Dependable Capacity Evaluation of Wind Power and Solar Power Generation Systems

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ABSTRACT

Integration of renewable energy sources, such as wind power and solar power, into the generation system can enhance country's energy security. These alternative energy help diversify sources of primary energy used to produce electricity. However, the biggest disadvantage of using these types of renewable energy power plants is that it might reduce power system reliability because these intermittent renewable energy sources have low dependable capacity. This paper aims to evaluate the dependable capacity of wind power and solar power generation systems. It considers uncertainties due to intermittent wind speed, solar irradiance, ambient temperature, and unavailability of their corresponding generators. Additionally, load uncertainty is also taken into account. The dependable capacity of the wind power and solar power generation systems are determined from the principle of generation system reliability evaluation. The reliability index such as Loss of Load Probability (LOLP) will be used as a key indicator to define the dependable capacity.

Keywords: Renewable energy, Dependable capacity, Uncertainty, Unavailability, Reliability indices

1. INTRODUCTION

Due to global warming problem and the deficiency of fossil fuels, especially oil and natural gas, renewable energy plays a key role as alternatives of these fuels. They help diversify sources of primary energy. However, some types of the renewable energy are intermittent and sometimes lead to a degradation of system reliability. For example, solar power generation can generate electricity only in daytime. Or, wind power generation can generate electricity only if wind speed exceeds the cut-in value. Recently, there are many research works proposed to estimate the dependable capacity of renewable energy generations, especially wind power and solar power generations. These papers try to propose clearer definition of the dependable capacity and utilize reliability-based concept to estimate it. For example, dependable capacity may be defined as an increase in effective load carrying capability (ELCC), an equivalent firm power (EFP), and equivalent conventional power (EPC) [1] - [3]. In addition, researchers in [1] propose a range of dependable capacity of PV plants that can be varied, depending on location and sun-tracking systems. In [2], the potential benefit of coordinating wind and hydro generations to enhance the ELCC is investigated. The conventional method based on EFC denoted as "secured capacity" is discussed in [3]. It is proposed for calculation of wind power capacity credit and capacity cost. Because of the intermittent nature of the renewable energy, they are considered to have low dependable capacity. In Thailand, the dependable capacity is generally defined as a proportion or percentage of output power of a generator with respect to its installed capacity that this generator can supply to the system when needed. Currently, there is neither standard nor reasonable methodology to evaluate this value, especially for the renewable energy power plant. However, by using past historical data of each type of renewable energy power plant, Electricity Generating Authority of Thailand (EGAT) defined the dependable capacity of the solar PV, wind, biomass, biogas, municipal solid waste (MSW), and small hydro power plants in Thailand as 21%, 2%, 36%, 0%, 36%, and 36%, respectively [4]. Although, it is accepted that the dependable capacity of the renewable energy power plant is low, the values defined by EGAT are considered as too much low. Thus, more reasonable method to recalculate the dependable capacity for the renewable energy power plant in Thailand is needed.

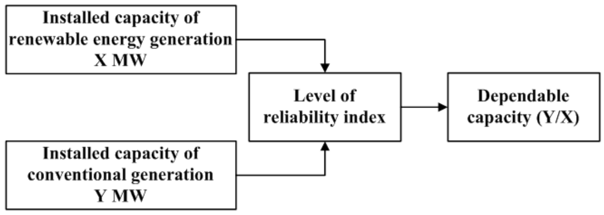

Fig.1: *Concept of dependable capacity used in this paper.*

The purpose of this paper is to propose a novel method to evaluate the dependable capacity of the renewable energy power plant. Only wind and solar PV power plants are considered in this paper. The proposed method takes uncertainties due to intermittent wind speed, solar irradiance, ambient temperature,

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and unavailability of their corresponding generators into consideration. Additionally, load uncertainty is also taken into account. The dependable capacity of the wind power and solar power generation systems are determined from the principle of generation system reliability evaluation. The reliability index such as Loss of Load Probability (LOLP) will be used as a key indicator to define the dependable capacity of the wind and PV power plants.

2. CONCEPT OF DEPENDABLE CAPACITY

There are many general definitions of dependable capacity, e.g. "the capacity that can be relied upon to carry system load for a specified time interval and period" and "the load carrying ability of a station or system under adverse conditions for a specified period of time" [1]-[4]. Alternatively, the dependable capacity of the renewable energy power plant may be technically defined as equivalent capacity of a conventional power plant that yields the same level of generation system reliability when added to the generation system. This definition is used in this paper. The concept of dependable capacity evaluation of the renewable energy power using above definition can be depicted in "Fig. 1".

