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Probabilistic Analysis of Solar Photovoltaic Output Based on Historical Data

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***Abstract*- Solar photovoltaic (PV) is one of the favorable renewable energy sources since it is considered environmentally friendly. Yet it is still at the infancy stage due to the high cost of PV cells. Furthermore, the PV output is dependent on the solar radiation intermittency and the location of installation. This paper presents a probabilistic analysis of a hypothetical solar photovoltaic system in Peninsular Malaysia. From the recorded meteorological data, an analysis of the probabilistic distribution function of the hourly solar radiation is carried out. A comparison has been made between two different locations in order to analyse their characteristics by using meteorological data of KLIA Sepang and Kuala Terengganu Airport. This paper adopts a method considering a multi-state model instead of two-state model which is used for modeling conventional generator to cater for the intermittency of solar radiation. A linear rounding method is recommended for simplification of the multi-state model for effective computation. The results show that based on irradiance data in Peninsular Malaysia, development of microgrid containing solar photovoltaic power system has a good potential for further development.**

I. INTRODUCTION

In Malaysia, coal and gas are the main sources for power system generations. However, there are growing concerns regarding depletion of these natural resources [1]. Additionally, the conventional fossil fuels release excessive carbon dioxide to the atmosphere and contribute to the global warming. Renewable energy resources have the potential to become an alternative to fossil fuels as the source for distributed generation systems (DER). Thus, the use of renewable energy has been actively promoted with investment incentives, including feed-in tariff.

Renewable energy resources such as solar, wind, biomass, wave and tidal energy support the available capacity to meet load demands which increase tremendously with time. Nowadays, the solar photovoltaic generator becomes important in generation planning because it produces no pollution to the environment, low cost of maintenance with high reliability and life span expectation of 20-30 years [2]. The solar photovoltaic power system is focused on in this paper since it is one of the fastest growing energy even though in Malaysia it is still in the early stages. This is due to the high cost of photovoltaic cells' installations and the previous solar electricity tariff rate [2]. In the recent budget (Tenth Malaysia Plan), the development of renewable energy had received a major boost towards promoting a greener environment [3].

The location of Malaysia in the equatorial region makes it very suitable for the installation of solar power system. In addition, Malaysia climate is categorized as an equatorial climate with tropical rainforest in which the country has high levels of temperature and humidity. The average temperature in Malaysia throughout the year is between 22^0C and 32^0C (72^0F and 90^0F) [4]. Weather conditions in Malaysia are suitable for solar photovoltaic implementation due to average direct sunlight with almost six hours every day with solar irradiation between 800 W/m^2 and 1000 W/m^2 [5].

The solar radiation varies with times and place due to the intermittent nature of the environment and weather in the specific area including cloud and rain. Two-state model used in conventional generators is not suitable to be employed in solar photovoltaic generators for reliability evaluations. This is due to the large error in accuracy if two-state model applies in solar photovoltaic generators [6]. Therefore, a multi-state model is well suited in modeling solar photovoltaic generators [7]. A linear rounding method is used to simplify the multi-state model in order to calculate the generated power and probability indices. This paper adopts the methodology presented in [8] and tests its applicability to the Malaysian meteorological data.

II. METHODOLOGY

Fig. 1 shows the flow chart describing the probability distribution function (*pdf*) analysis for solar photovoltaic generation. These methodologies will be explained step-by-step in the following subsections.

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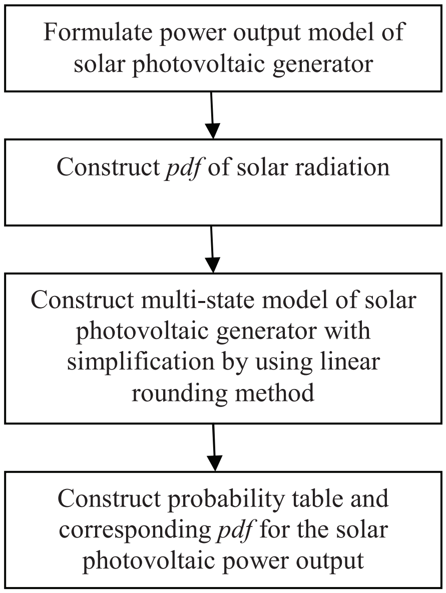

