Reliability Analysis of Hybrid Energy System

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Abstract - A hybrid energy system integrates renewable energy sources like wind, solar, micro-hydro and biomass, fossil fuel power generators such as diesel generators, and energy storage. Hybrid energy system is an excellent option for providing electricity for remote and rural locations where access to grid is not feasible or economical. Reliability and cost-effectiveness are the two most important objectives when designing a hybrid energy system. One challenge is that the existing methods do not consider the time-varying characteristics of the renewable sources and the energy demand over a year, while the distributions of a power source or demand are different over the period, and multiple power sources can often times complement one another. In this paper, a reliability analysis method is developed to address this challenge, where wind and solar are the two renewable energy sources that are considered. The cost evaluation of hybrid energy systems is presented. A numerical example is used to demonstrate the proposed method.

1. Introduction

One of the key strategies to achieve a sustainable environment is the utilization of the renewable energy systems (or RES for short) and keeps the system more reliable. Recently, the United Nations named 2012 as the year of renewable energy and put pressure on countries to reduce greenhouse gases with the aim of achieving a sustainable environment as a long-term goal.

In addition, based on International Energy Agency report (Energy Technology Perspectives 2010), it is estimated that over 20% (1.4 billion) of global population has lack of access to electricity. So the importance of using renewable energy systems in remote area is quite significant. A hybrid energy system (HES) integrates renewable energy sources like wind, solar, micro-hydro and biomass, fossil fuel power generators such as diesel generators, and energy storage. Hybrid energy system is an excellent option for providing electricity for these remote and rural locations where access to grid is not feasible or economical (Sreeraj et al. 2010).

But these resources have variable characteristics which depend on their nature. For example, the climate changes affect wind's speed, direction and its velocity. Likewise, the mean and variance of speed, direction and velocity of wind are typically larger in winter and spring, but smaller in summer (Klink 1999; Tuller 2004). In addition, there is no sun during night, and during the daytime the light intensity is related to several factors such as cloud, air dust and sand storm in desert location (Sreeraj et al. 2010; Park et al. 2009). Due to such intermittent nature of renewable power sources, there is large uncertainty in renewable power generations. Thus, it is a key consideration to ensure that the power generation can reliably meet the demand.

Reliability is generally defined as the probability that the hybrid energy system meets the electricity demand. The existing methods do not consider the time-varying characteristics of the renewable sources and the energy demand over a year, while the mean and variance of a power source or demand are different over the period, and multiple power sources can often times complement one another. That is, for a certain power source or demand, it is not accurate to use the same mean and variance to describe it at different times in a year. A reliability analysis method is developed in this paper to address this challenge.

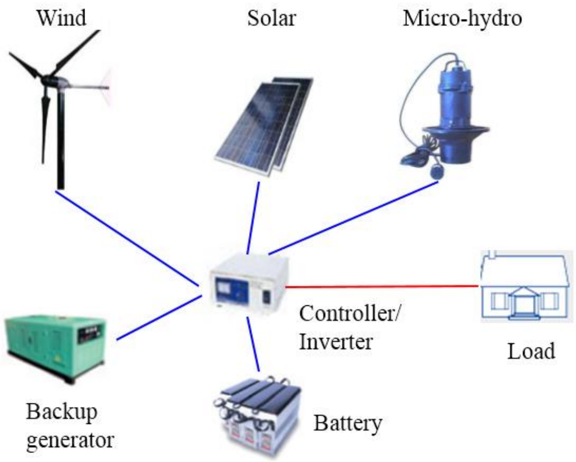

Fig.1. General Structure of HES

2. System components and the proposed method

Fig.1 shows a general structure of HES, which consists of renewable energy sources such as wind turbine, solar PV array and micro-hydro, battery, backup generator, system controller and inverter. The system generates electricity to meet the demand. The HES obeys dispatch strategy during its life time. So, first the power generated by HES will be used to meet the demand, and in any case that there is power surplus, it will charge the battery and the remaining power will be sent to dump load. Then, the surplus power which is stored in battery can cover the extra demand later when the RES power generation is lower than the demand at those points. In addition, a conventional generator can be used in any case when the RES and battery cannot meet the demand.

In the proposed reliability analysis method for HES, to consider the time-varying characteristics of renewable power, for a renewable power source (e.g. wind), a random variable is used to represent the power output for each month. That is, we will have 12 random variables for each renewable power source. The random variable is wind speed for wind power, and solar irradiation for solar power. In the next section, we will present how to compute the energy output for HES.