3. RENEWABLE ENERGY GENERATION MODELS

This section briefly explains theoretical frameworks used in this paper. Two types of renewable energy generation, solar PV and wind, models are discussed.

3.1 Wind Power Generation

Wind turbine captures the kinetic power in wind speed and changes it to the pneumatic power according to Betz's law. The output power of wind power plant depends on the capacity of wind turbine generators (WTGs) and wind speed. So the model of wind power plant will be divided into 2 parts, the wind speed model and wind generation model.

3.1.1 Wind Speed Model

In this paper, wind speed model consists of 2 parts which are average hourly wind speed ($v_{trend,t}$) and uncertainty of wind speed ($v_{noise,t}$) [6].

$$v_{w,t} = v_{trend,t} + v_{noise,t} \tag{1}$$

where $v_{trend,t}$ is an average hourly wind speed, and $v_{noise,t}$ represents an uncertainty part of wind speed. Take derivative to the wind speed model, it yields (2).

$$dv_{w,t} = dv_{trend,t} + dv_{noise,t} \tag{2}$$

The $dv_{noise,t}$ can be explained by a normal distribution, having zero mean and time dependent variance, i.e. $v_{noise,t} \sim N(0, \sigma^2 v_{w,t}^2 t)$. By applying the Ito's Lemma to above equation, wind speed at every points of time can be expressed as

$$V_{w,t} = v_{trend,t} \exp\left(-\frac{1}{2}\sigma^2 t + \sigma Z\sqrt{t}\right) \tag{3}$$

where σ, t and Z are the variance of wind speed that can be estimated by the maximum likelihood method to the historical data, time point, and standard normally distributed random number respectively.

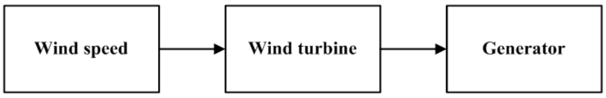

Fig.2: *The operating model of wind generation.*

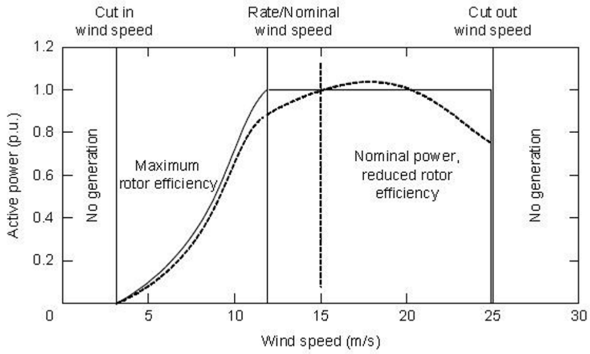

Fig.3: *The level of wind speed in wind power generation.*

3.1.2 Wind Generation Model

Wind generation has a basic operation that can be shows in "Fig. 2". Firstly, when the wind flows through blades of wind turbine, it will catch and turn wind power to mechanical power. Blades are connected with gearbox and shaft that are used to drive the generator. Then, generator will convert mechanical power to electrical power.

Generally, there are 4 levels of wind speed.

- Cut-in wind speed is a first level of wind speed (3-5 m/s). At this level, wind turbine will start moving and generator starts generating electrical power.
- Maximum rotor efficiency wind speed is a level of wind speed that is higher than the Cut-in wind speed but lower than rated wind speed.
- Rated or nominal output wind speed (about 12 m/s) is a level that the turbine produces rated output power.
- Cut-out wind speed (about 20 m/s), is a level of speed that the turbine stop moving to prevent damage of equipment.

The output power of wind power plant in steady-state operation can be calculated by following equations [7].

$$P_w = \begin{cases} 0 & ; v_w < v_{ci}, v_{co} < v_w \\ \left(\frac{v_w^3 - v_{ci}^3}{v_r^3 - v_{ci}^3}\right) P_r & ; v_{ci} < v_w < v_r \\ P_r & ; v_r < v_w < v_{co} \end{cases} \quad (4)$$

where P_r, v_{ci}, v_r and v_{co} are rated power (W), cut-in, rated, and cut-out wind speeds, respectively

Finally, the real electric power that is injected in the power system is calculated by

$$P_{e,w} = P_w \times eff_w \quad (5)$$

where eff_w is the efficiency of the corresponding converters.

3.2 Solar Power Generation

Generally, solar PV power plant can generate electricity only if the solar module receives solar irradiance. However, the output power of the module decreases as the ambient temperature increases. In fact, solar irradiance and ambient temperature have some relationship. A day with high solar irradiance comes with high ambient temperature. Conversely, low solar irradiance comes with low ambient temperature. Consequently, the dependence between the solar irradiation and the ambient temperature should be taken into account in determining the output power of the PV module.