Fig. 1. A flow chart describing the probability distribution function analysis

i. *Solar Photovoltaic Generator's Power Output Model*

Solar photovoltaic generate power by converting the sunlight directly into electricity. However, the solar energy received depends on the availability of solar photovoltaic cells and the weather of locations. The generated power $P_{bi}(G_{bi})$ corresponding to a given solar radiation G_{bi} for band i (i=1,2,3,…,N_b) can be calculated by the following mathematical equation [8].

$$P_{bi}(G_{bi}) = \begin{cases} P_{sn}\,(G_{bi}^{2} / G_{std}\,R_c) & ;\ 0 \le G_{bi} < R_c \\ P_{sn}\,(G_{bi} / G_{std}) & ;\ R_c < G_{bi} \le G_{std} \\ P_{sn} & ;\ G_{bi} > G_{std} \end{cases} \quad (1)$$

Where

- P_{bi} : solar radiation-to-energy conversion function for solar radiation band i of the solar photovoltaic generator [W]
- G_{bi} : forecasted solar radiation at band i [W/m^2]
- G_{std}: solar radiation in the standard environment, usually is set to 1000 W/m^2
- R_c : a certain radiation point, usually is set to 150 W/m^2
- P_{sn} : equivalent rated capacity of solar photovoltaic generator [W]

ii. *Solar Photovoltaic Probability Density Function*

The outage capacity probability distribution function (*pdf*) of the solar photovoltaic generator can be obtained by combining the solar radiation's power output model and the solar radiation *pdf* model as shown in Fig. 2 that yields the multi-state model. The probabilities of the same generated power are cumulated as presented at G_{std} in the Fig. 2. Therefore, the state number is not the same from the solar radiation band number [9].

iii. *Solar Photovoltaic Multi-state Model with Simplification using Linear Rounding Method*

The band sizes of the multi-state model must be equal, but it may be impractically large due to the convolution integral [10]. Therefore, a simplification of the model needs to be made in order to get reasonable computational requirements.

A linear rounding method is proposed in which shares the ratio of probability linearly, is used for model simplification. This paper uses the same technique to simplify the multi-state model by using the linear rounding method presented in Fig. 3 graphically and mathematically described by equation (2) and (3).

For this project, all the parameters utilized for the solar photovoltaic generation are similar to the one that used in analyzing solar radiation at Jinju, South Korea [8]. The specified parameters of the solar photovoltaic generator for the simple system are given in Table 1.

