A Probabilistic Approach to Assess the Adequacy of Wind and Solar Energy

Sampurna Das[1], Samita Rani Pani[2], Pawan Kumar Modi[1]

[1]Department of Electrical Engineering, VSSUT Burla, Sambalpur, Odisha, India

[2]School of Electrical Engineering, KIIT University, Bhubaneswar, Odisha, India

E-mail: sampurnadas2014@gmail.com, panisamita@gmail.com, pkmodiphd@rediffmail.com

***Abstract*— Wind energy will become important source for power generation in the near future followed by solar energy. However, these sources are unstable and variable energy, and behave in a different way to conventional sources. This paper incorporates wind and solar energy in reliability evaluation of generation system as renewable power penetration become increasingly significant. Suitable techniques are used for modeling of wind turbine generator and solar cell generator. The effect of increasing power penetration level on their respective model is studied. Comparative results for wind and solar generation model are presented at different penetration level. Capacity credit is also calculated for each source. The effects of increasing power penetration on the capacity credit values are analyzed. The analysis states that capacity benefit from renewable energy sources (RES) are relatively reducing at higher penetration level.**

***Index Terms*— Generation system, reliability, multi-state model, wind energy, solar energy.**

I. Introduction

THE utilization of renewable energy sources have been receiving significant consideration in recent time [1]. Due to the variable nature of sources the output power of wind turbine generator (WTG) and solar cell generator (SCG) can vary over a wide range between zero and the rated capacity randomly [2]. The generation models of conventional units are suitably represented by using two states in reliability study. A state of a generating unit is nothing but a capacity level and the associated probability of its existence. However, this model is not appropriate to represent the variable energy as an operational model because the wind speed and solar radiation can't be continued at a stable power output level. These variable energy sources have more number of power output states in addition to UP and DOWN states. Fig. 1 describes the multi-state operational model. As it is seen in the figure, multi-state operation of renewable sources are sequential (i.e. switching of state from first to last without being intermediate states can not be followed). Transition from down to up state occur with repair of unit and reverse transition is followed by failure of unit. Here, μ represents unit repair rate and λ represents unit failure rate.

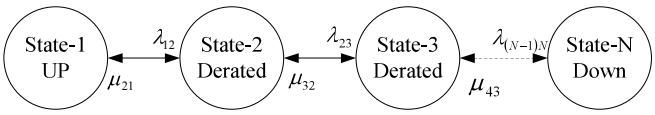

Fig. 1. A multi-state operational model of a variable source

It is very important to accurately represent wind speed and solar radiation characteristics. It has been shown in [3], [4] that the long term characteristics of wind of a particular wind site can be represented using time series model. A common wind speed model is developed in [5]-[6] for any geographical location lacking adequate historical data. Additionally, the probability distribution function (PDF) of solar radiation is constructed using a decomposition model explained in [7].

Taking into account the constantly changing output power from a generating unit, they are modeled using more number of derated states. The multi-state model of WTG is formed in [8] by combining the wind speed model and power output model. Similarly, SCG multi-state model is developed by integrating solar radiation characteristics with power output characteristics of SCG [9].

The effect of wind penetration level on the multi-state model of WTG is studied. The result showed that with increasing penetration level the required number of state in WTG model increased [10]. There are only few research works available on the effect of solar penetration level on SCG modeling.

In this paper the effect of increasing solar penetration level on the SCG model is studied using a basic reliability test system. At different penetration level comparison of WTG and SCG model is presented.

Capacity credit indicates how much a new power plant can be dependent upon. As known variable energy sources are not dependable. So, capacity credit is a measure of increase in peak load carrying capability of the system [11] or how much conventional generation it can allow to be shut down in the system [12]. This paper includes evaluation of capacity credit for RES. Effect of increasing penetration level on capacity credit values is also studied.

II. Modeling of Renewable Resources

This section explains the generation of hourly wind speed and hourly solar radiation data and their probability of distribution.

A. Hourly Wind Speed Modeling

Hourly wind speed values can be produced if annual average wind speed (μ) and standard deviation (σ) values are known for a particular wind site. Following steps are used to develop

978-1-4799-5141-3/14/$31.00 ©2016 IEEE

hourly wind speed model considering probability distribution of wind speed is normal.