3.2.1 Solar Irradiance and Ambient Temperature Model

Similar to the wind speed model, in this paper, the solar irradiance and the ambient temperature models consist of 2 parts which are average hourly values (G_{trend} and $T_{amb,trend}$) and uncertainty values (G_{noise} and $T_{amb,noise}$).

$$G_t = G_{trend,t} + G_{noise,t} \quad (6)$$

$$T_{amb,t} = T_{ambtrend,t} + T_{ambnoise,t} \quad (7)$$

Then, $dG_{noise,t}$ and $dT_{ambnoise,t}$ can be defined as

$$dG_{noise,t} = \sigma_G \cdot G_t \sqrt{dt} \cdot Z_G \quad (8)$$

$$dT_{ambnoise,t} = \sigma_T \cdot T_t \sqrt{dt} \cdot Z_T \quad (9)$$

where σ_G and σ_T are variances of hourly solar irradiance and ambient temperature estimated by the maximum likelihood method, Z_G and Z_T are normally distributed random numbers, which are correlated.

By applying Ito's lemma, solar irradiance and ambient temperature model can be expressed as

$$G_T = G_{trend,t} \exp\left(-\frac{1}{2}\sigma_G^2 t + \sigma_G Z_G \sqrt{t}\right) \quad (10)$$

$$T_{amb,T} = T_{ambtrend,t} \exp\left(-\frac{1}{2}\sigma_T^2 t + \sigma_T T \sqrt{t}\right) \quad (11)$$

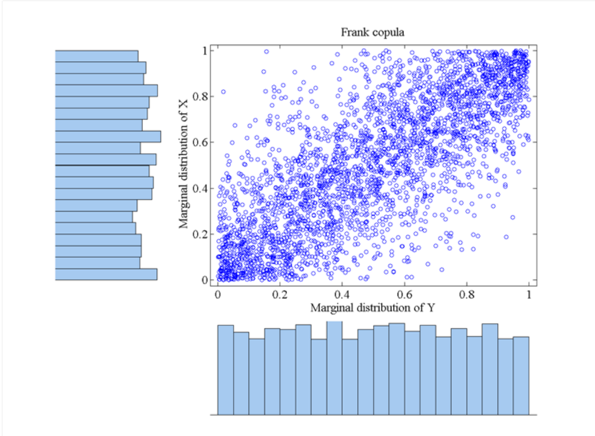

Fig.4: *Frank copula.*

Copula is a mathematical theory that can describe the relationship between random variables in the form of joint cumulative distribution function (joint cdf). Sklar's theorem is the main principle in the copula [8]. It states that H is a joint cdf of random variables if it has a copula C such that

$$H(x_1, x_2, ..., x_n) = C(F_1(x_1), F_2(x_2), ..., F_n(x_n)) \quad (12)$$

where $\forall i, x_i \in R$ and $F_1(x_1), F_2(x_2), ..., F_n(x_n)$) are marginal distribution function of $x_1, x_2, ..., x_n$ respectively.

Generally, there are many standard copula functions. Each of them has different behaviour. This paper uses 3 copula functions to describe the relationship between solar irradiance and ambient temperature which are Frank copula, Gumbel copula and Clayton copula.

- Frank copula presents a relationship of 2 random variables that move in the same direction but does not have tail dependence.
- Maximum rotor efficiency wind speed is a level of wind speed that is higher than the Cut-in wind speed but lower than rated wind speed.
- Gumbel copula is similar to the Frank copula but has tail dependence at the upper right of joint cumulative distribution function of 2 random variables.
- Clayton copula is opposite to the Gumbel copula. However, it has tail dependence at the lower left of joint cumulative distribution function of 2 random variables.

By using the copula concept, the relationship between solar irradiance and ambient temperature can be illustrated in "Fig. 7"

3.2.2 Solar Generation Model

Solar power generation has a basic operation; that is, solar module receives solar irradiance then it will convert photon into electricity. Therefore, the key factor that affects the output power of solar cell is so-