TABLE I
THE PARAMETER OF SOLAR PHOTOVOLTAIC GENERATOR

R_c	150 W/m^2
G_{std}	1000 W/m^2
P_{sn}	10 MW

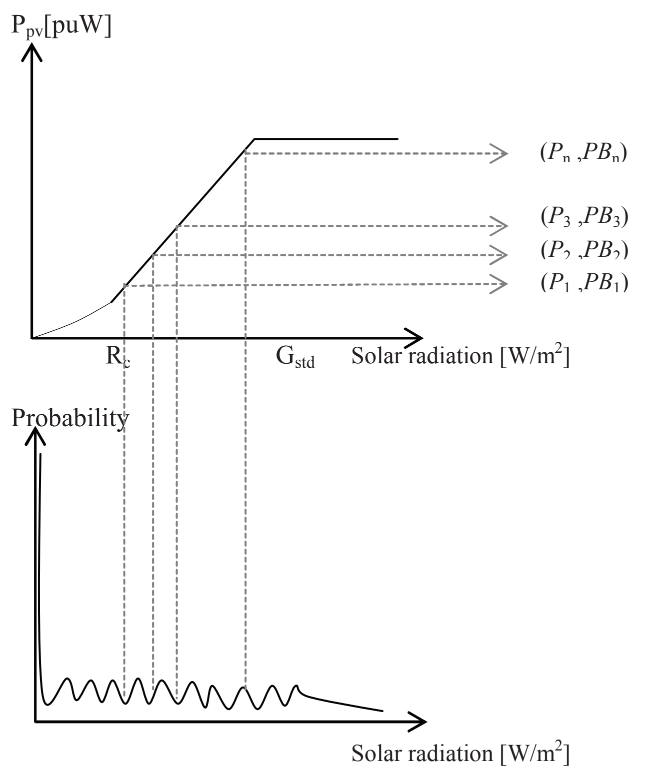

Fig. 2. The relationship between power output and solar radiation model [9]

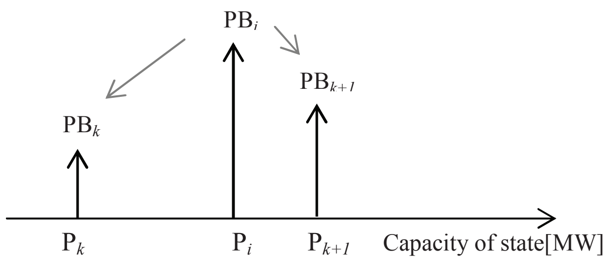

Fig. 3. Illustration of the proposed rounding method

$$PB_k = ((P_{k+1} - P_i) / \Delta P) \times PB_i \quad (2)$$

$$PB_{k+1} = ((P_i - P_k) / \Delta P) \times PB_i \quad (3)$$

Where

$\Delta P = P_{k+1} - P_k$ [MW]

k = state number of the simplified multi-state model

i = state number of the original multi-state model

iv. Solar Photovoltaic Power Output Probability Table

The probability table of solar photovoltaic power output will be discussed on the next section.

III. Results

The *pdf* model of solar radiation is constructed by using the actual data at KLIA Sepang and Kuala Terengganu Airport. The results of the *pdf* pattern of solar radiation taken in three years (2006-2008) for both locations are shown in Fig. 4 and 5 respectively. From the graphs, both solar radiation *pdf* at KLIA Sepang and Kuala Terengganu Airport are identical to each other. As no radiation occurs at night times and the remained half of probability of solar radiation is distributed during the day, the solar radiation *pdf* model appears to be approaching a binomial distribution than a normal distribution.

