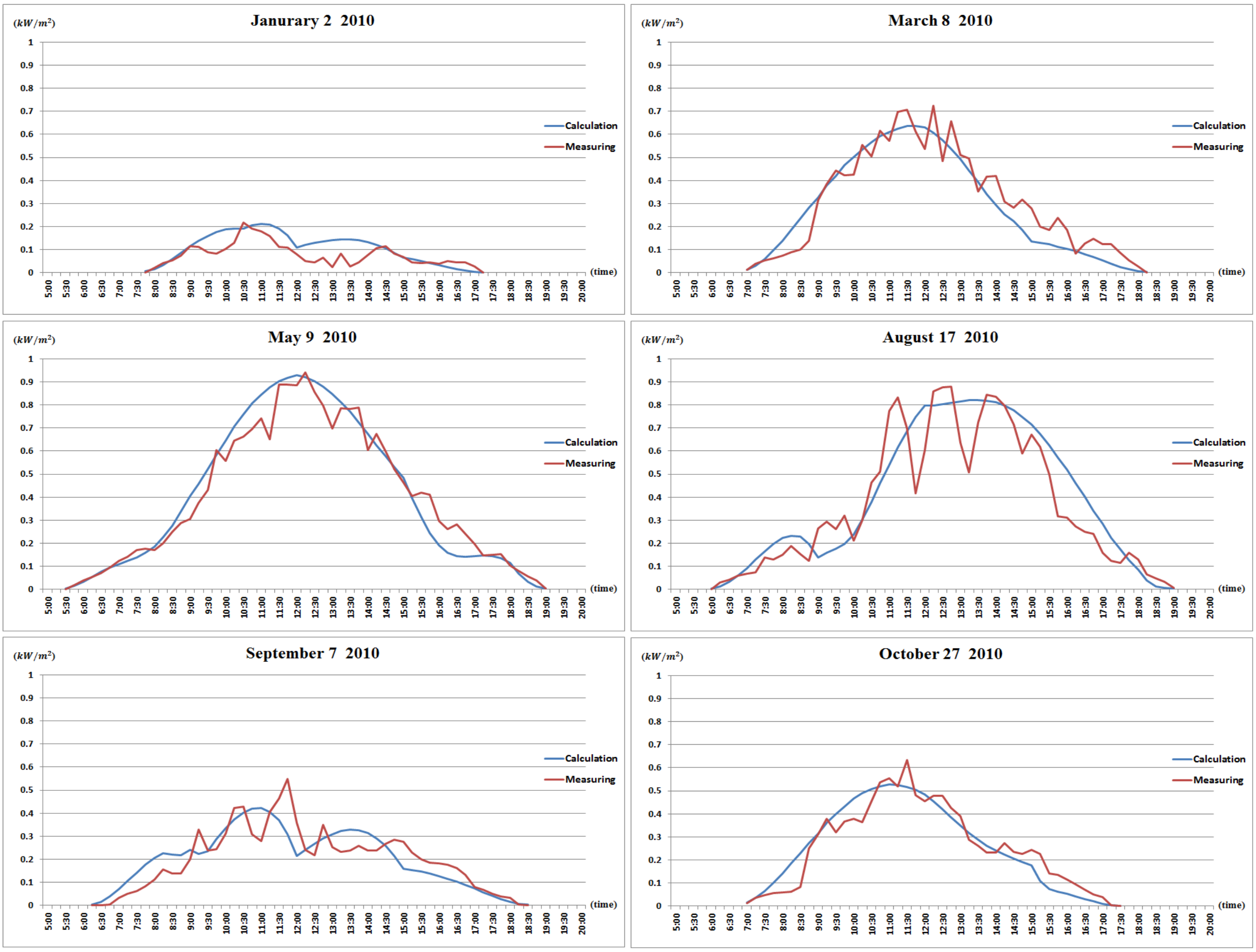

Fig. 5. Comparison of the observation value and irradiance pattern for 2010 (Cloudy days).

Moreover, RMSE and MBE also manifested as a result that is close to 0, showing very similar forecast result. On cloudy days, interpolation was carried out in every 15 minutes due to the nature of the cloud cover information that is collected every three hours. Thus, errors are resulted during the interpolation. Because only the information regarding cloud cover was utilized, transmittance following the different types of cloud was not factored in. Thus, errors were resulted when the same cloud cover was applied during a day. However, it was confirmed that the observed and forecasted values show similar patterns in the overall pattern. Figure 4 expresses comparison of the observation value and irradiance pattern measured every 15 minutes in a clear day with the daily cloud cover measured 0~1. Moreover, Fig. 5 expresses a comparison of pattern in every 15 minutes after choosing a day with cloud cover fluctuation that lies in between 2~10. These figures demonstrate that the overall irradiance forecast pattern is similar to the observation values.

4. CONCLUSIONS

This paper conducted irradiance forecast simulation by utilizing meteorological radiation and the CRM models.. The results were compared with the values of KIER's irradiance observation for the year 2010 to verify the validity of the irradiance forecast model. In 2010, correlation analysis was conducted using all the days, which manifested high correlation. It is not easy to compare directly with the previous works because they usually predict daily irradiation differently from this work that estimates hourly irradiation. However, the high correlation value compared to the previous works shows the effectiveness of the proposed model. Observation and forecast values were compared through the irradiance forecast over a day. In case of a clear day, the correlation coefficient is very high with 0.98 or greater and the irradiance pattern is very similar. On the day when there is a change in the clouds, only limited cloud cover information from a weather forecast was available. Thus, errors are resulted since transmittance for the time was not able to be obtained precisely. However, overall pattern demonstrated that the observation and forecast patterns look similar, and it was verified by this research that the proposed irradiance forecast model's reliability is valid. This work proposed an irradiance forecast model combining existing irradiance forecast models. Irradiance forecast was executed by converting weather information obtained from the weather forecast into cloud cover information based on the above mentioned irradiance model. This results show that it is possible to obtain valid results with irradiance forecast, using weather forecast. The future work includes research for improving the result of irradiance forecast on cloudy days by using the information from the weather forecast.

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