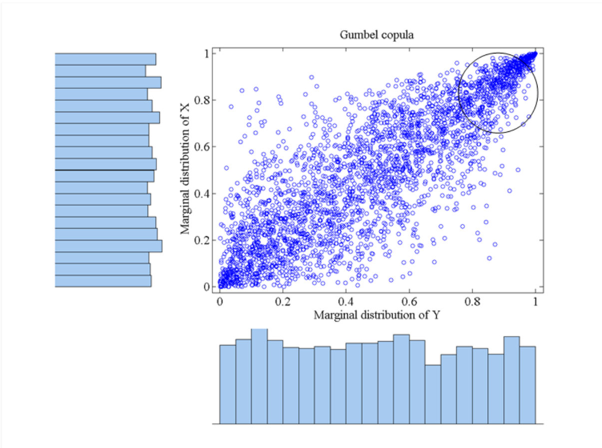

Fig.5: *Gumbel copula.*

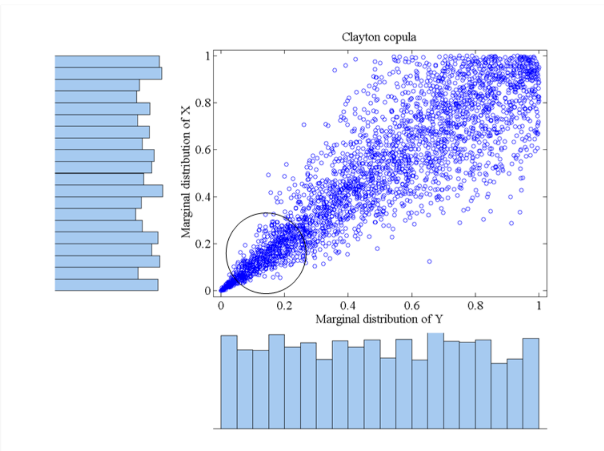

Fig.6: *Clayton copula.*

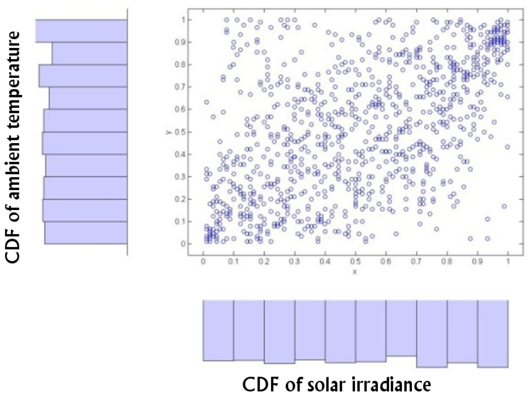

Fig.7: *Joint cumulative distribution function of solar irradiance and ambient temperature.*

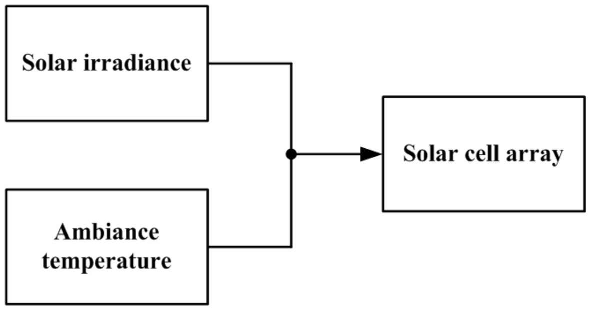

Fig.8: *The operating model of solar power generation.*

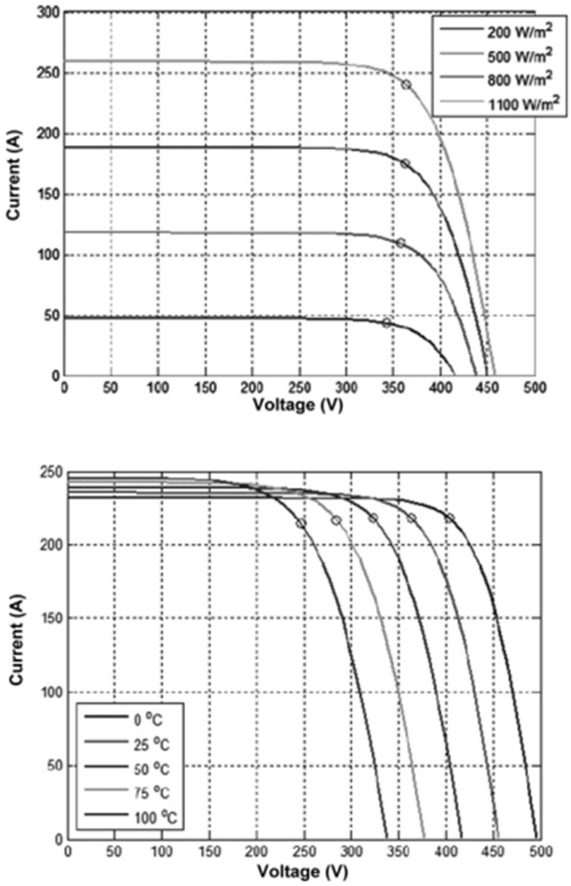

Fig.9: *Effects of solar irradiance and ambience temperature in solar power generation.*

lar irradiance. Ambient temperature is another critical factor. The output power of the module decreases as the ambient temperature increases. Solar irradiance directly affects the current that is produced from the solar module and ambient temperature directly affects the voltage. These 2 factors influent operating condition of the solar module and the output power of the solar PV power plant as depicted in "Fig. 8" and "Fig. 9", respectively.