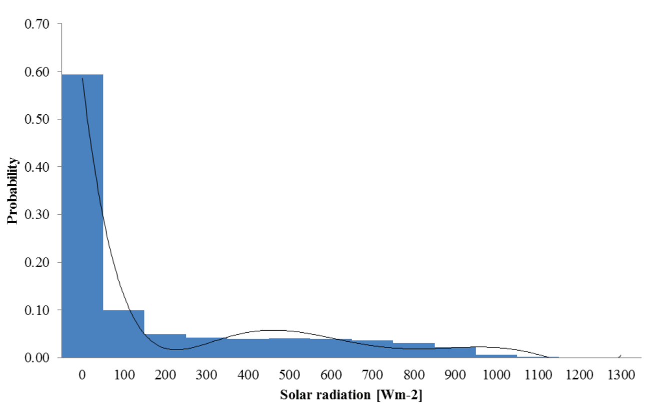

Fig. 4. The solar radiation *pdf* at KLIA Sepang

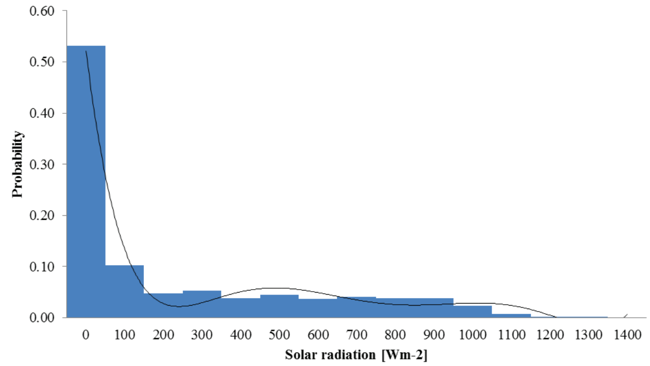

Fig. 5. The solar radiation *pdf* at Kuala Terengganu Airport

Table 2 and 3 shows the solar photovoltaic power (P_{bi}) corresponds to their solar radiation with state probability (P_{bi}). In [6], it is stated that data from five states are enough to maintain the accuracy of the transferred data, hence it is also applied in this paper for modeling solar photovoltaic generator. The probabilities are cumulated for 1000 and 1100 W/m^2 at KLIA Sepang due to the same generated power. The same situation applied to the Kuala Terengganu Airport, in which the probabilities for 1000, 1100, 1200 and 1300 W/m^2 are cumulated.

TABLE II
Solar Radiation, Power and Probability of Solar Photovoltaic Generator at KLIA Sepang

Solar Radiation [W/m^2]	Solar Photovoltaic Power (P_{bi}) [MW]	State Probability (P_{bi})
0	0	0.5938
100	0.667	0.0997
200	2.000	0.0488
300	3.000	0.0417
400	4.000	0.0392
500	5.000	0.0414
600	6.000	0.0392
700	7.000	0.0371
800	8.000	0.0309
900	9.000	0.0217
1000	10.000	0.0061
1100	10.000	0.0003
1200	10.000	0.0000

TABLE III
SOLAR RADIATION, POWER AND PROBABILITY OF SOLAR PHOTOVOLTAIC GENERATOR AT KUALA TERENGGANU AIRPORT

Solar Radiation [W/m^2]	Solar Photovoltaic Power (P_{bi}) [MW]	State Probability (P_{bi})
0	0	0.5314
100	0.667	0.1022
200	2.000	0.0474
300	3.000	0.0531
400	4.000	0.0374
500	5.000	0.0449
600	6.000	0.0369
700	7.000	0.0404
800	8.000	0.0384
900	9.000	0.0373
1000	10.000	0.0234
1100	10.000	0.0067
1200	10.000	0.0005
1300	10.000	0.0001

A linear rounding method has been used to calculate the probability of solar photovoltaic generator output at KLIA Sepang and Kuala Terengganu Airport for 10 MW capacity as shown in Table 4 and 5.

By comparing both probabilities at the multi-state model, it shows that higher probability at 10 MW capacity at Kuala Terengganu Airport rather than at KLIA Sepang by 6.83%. The environmental factor such climate conditions (clouds and fog) effects the solar radiation which gives different readings in both places as well as the intermittent of radiance that arrives to the earth surface. The orientation of solar photovoltaic panel also plays an important role in capturing the optimum irradiance.

TABLE IV
ROUNDING OF THE POWER AND PROBABILITY OF SOLAR PHOTOVOLTAIC GENERATOR AT KLIA SEPANG

P_i [MW]	P_k / Prob.	0 MW	3 MW	5 MW	7 MW	10 MW
0	0.5938	0.5938	-	-	-	-
0.667	0.0997	0.0775	0.0222	-	-	-
2	0.0488	0.0163	0.0325	-	-	-
3	0.0417	-	0.0417	-	-	-
4	0.0392	-	0.0196	0.0196	-	-
5	0.0414	-	-	0.0414	-	-
6	0.0392	-	-	0.0196	0.0196	-
7	0.0371	-	-	-	0.0371	-
8	0.0309	-	-	-	0.0206	0.0103
9	0.0217	-	-	-	0.0072	0.0145
10	0.0064	-	-	-	-	0.0064
Total	1	0.6876	0.116	0.0806	0.0845	0.0311