3. Energy output computation

3-1.Wind formula

The wind power output can be calculated using the formula presented in Jin and Tian (2010):

$$\mathrm{P(x)} = \begin{cases} 0, & \text{if } \mathrm{x} < v_c\,, \mathrm{x} > v_s \\ 0.5\eta_{max}\rho A x^3, & \text{if } v_c \le x \le v_r \\ Pr, & \text{if } v_r \le x \le v_s \end{cases} \tag{1}$$

where $P(x)$ is the generated wind power. Vc is cut-in speed, Vr is rated wind speed, Vs is cut-off speed, η efficiency of turbine, ρ is the air density, $A = \pi r^2 = \pi(\frac{D^2}{4})$ is the area covered by the wind turbine blades and Pr is rated power.

3-2. Solar formula

The solar power generation can be calculated based on the general formula presented by Sreeraj et al. (2010):

$$\mathrm{P} = \eta\ A\ \mathrm{G_T} \tag{2}$$

where η is efficiency of PV generator, G_T is global irradiation and A is area of the PV array.

In the formula above, the efficiency of a PV module is actually depending on the irradiance with a nonlinear relationship. Thus, if it is set based on STC conditions, in a real case, errors will present at the range lower than

$1000\ \frac{W}{m^2}$ irradiance, which are a considerable proportion within a day. So, considering the nonliner relationship between efficiency and irradiation, the following formulas can be used:

$$\eta = \eta_{T_{ref}}\ [1\text{-}\ \beta_{ref}\ (T_c\ \text{-}\ T_{ref}) + \gamma\ log_{10}G_T] \quad \text{(Noton et al. 2005)} \tag{3}$$

$$\eta = \eta_{T_{ref}}\ [1\text{-}\ \beta_{ref}\ (T_{ci}\ \text{-}\ T_{ref}) + \gamma\ log_{10}I_i] \quad \text{(Evans 1981) \& (Cristoferi et al. 1981)} \tag{4}$$

By substituting formula (3) in (2),

$$P = \eta_{T_{ref}}\ [1\text{-}\ \beta_{ref}\ (T_{ci}\ \text{-}T_{ref}) + \gamma\ log_{10}G_T]\ A\ G_T \quad \text{(Cristofari et al. 2006)} \tag{5}$$

where $\eta_{T_{ref}}$ is the reference PV electrical efficiency, β_{ref} is temperature coefficient, T_{ci} is PV cell temperature, T_{ref} is reference temperature, and γ is solar radiation coefficient.

3-3. Battery formula

The following key equations are used to describe battery in a hybrid energy system (Mostofi and Shayeghi 2012):

$$\Delta\ P(t) = P_{ren}(t) - P_{load}(t) \tag{6}$$

where $P_{ren}(t)$ is the total power generated by renewable generators, and $P_{load}(t)$ is total power consumption.

During charging, $\Delta\ P(t) > 0$, and in discharging time, $\Delta\ P(t) < 0$.

$$SOC(t+1) = SOC\ (t) +\ \eta_{bat}\ \left(\frac{P^i_{bat}(t)}{V_{bus}}\right) \Delta t \tag{7}$$

where state of charge, or $SOC\ (t)$ for short, is the amount of power stored in the battery in day *t*, η_{bat} is the battery efficiency, V_{bus} is the voltage of the bus in the battery, and $P^i_{bat}(t)$ is the total power stored in the battery in day *t*.

4. Renewable power output analysis

4-1. Probability distribution of wind speed

Considering the random characteristic of wind speed, it is desirable to describe it with statistical models. Two types of wind speed models have been reported in the literature. The first type is normal distribution, which was reported by Haghifam and Omidvar (2006), and Karki et. al (2006), and its probability density function is given as follows:

$$f(x) = \left[\frac{1}{\sigma\sqrt{2\pi}}\ exp - \left(\frac{(x-\mu)^2}{2\sigma^2}\right)\right] \tag{8}$$

where x is wind speed, μ and σ are mean and standard deviation of wind speed, respectively. The second type is Weibull distribution, which was reported by Vallee et. al (2007), Spahic et. al (2008) and Haghifam and Omidvar (2006). Its probability density function is given as follows:

$$f(x) = \frac{\beta}{\alpha^\beta} t^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^\beta},\ \ t \geq 0 \tag{9}$$

where α is the scale parameter, β is the shape parameter. The majority of the studies show that Weibull distribution is more suitable for modeling wind speed. The case study in this paper, to be presented later, also shows that Weibull distribution is the best type for modeling wind speed data used in this case study. It is suggested that probability plotting can be done first given the available wind speed data, so as to identify the most suitable distribution type.