- Generate wind speed values randomly in the range $(\mu \pm 5\sigma)$ using normal pdf. This distribution ensures including extreme wind speed values regardless of their less probability of occurrence.
- Repeat the previous step till wind speed is generated for hourly wind speed model.
- Divide the total wind speed range into N interval, and each step has a length of $\frac{10\sigma}{N}$.
- The centre points of each interval are represented by WB_i ($i = 1,2,\ldots\ldots N$). The midpoint values are given in (1).

$$WB_i = \begin{cases} \mu + (10\sigma/N)\times(i - 0.5\times N) & even\ N \\ \mu + (10\sigma/N)\times(i - 0.5\times(N+1)) & odd\ \ N \end{cases} \quad (1)$$

- The probability of each step P_i, ($i = 1,2,\ldots\ldots N$) are calculated using (2).

$$P_i = \frac{N_i}{N_t} \quad (2)$$

Where, N_i is the number of simulated wind speed data in the step WB_i ($i = 1,2,\ldots\ldots N$)

N_t -Total number of simulations for wind speed data.

- Now each wind speed band is represented by a wind speed value and its corresponding probability. The intervals which have negative wind speed value are converted to zero as they don't have any physical meaning.

B. Hourly Solar Radiation Modeling

Unlike wind speed, solar radiation can't be modeled using pdf. Probability distribution function is utilized to describe variables which are completely random. In case of solar radiation which is certain to be zero at the night time can't be described using pdf. In this work hourly solar radiation value are estimated using decomposition model. Decomposition model use the known global solar radiation data on horizontal surface to predict the direct and diffuse radiation component and from that radiation received by inclined surface is estimated. In this paper monthly average daily solar radiation data was used to generate hourly solar radiation data. The daily average solar radiation data is collected from the website of atmospheric science data center (A renewable energy resource website supported by NASA research center).

Given latitude and longitude of location are 22.567N and 88.367E, Fig. 2 shows probability distribution of solar irradiation. The pdf is plotted in semi-logarithmic scale in order to view the pattern in more detail.

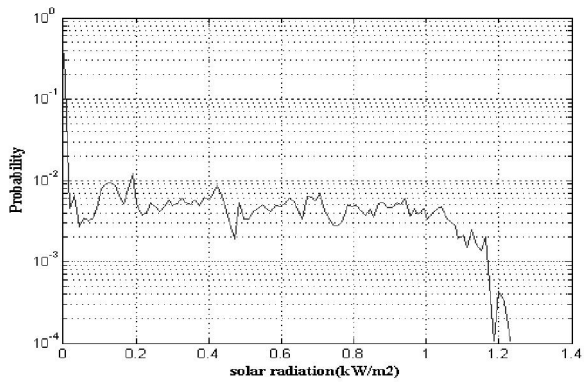

Fig. 2. Semi-logarithmic pdf of solar radiation on inclined plane

Fig. 2 shows the probability of zero solar radiation is 0.56. It is because half of the distribution is zero

III. CALCULATION OF OUTPUT POWER OF WTG AND SCG

This section explains the calculation of output power of the SCG and WTG corresponding to each state using respective power performance curve.

A. Calculation of WTG Output Power

Wind power output and wind speed has a nonlinear relationship. Power output from a WTG mainly depends upon available wind energy and on the WTG parameters. The design parameters of the WTG are cut in wind speed (V_{ci}), cut out wind speed (V_{co}), rated wind speed (V_r) and the rated power of WTG (P_r). The power output characteristic of WTG is shown in Fig. 3 and can be mathematically formulated as in (3).

$$P = \begin{cases} 0 & 0 \le WB_i < V_{ci} \\ A + B\times WB_i + C\times WB_i^2 & V_{ci} \le WB_i < V_r \\ P_r & V_r \le W_i \le V_{co} \\ 0 & V_{co} < W_i \end{cases} \quad (3)$$

WB_i is the wind speed in the ith band

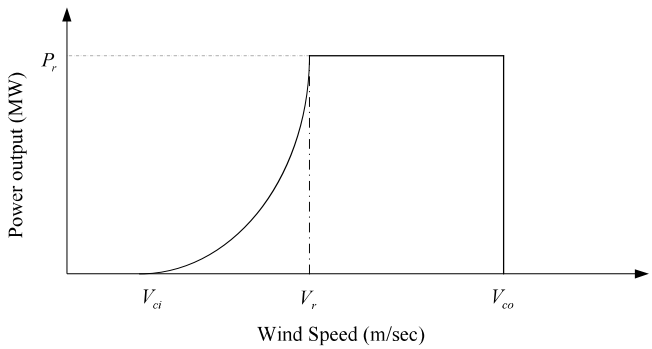

Fig. 3. Power Curve of WTG

The constants A, B and C are formulated in [13].