TABLE V
ROUNDING OF THE POWER AND PROBABILITY OF SOLAR PHOTOVOLTAIC GENERATOR AT KUALA TERENGGANU AIRPORT

P_i [MW]	P_k / Prob.	0 MW	3 MW	5 MW	7 MW	10 MW
0	0.5314	0.5314	-	-	-	-
0.667	0.1022	0.0795	0.0227	-	-	-
2	0.0474	0.0158	0.0316	-	-	-
3	0.0531	-	0.0531	-	-	-
4	0.0374	-	0.0187	0.0187	-	-
5	0.0449	-	-	0.0449	-	-
6	0.0369	-	-	0.0184	0.0184	-
7	0.0404	-	-	-	0.0404	-
8	0.0384	-	-	-	0.0256	0.0128
9	0.0373	-	-	-	0.0124	0.0249
10	0.0306	-	-	-	-	0.0306
Total	1	0.6267	0.1261	0.0820	0.0969	0.0683

IV. CONCLUSIONS

This paper provides a probabilistic analysis of solar photovoltaic output based on meteorological data from two different locations, KLIA Sepang and Kuala Terengganu Airport. Based on these actual solar radiation data, the *pdf* model of solar radiation appears to be approaching a near binomial *pdf* than normal *pdf*. The multi-state model is implemented instead of two-state model due to randomness of solar radiation which is also location dependent. Thus, a simplification of multi-state model using a linear rounding method is proposed for more efficient computation, which is much more practical. The proposed method is applicable to be used in Malaysia based on historical data. The outcome of these results will facilitate reliability evaluation of power system incorporating solar photovoltaic.

V. ACKNOWLEDGMENT

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VI. REFERENCES

[1] S. C. Chua, T. H. Oh, "Review on Malaysia's National Energy Developments: Key Policies, Agencies, Programmes and International Involvement", *Renewable and Sustainable Energy Reviews* 14, pp. 2916-2925, 2010.

[2] S. Mekhilef, A. Safari, W.E.S. Mustaffa, R. Saidur, R. Omar, M.A.A. Younis, "Solar energy in Malaysia: Current state and prospects", *Renewable and Sustainable Energy Reviews,* Vol 16, Issue 1, pp. 386-396, January 2012.

[3] Sustainable Energy Development Authority Malaysia, "Malaysia Pledge on Energy Efficiency", 30 Oct 2013.

[4] Kuala Lumpur, Malaysia Weather Averages. http://www.worldweatheronline.com/Kuala-Lumpur-weather-averages/Kuala-Lumpur/MY.aspx#ziwHrpqUi7O3v69w.99

[5] A. Ghazali M., A. M. A. Rahman,"The Performance of Three Different Solar Panels for Solar Electricity Applying Solar Tracking Device under the Malaysian Climate Condition," *Energy and Environment Research*,Vol 2, No 1, pp. 235-243, 2012.

[6] J. Choi, J. Park, K. Cho, M. Shahidehpour, "Grid Constrained Probabilistic Reliability Evaluation of Power Systems Including Wind Turbine Generator", *Power and Energy Society General Meeting*, IEEE, 2010.

[7] M. Aien, A. Biglari, M. Rashidinejad, "Probabilistic Reliability Evaluation of Hybrid Wind-Photovoltaic Power Systems", *Electrical Engineering (ICEE), 21st Iranian Conference,* 2013.

[8] J. Park, W. Liang, J. Choi, A. A. El-Keib, M. Shahidehpour, and R. Billinton, "A Probabilistic Reliability Evaluation of Power System Including Solar/Photovoltaic Cell Generator," *In Power & Energy Society General Meeting,* IEEE PES 2009, 2009.

[9] J. Choi, J. Park, M. Shahidehpour, R. Billinton, "Assesment of CO_2 Reduction by Renewable Energy Generators", *Innovative Smart Grid Technologies (IGST)*, IEEE, 2010.

[10] L. Wu, J. Park, J. Choi, A. A. El-Keib, "Probabilistic Reliability Evaluation of Power System Including Wind Turbine Generators Considering Wind Speed Correlation", *Journal of Electrical Engineering & Technology*, Vol 4, No. 4, pp. 485-491, 2009.

VII. BIOGRAPHIES

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