Based on Equation (1), and the wind speed probability distribution, the corresponding wind power output and its associated uncertainty can be calculated. The wind power output can then be used in reliability evaluation of hybrid energy systems.

4-2. Probability distribution of solar irradiation

For solar irradiation, some believe that it follows Beta distribution. But in a continued period it can be considered as normal distribution (Zhang et al., 2011):

$$f(G_T) = \left[\frac{1}{\sigma\sqrt{2\pi}}\ exp - \left(\frac{(G_T-\mu)^2}{2\sigma^2}\right)\right] \tag{10}$$

where G_T is solar irradiation, μ and σ are mean and standard deviation of G_T, respectively.

The solar power output mean and variance can be evaluated using the following formulas (Zhang et al. 2011):

$$f(P_{pv})=(\frac{1}{\delta_{GT}\sqrt{2\pi}})*(e^{-\frac{(\frac{P}{A\eta_{Tref}-A\eta_{Tref}\beta_{ref}(T_{ci}-T_{ref})}-\mu_{G_T})^2}{2\sigma_{G_T}^2}} * (\frac{1}{A\eta_{Tref}-A\eta_{Tref}\beta_{ref}(T_{ci}-T_{ref})}) \quad (11)$$

$$M(p) = \int_{p=0}^{p=Max} P\, f(P_{pv})dp \quad (12)$$

$$Var(p) = \int_{p=0}^{p=Max} (P-\mu)^2 f(P_{pv})dp \quad (13)$$

$$Var(p) = M(P^2) - (M(p))^2$$

where P is the power output by PV array from Eq. (5), and γ is considered zero here (Cristofari et al. 2006; Nottton et al. 2005). $f(P_{pv})$ is probability density function of the power output.

5. System reliability and cost assessment

To assess system reliability, different approaches and indices can be used (Phoon, 2006), as shown in Fig.2. Among these indices, two of the most common indices for measuring power system reliability are Loss of Load Probability (LOLP) and Loss of Load Expectation (LOLE). LOLE is the number of days per year when daily peak demand passes available power generating capacity, and LOLP is overall probability that there will be a shortage of power (Allan and Billinton, 1996). These two indices are used in this paper to measure power system reliability.

LOLP is a key measure of power system reliability, and it is defined as:

$$\text{LOLP} = P(Y \geq D) \quad (16)$$

where Y is the total power output considering the power contributions from wind, solar and battery. D is the power demand level, which is assumed to be a constant in this work. The relationship between these two is given as follows (Phoon, 2006):

$$\text{LOLE} = \text{LOLP} \times \text{T} \quad (17)$$

where T = 365 days, if the load model is an annual continuous load curve with day maximum load. In this case, the LOLE unit is days per year. T can also be equal to 8760 hours, if the load model is an hourly load curve. In this case, the LOLE unit is hours per year. To calculate LOLE, we need to compare hourly or daily power generation with the corresponding hourly or daily load demand (Mabel et al. 2011, Kumar et al. 2011).

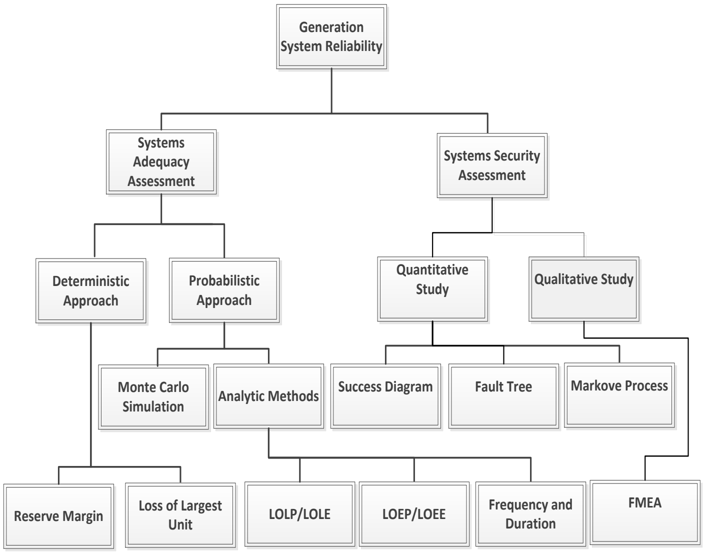

Fig. 2. system reliability assessment indices (Phoon, 2006)