The output power of solar power generation can

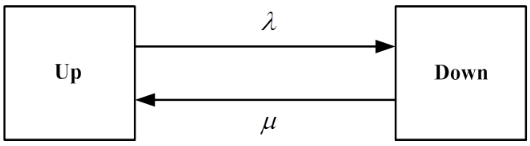

Fig.10: *Two-state model for power plant.*

be calculated by the following equation [9],

$$P_{pv,t} = P_m \frac{G_t}{G_{STC}}(1 - \gamma(T_{cell} - T_{STC})) \qquad (13)$$

The relationship between solar cell temperature (T_{cell}) and ambience temperature (T_{amb}) can be described by this equation [10],

$$T_{cell} = T_amb + \left(\frac{NOCT - 20^\circ}{800}\right) G_t \qquad (14)$$

where P_m is rated output power (W), G_{STC} is solar irradiance at Standard Test Condition (STC) which is 1000 W/m2, Îş is temperature coefficient ($^\circ C^-1$) in range -0.005 to -0.003, T_{STC} is temperature of solar cell at STC and $NOCT$ is Nominal Operating Cell Temperature, which are 25 °Cand 46 °C respectively.

In fact, the solar module generates electrical power in direct current (DC) form. It must be later converted to alternating current (AC). Thus, the real electric power that is injected in the power system is calculated by [7]

$$P_{e,pv} = P_{pv} \times eff_{pv} \qquad (15)$$

where eff_{pv} is the efficiency of the corresponding converters.

4. OTHER RELEVANCE PRINCIPLES

According to the concept explained in section II, the dependable capacity of the renewable energy power plant is determined using renewable energy model, generator model, and load model. All of these models are then used in the reliability evaluation in order to compare the level of generation system reliability between the cases of system with renewable energy power plant and with conventional power plant. The generator model and load model are discussed in this section.

4.1 Generating Unit Unavailability

Probabilistic model of the generating units used in both renewable energy power plants and conventional power plants are based on two-state Markov model as shown in “Fig. 10”. The operating time in the normal state (Up) is called Time to Failure (TTF) and the repair time in the failure state (Down) is called Time to Repair (TTR).

Once, the statuses of the generator have been determined. Then, the operating cycle of the generator in sequence of time can be constructed as shown in “Fig. 11” [11].

TTF_i and TTR_i are time to failure and time to repair at i th state, respectively. Both of them can be simulated by the Monte Carlo simulation technique using following equations,

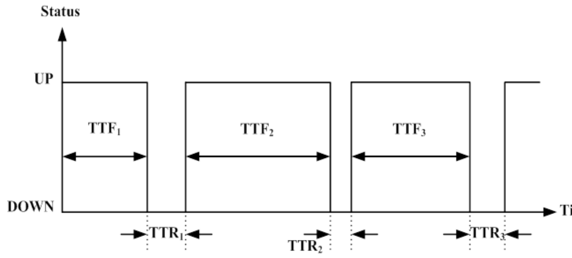

Fig.11: *The operating states of power plant.*

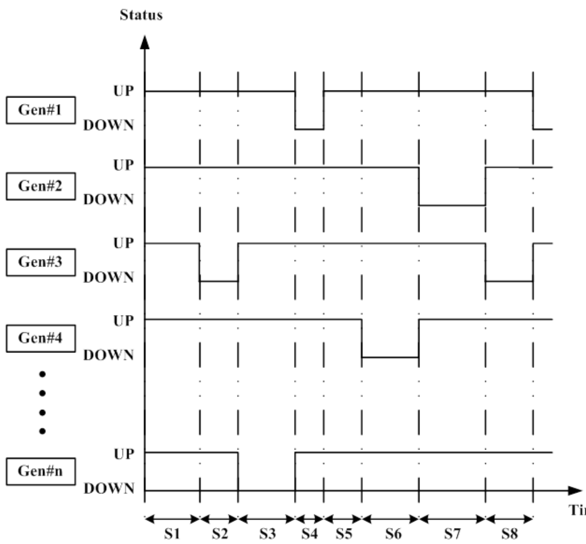

Fig.12: *The operating state of all generators.*

$$TTF = \frac{1}{\lambda} ln(1 - U) \qquad (16)$$

$$TTR = r + Z \times (0.1r); \quad r = \frac{1}{u} \qquad (17)$$

where U, Z, λ and μ are a uniformly distributed random number, a normally distributed random number, expected failure rate, and expected repair rate, respectively

The operating state of the entire generation system in each simulated scenario can be obtained by considering operating states of all generators, simultaneously. This process can be explained in “Fig. 12”.