B. Calculation of Output Power of SCG

The solar cell power output model [14] can be obtained by multiplying the solar irradiation by its efficiency as in (4).

$$P_i(G_{bi}) = \begin{cases} P_{sn}\left(\dfrac{G_{bi}^2}{G_{std}R_c}\right) & 0 \le G_{bi} < R_c \\ P_{sn}\dfrac{G_{bi}}{G_{std}} & R_c < G_{bi} \le G_{std} \\ P_{sn} & G_{bi} > G_{std} \end{cases} \quad (4)$$

Where,

P_{sn} =Rated capacity of SCG (MW)

R_c =A certain radiation point set usually as 150 W/m^2

G_{bi} = Forecasted solar radiation at band i.

G_{std} = Solar radiation in the standard environment condition set usually as 1000 W/m^2 .

IV. Reliability Index

A. Expected Energy not Supplied

Expected energy not supplied (EENS) is the amount of energy (MWh) that could not be served by the generation system due to the insufficient generating capacity over load demand. The EENS is an appealing index as it measures the degree of deficiencies. The evaluation of EENS is illustrated in Fig. 4. The area under load duration curve is the total energy required in a particular time period. When a capacity level is greater than the reserve, energy curtailment occurs as shown by hatched area in Fig. 4. Mathematically, EENS can be represented using (5).

$$EENS = \sum_{k=1}^{n} E_k P_k \quad (5)$$

Where

O_k = Magnitude of capacity outage in interval k.

P_k = Probability of capacity outage equal to O_k

E_k = Energy curtailed due to capacity outage equal to O_k

P_k is obtained from the capacity outage probability table of generation system.

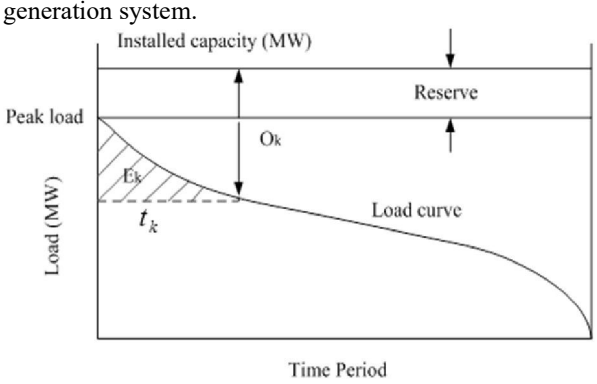

Fig. 4. Evaluation of EENS

B. Effective Load Carrying Capability

Effective load carrying capability (ELCC) is the additional load that can be supported by adding a new generating unit to the system. This index is easy to interpret as the system adequacy is realizable due to added capacity. The bold line and the dotted line in Fig. 5 indicate the characteristics before and after the addition of extra capacity respectively. The peak load carrying capability of the system has increased due to the addition of new generation for a fixed risk level as shown in Fig. 5.

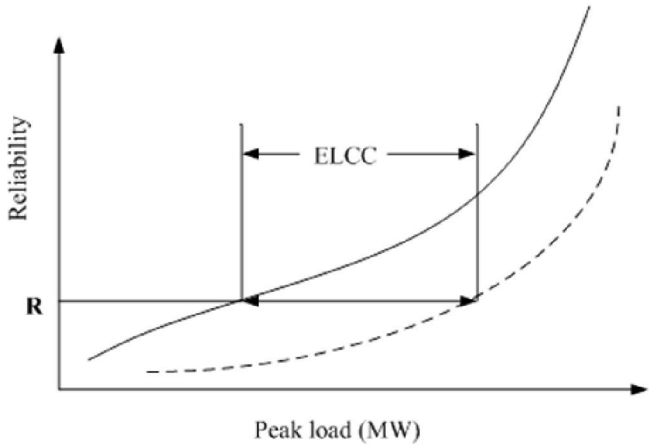

Fig. 5.Evaluation of ELCC

ELCC is utilized to calculate the capacity credit of generating source. Capacity credit is a measure of how much electricity any new power plant can be dependent upon. In case of variable energy sources which really can't be dependent upon, it is expressed as how much additional load that can be carried out. Mathematically capacity credit is expressed as in (6).

$$Capacity\ credit(\%) = \frac{ELCC}{C_A} \times 100 \quad (6)$$

Where, C_A is the additional capacity added.

V. Evaluation Methodology

In this section the details of methodology used to evaluate adequacy of intermittent energy sources are described. A reliability test system containing 11 conventional generating units is utilized for the purpose of evaluation. Here, we have used 2-state generation model for conventional unit while renewable energy sources use multi-state model as already explained in previous section. While performing practical studies, original multi-state model has found to be computationally expensive. So, a simplified multi-state model is derived from the original multi-state model using linear rounding method [15]. The evaluation method is represented using a flow chart in Fig.7.