In this work, a simulation approach is used for system reliability evaluation. The random variables representing the wind speed and solar irradiation can be obtained using the methods presented in Section 4. During the simulation process for system reliability evaluation, wind speed and solar irradiation values are sampled from the random variables, and the corresponding power generated from these sources can be calculated. The way to consider battery charging and discharging processes are also presented earlier in Section 3. During a certain short period, the generated renewable energy plus the battery is compared with the electricity demand, and it can be found if the system can meet the demand during that interval. The overall system reliability can be evaluated using this simulation process.

In this work, we also perform cost evaluation for hybrid energy systems. The method presented in Yang et al (2008) is used for cost evaluation. Three cost factors are considered: initial components costs, operations & maintenance costs, and interests. Initial component costs include costs of hybrid energy system components, such as PV array, wind turbines, battery, tower, etc. Operations and maintenance cost is considered to be constant in a year, and it is dependent on the rated capacities of the renewable energy components. A hybrid energy system is typically used for a long period of time, and thus interest is considered to account for the time value of money.

6. An example

To find wind speed and solar irradiation, the raw data was retrieved from Renewable Energy Organization of Iran, for a location that called Eshtehard. And we investigate the reliability corresponding to different demand levels for individual houses.

The following parameters are used for HES. In this example, we only consider wind, solar, battery and inverter for reliability analysis. Other factors will be considered in future research. The battery capacity is assumed to be 1000 Ah, and the inverter efficiency is 0.92. Other data is presented in Table 1, based on (Nottton et al. 2005).

Table 1- Amount of different parameters

	parameters	amount
Wind turbine	V_C	3 m/s
	V_r	14 m/s
	V_s	25 m/s
	η	30%
	ρ	1.2 $\frac{kg}{m^3}$
	D	10 m
	r	5 m
Solar PV array*	$\eta_{T_{ref}}$	0.13
	A	60 m^2
	β_{ref}	0.0044 $°C^{-1}$ for pc-si
	T_{ci}	38°C
	T_{ref}	25°C
	γ	0.12 (usually consider 0)

Based on the data available in this case study, first we need to verify the type of distribution that the wind speed follows. Applying probability plotting to the wind speed data in all the 12 months, it is found that Weibull distribution is the suitable type to model the wind speed data in this case study, while normal distribution can not fit the data well. A sample probability plot for the wind speed data in January is given in Fig. 3. Subsequently, Weibull parameters are estimated for each month, and wind speed distribution is obtained for each month. The Weibull distribution probability density function for January, as an example, is presented in Fig. 4. As described in Section 4, wind power output can be calculated based on wind speed. The wind power output monthly average is presented in Fig. 5. We can clearly see the variations in the wind power output in different months.

Similarly, based on the methods presented in Section 4, solar power can be calculated based on the solar irradiation data. The calculated solar power output monthly average is plotted in Fig. 6. We can see the solar power output differences among different month. It can also be observed that there is higher solar power output in the summer, which is expected.

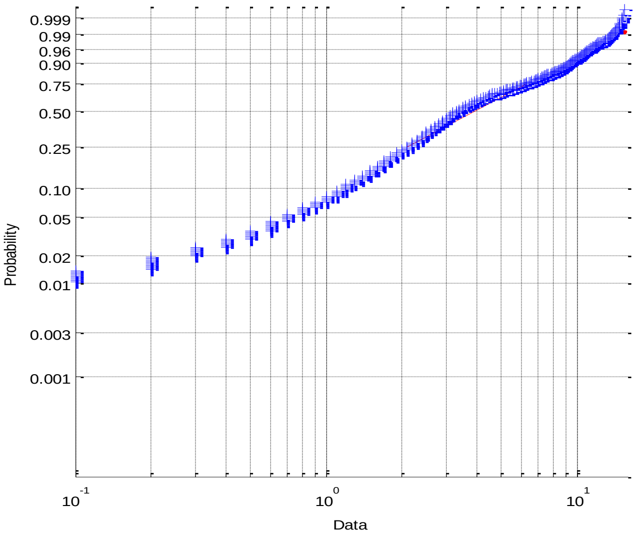

Fig. 3. Wind speed data probability plot (January)