4.2 Load Model

In this paper, load model is divided into 2 parts which are average load and variance of average load

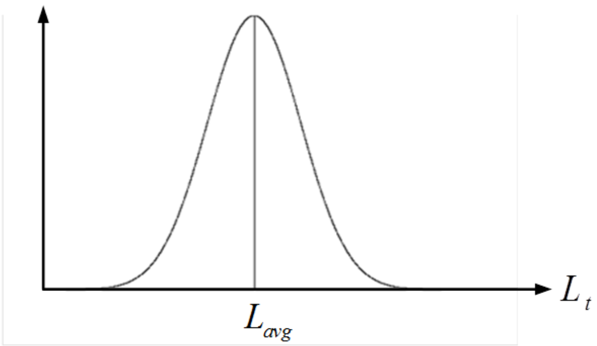

Fig.13: *Load model.*

[12] explained by the normal distribution as shown in "Fig. 13".

$$L_t = L_{avg} + Z \times (0.6\sqrt{L_{avg}} \quad (18)$$

where L_t, L_{avg} and Z are load at time t, average load, and a normally distributed random number.

5. RELIABILITY EVALUATION

It should be noticed here again that the dependable capacity of the renewable energy power plant is determined using renewable energy model, generator model, and load model. All of these models are then used in the reliability evaluation in order to compare the level of generation system reliability between the cases of system with renewable energy power plant and with conventional power plant.

The reliability index relayed to Loss of Load Probability (LOLP) is used as the key indicator to define the dependable capacity. The LOLP can be calculated from the results obtained from the Monte Carlo simulation using (19) [11],

$$LOLP = \frac{\sum_t^T d(P_t < L_t)}{T} \quad (19)$$

where $d(P_t < L_t)$ is duration of the event that total output power of all generators is less than load at that time and T is total simulated time period.

6. DEPENDABLE CAPACITY EVALUATION OF THE RENEWABLE ENERGY POWER PLANT

The conceptual idea of the proposed method to evaluate the dependable capacity of the renewable energy power plant focused only on the solar PV and wind power are summarized as a flowchart illustrated in "Fig. 14". It starts from simulating the ambient conditions which are the wind speed in the case of the wind power plant and the solar irradiance and the ambient temperature in the case of the solar PV. Subsequently, the output power of the renewable energy power plant is calculated. After that the system load is then simulated. Next, the operating statuses, UP and DOWN, of all generating units in the system including that of the renewable energy power plant are then simulated. These data will then be used in the generation system reliability assessment, and the LOLP is then determined. These processes are iteratively performed until the LOLP of the cases of the renewable energy power plant and the conventional power plant have the same LOLP. The dependable capacity is then defined as the equivalent capacity of a conventional power plant that yields the same level of LOLP when added to the generation system.