Fig. 7.Flow Chart for Evaluation of Reliability Index

VI. CASE STUDY

A. Reliability Test System

Roy Billinton test system (RBTS) is a standard reliability test system. It consists of 6-buses, 9 transmission lines and 11 conventional generating units [16]. The generating unit rating and reliability data for the RBTS are given in Table I. MTTF and MTTR are mean time to failure and repair respectively. FOR is forced outage rate of the generating unit.

TABLE I
GENERATION RELIABILITY DATA OF 6 BUS RBTS

Bus No.	No. of Units	Rating (MW)	MTTF (hr.)	MTTR (hr.)	FOR
1 (Thermal)	2	40	1460	45	0.03
	1	10	1752	45	0.02
	1	20	4380	45	0.025
2 (Hydro)	4	20	3650	55	0.015
	2	5	4380	45	0.01
	1	40	2920	60	0.02

B. Parameters of Wind Power Generation

The parameters of WTG and wind speed data are given in Table II. These parameters are used to develop the wind speed model and power output model.

TABLE II
DATA OF WIND SPEED AND WIND TURBINE GENERATOR

Wind		Wind Turbine Generator	
Wind speed range	0~50 m/s	WTG capacity	0.225 MW
Mean wind speed(μ)	10 m/s	Cut-in speed	5 m/s
Standard Deviation(σ)	8 m/s	Rated speed	15 m/s
		Cut-out speed	25 m/s

C. Parameters of Solar Power Generation

The specified parameters of SCG power generation model are given in Table III.

TABLE III
PARAMETERS OF SOLAR CELL GENERATOR

R_c	$150\,W/m^2$
G_{std}	$1000\,W/m^2$
P_{sn}	$150\,W$

D. Load Model

The annual peak load of RBTS is 185MW. The used load model in the present study is the annual peak load variation curve from 100% to 40% of peak load.

E. Effect of Penetration level on modeling

Penetration of renewable energy is the fraction of the renewable capacity to the total generation capacity (RES + conventional capacity). Within the next twenty years renewable energy source penetration will rise to 10% to 15%. So, determination of the required number of states at practical energy penetration level becomes important. Addition of 27MW of capacity to the RBTS amounts to about 10% penetration and 42 MW amounts to 15% approximately. Similarly up to 20% penetration level the effect is studied

The reduced number of states in the generation model makes computation easier while compromising accuracy. So, an evaluation model that allows system EENS results within an error of ±0.5% would be considered appropriate model. Fig. 8 to Fig. 11 plots the error in EENS (%) against number of states used in modeling for both WTG and SCG. Observations from these figures are enumerated in Table IV.

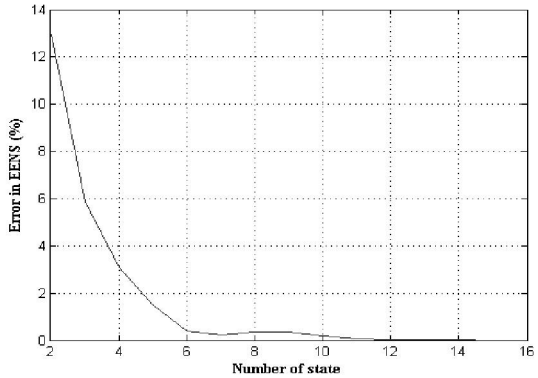

Fig. 8.Variation of error in EENS with state number for Peak load 185MW (Wind penetration level=10%)

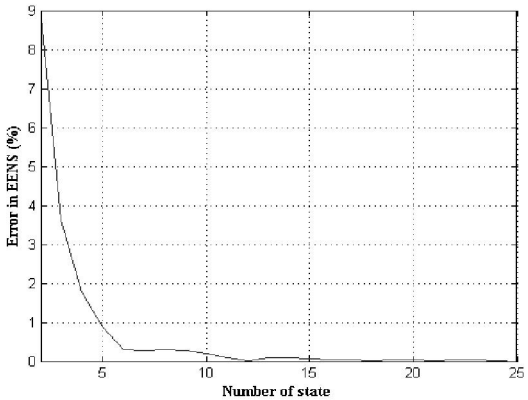

Fig. 9. Variation of error in EENS with state number for Peak load 185MW (Solar penetration level=10%)