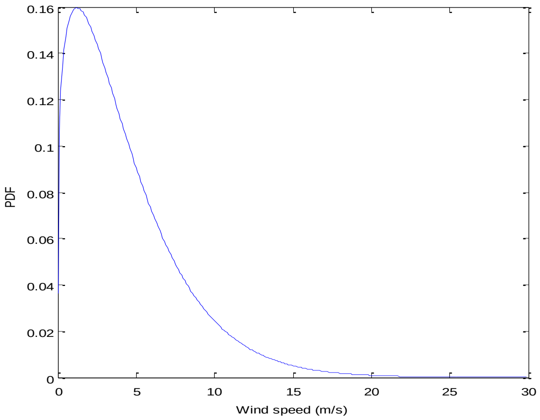

Fig. 4. Weibull distribution probability density function for January

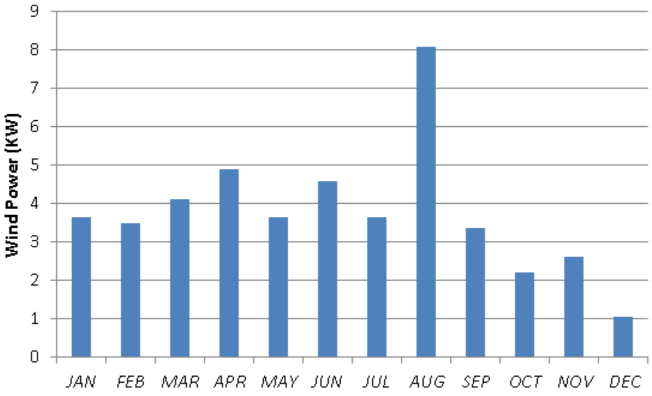

Fig. 5. Wind power output monthly average

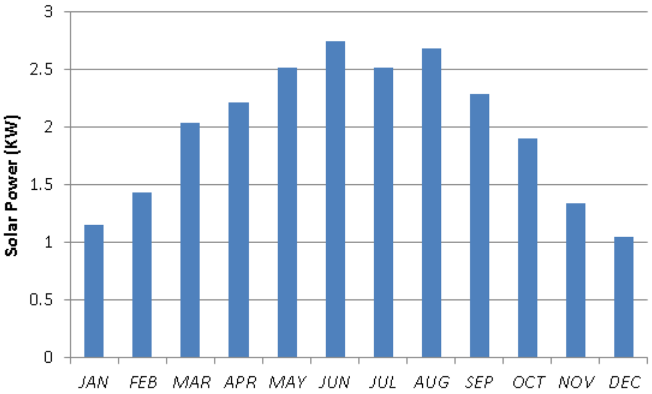

Fig. 6. Solar power output monthly average

In this paper, we assume the demand is constant. We investigate the reliability of the HES corresponding to different demand levels. The results are shown as follows:

- Demand level #1: 30 KWh/day
  - LOLP = 0 (or LOLE =0 days/year)
- Demand level #2: 60 KWh/day
  - LOLP = 0.0045 (or LOLE =1.67 days/year)
- Demand level #3: 80 KWh/day
  - LOLP = 0.025 (or LOLE =9.22 days/year)
- Demand level #4: 100 KWh/day
  - LOLP = 0.058 (or LOLE =21.0 days/year)

As can be seen from the results, the HES in this example has no problem in meeting demand at 30 KWh/day or lower. When the demand is high, HES with higher wind and solar power generating capacities will be needed to meet the customer demand in a reliable way.

When evaluating the cost of the hybrid energy system, we use the same data presented by Yang et al (2008). For the convenience of readers, the data used in this paper is summarized in Table 2. For the hybrid energy system considered in this example, the total initial cost is calculated to be 566,310 US$, and the Net Present Value (NPV) over 15 years is 686,130 US$.

Table 2: component costs (Yang et al 2008)

Component	Initial component cost	Operations and maintenance cost
PV array	6,500 US$/KW	65 US$/KW
Wind turbine	3,500 US$/KW	95 US$/KW
Battery	1,500 US$/KAh	50 US$/KAh
Tower	250 US$/m	6.5 US$/m
Other components	8,000 US$	80 US$

7. Conclusions

It is important that power system provide sufficient and reliable power to the customers. Hybrid energy system is an excellent option for providing electricity for these remote and rural locations where access to grid is not feasible or economical. Reliability and cost-effectiveness are the two most important objectives when designing a hybrid energy system. One challenge is that the existing methods do not consider the time-varying characteristics of the renewable sources and the energy demand over a year, while the mean and variance of a power source of demand are different over the period, and multiple power sources can often times complement one another. A reliability analysis method is developed in this paper to address this challenge, and a numerical example is used to demonstrate the proposed method, as well as cost evaluation of hybrid energy systems. In future research, we will consider other power sources and varying demand, as well as the optimal design of hybrid energy systems.