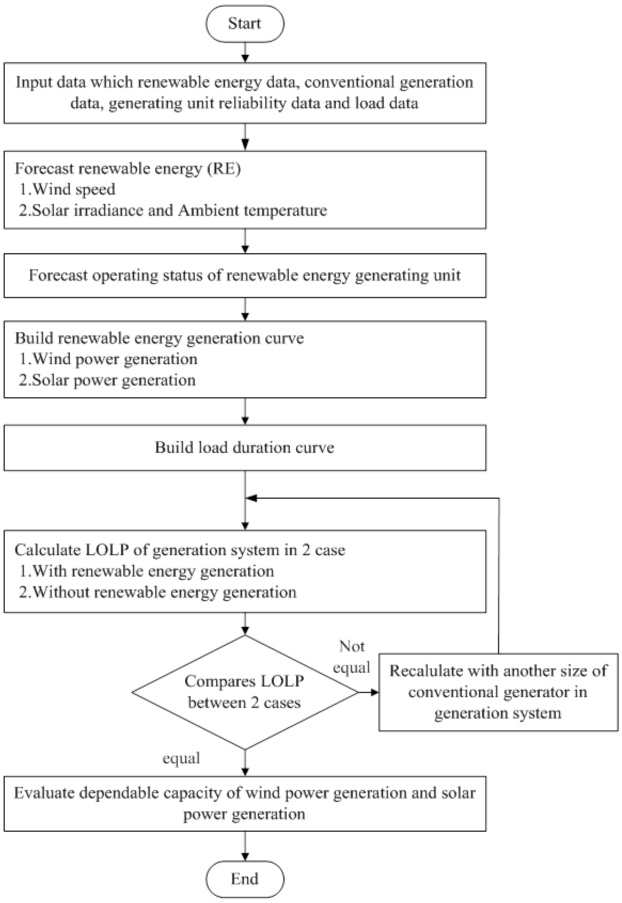

Fig.14: *Flowchart of the dependable capacity evaluation of wind and solar PV power plants.*

7. RESULT

The dependable capacity evaluation method for wind and solar PV power plants proposed in this paper was tested. The simulation time is 10 years and the average peak load of the system is 10 MW. Sum of the installed capacity in generation system equals to the average peak load. Besides, μ, λ of the conventional generator of this test system are 0.47 f/yr. and 0.03 r/yr., respectively.

Table 1: *Data of BWC EXCEL-R/240.*

Rated Power	10	kW
Cut-in Wind Speed	3.1	m/s
Rated Wind Speed	12.1	m/s
Cut-out Wind Speed	25.0	m/s

Table 2: *Data of NORDTANK NTK150XLR.*

Rated Power	150	kW
Cut-in Wind Speed	4.0	m/s
Rated Wind Speed	13.0	m/s
Cut-out Wind Speed	25.0	m/s

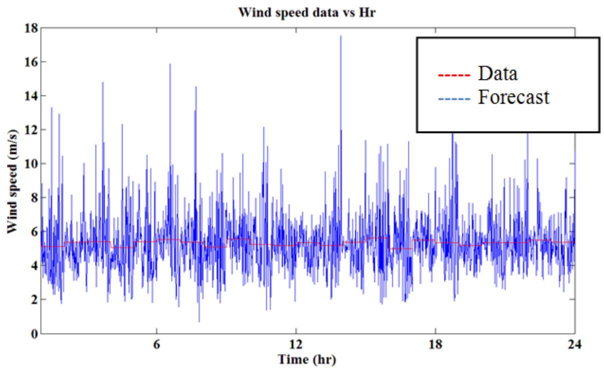

Fig.15: *Wind speed forecast from simulation.*

7.1 Test Results for Wind Power Generation and Solar Power Generation

In wind power generation, test system consists of 3 wind turbine generators which are 150 kW and 2x10 kW. μ, λ of these generators for this test system are 0.49 f/yr. and 0.01 r/yr. respectively. Data of wind turbine generator can be shown in the following tables [13].

The result for wind speed model that is used in this paper can be shown in “Fig. 15”, the output power from 2 wind turbine generators can be shown in “Fig. 16-17”.

In solar power generation, test system is similar to the test system of wind power generation. It consists of 2 types of solar cell arrays which are polycrystalline and amorphous silicon cells. Total installed capacity of the solar power plant is 1.012 MW [13] and μ, λ of these generators for this test system are 0.49 f/yr. and 0.01 r/yr., respectively.

The result for solar irradiance and ambient temperature models used in this paper can be shown in “Fig. 18” and “Fig. 19”, and the output power from solar power generation can be shown in “Fig. 20”.