References:

[1]. R. Allan, R. Billinton. Reliability Evaluation of Power Systems, Springer, 1996.

[2]. Chompoo-inwai C., Leelajindakrairerk M., Banjongjit S., Fuangfoo P., Lee W.-J., "Design optimization of wind power planning for a country with low–medium-wind-speed profile," IEEE Transactions on Industry Applications, Vol. 44, No. 5, pages 1341-1347, 2008.

[3]. Cristofari C., Poggi P., Notton G., Muselli M., "Thermal modeling of a photovoltaic module", Proceedings of Sixth IASTED International Conference on "Modeling, Simulation, and Optimization", Gaborone, Botswana, Pages 273–278, 2006.

[4]. Evans, D.L., "Simplified method for predicting photovoltaic array output", Solar Energy, Vol. 27, No.6, Pages 555-560, 1981.

[5]. Haghifam M.-R., Omidvar M., "Wind farm modeling in reliability assessment of power system," Proceedings of the International Conference on Probabilistic Methods Applied to Power Systems, pages 1-5, 2006.

[6]. Jin T and Tian. Z., "Uncertainty Analysis for Wind Energy Production with Dynamic Power Curves", 11th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Singapore, Pages 745-750, 2010.

[7]. Karki R., Hu P., Billinton R., "A simplified wind power generation model for reliability evaluation," IEEE Transaction on Energy Conversion, Vol. 21, No. 2, pages 533-540, 2006.

[8]. Klink K., "Climatological Mean and Interannual Variance of United States Surface Wind Speed, Direction and Velocity", International Journal of Climatology, Vol.19, No.5, Pages 471- 488, 1999.

[9]. Kumar A., Zaman. M. Goel Nita., Goel Nishit, Church R., "Environmental impact on optimization analysis for standalone and hybrid power generating units", IEEE CCECE, Niagara Falls, Canada, Pages: 000994 – 000998, 2011.

[10]. Mostofi F. and shayeghi H., "Feasibility and Optimal Reliable Design of Renewable Hybrid Energy System for Rural Electrification in Iran", International Journal of Renewable Energy Research, Vol.2, No.4, 2012.

[11]. Notton G., Cristofari C., Mattei M., Poggi P., "Modeling of a double-glass photovoltaic module using finite differences", Applied Thermal Engineering, Vol.25, No.17–18, Pages 2854–2877, 2005.

[12]. Park J., Liang W., Choi J., "A Probabilistic Reliability Evaluation of a Power System Including Solar/Photovoltaic Cell Generator", Power & Energy Society General Meeting, IEEE, Pages 1-6, 2009.

[13]. Phoon H.Y., "Generation system reliability evaluations with intermittent renewables", a thesis of Master of Science in energy systems and the environment, University of Strathclyde, 2006.

[14]. Renewable Energy Organization of Iran, "Wind statistics and the wind atlas stations", http://suna.ir/ationoffice-windenergyoffice-windamar-fa.html.

[15]. Sreeraj E.S., Chatterjee K., Bandyopadhyay S., "Design of isolated renewable hybrid power systems", Solar Energy, Vol.84, No.7, pages 1124-1136, 2010.

[16]. Tuller S.E., "Measures Wind Speed Trends on the West Coast of Canada, International Journal of Climatology", International Journal of Climatology, Vol.24, Pages 1359-1374, 2004.

[17]. Vallee F., Lobry J., Deblecker O., "Impact of the wind geographical correlation level for reliability studies," IEEE Transactions on Power Systems, Vol. 22, No. 4, pages 2232-2239, 2007.

[18]. Yang H., Zhou W., Lu L., Fang Z. "Optimal sizing method for stand-alone hybrid solar-wind system with LPSP technology by using genetic algorithm". Solar Energy, Vol. 82, No. 4, Pages 354-367, 2008.

[19]. Zhang Z., Li G., Wang S., Wang J., Wang Z., "Stochastic Evaluation of Voltage in Distribution Networks Considering the Characteristic of Distributed Generators", IEEE, Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 4th International Conference, Pages 1132- 1137, 2011.

Brief Bio:

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