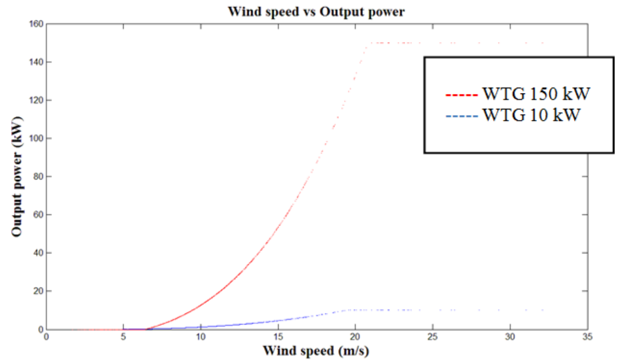

Fig.16: *Output power from 2 wind turbine generators.*

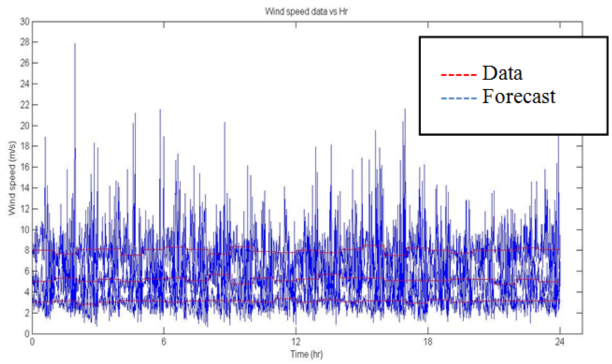

Fig.17: *The output power from a wind power generation.*

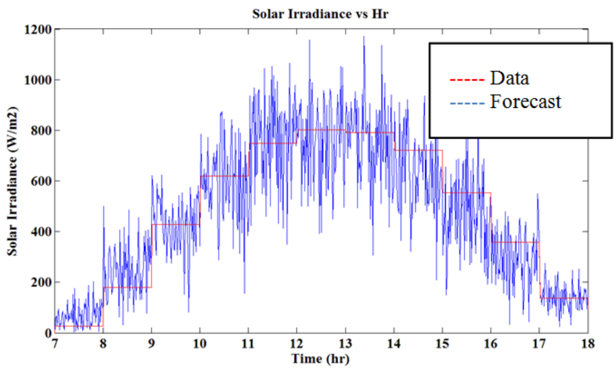

Fig.18: *Solar irradiance forecast from simulation.*

7.2 Test Results for Dependable Capacity Evaluation

The dependable capacity evaluation method is tested with the variation level of renewable energy such as 50%, 100%, and 150% of the nominal output rating. The results of dependable capacity evaluation of wind power generation (Wind) and solar power generation (Solar) are shown in Table 3.

From Table 3, at 100% level of nominal output power (at standard ambient condition) or at the base case, the dependable capacity of wind and solar power

Table 3: *Result of Dependable Capacity Evaluation.*

Level of nominal output rating	Plant Factor (%)		Dependable Capacity(%)	
	Wind	Solar	Wind	Solar
50%	0.6161	10.0516	0.4364	11.0516
100%	10.5366	18.5878	9.3004	20.1066
150%	33.3235	24.9029	31.7857	27.7874
200%	59.6549	28.9378	59.1873	32.1102

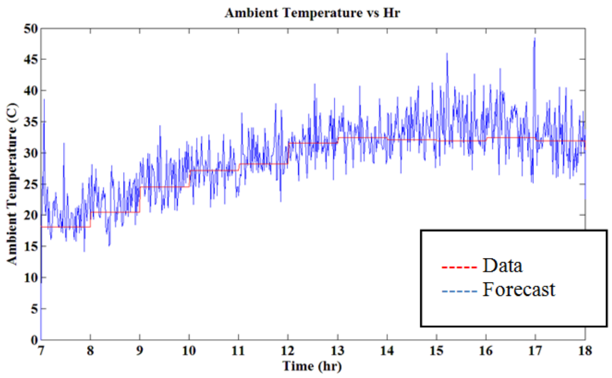

Fig.19: *Ambient temperature forecast from simulation.*

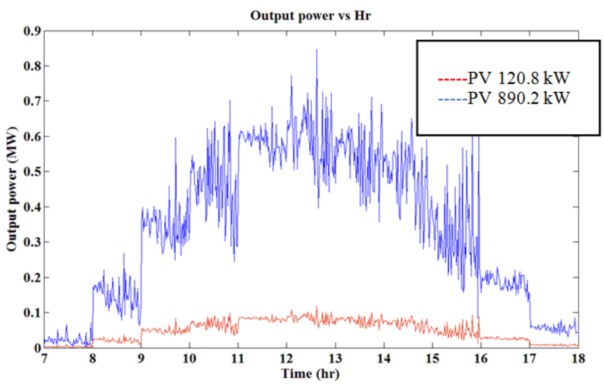

Fig.20: *Output power of the PV system from simulation.*

plants are 9.3% and 20.11%, respectively. However, higher level of nominal output rating can lead to higher dependable capacity. For example, at 200% level of the normal ambient condition, it shows that the wind speed is 200% higher than expected. With this speed, the wind power plant can behave like a conventional power plant with approximately 60% dependable capacity.

8. CONCLUSION

The purpose of this paper is to evaluate the dependable capacity of renewable energy generation including wind power generation and solar power generation.Considering both of the uncertainties of renewable energy and unavailability of its corresponding generator. Load uncertainty is also taken into account. The dependable capacity of renewable energy generation will then be determined from reliability indices which is Loss of Load (LOLP).

The result shows that the dependable capacity of wind power generation and solar power generation are 9.3% and 20.11% of its installed capacity respectively. Increasing level of renewable energy can increases dependable capacity and plant factor of renewable energy generation.

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