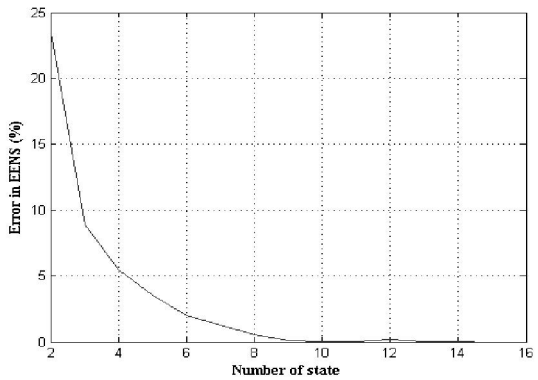

Fig. 10. Variation of error in EENS with state number for Peak load 185MW (Wind penetration level=15%)

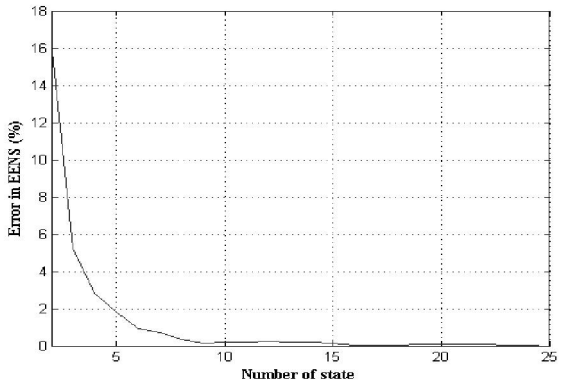

Fig. 11.Variation of error in EENS with state number for Peak load 185MW (Solar penetration level=15%)

Table IV lists the number of state required to model WTG and SCG at different penetration level (assuming maximum allowable error in EENS is 0.5%). Optimum number of state required is the number of state at which the accuracy of the EENS saturates.

TABLE IV
NUMBER OF STATE REQUIRED FOR MODELING AT DIFFERENT PENETRATION LEVEL

Penetration Level (%)	Minimum Number of State for WTG	Minimum Number of State for SCG
Up to 5	4	4
Up to 10	6	6
Up to 15	9	8
Up to 20	11	10

From Table IV, it is clear that as the penetration level increases the number of minimum state required increases for modeling. It is also evident that in comparison to WTG, SCG requires less number of states as the penetration level becomes greater than 10%. It's because wind speed is highly variable and solar radiation shows constancy at the night time.

F. Effect of Penetration Level on Capacity Credit

In this section penetration level ranging from 10-30% is studied. Capacity credit is evaluated at each penetration level using (6).Fig. 12 and Fig. 13 plot EENS against penetration level % for wind and solar respectively.

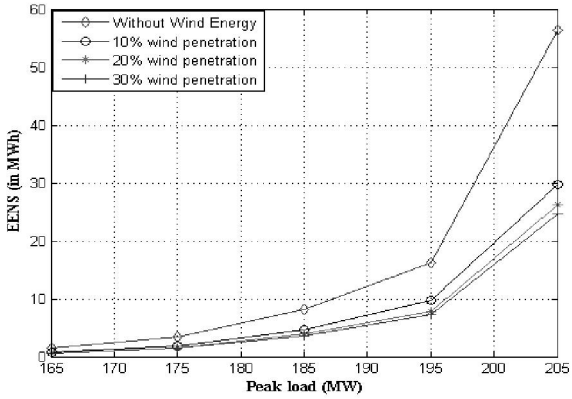

Fig. 12.Plot of EENS as a function of wind penetration level

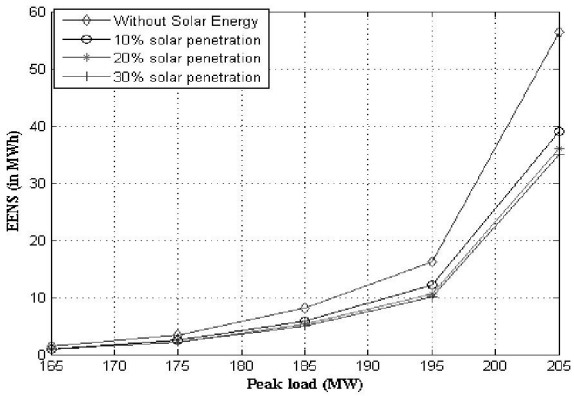

Fig. 13. Plot of EENS as a function of solar penetration level

Table V lists the calculated capacity credit values for wind and solar energy integrated system as observed from Fig. 12 and Fig. 13. From the table, it is observed that relative capacity benefit tails off with increase in penetration level. However this does not mean that the PLCC of the system is reduced but rather that additional wind/solar capacity addition to the system will carry less peak load than the previously added capacity. This is due to the fact that all WTG and SCG are subjected to the same wind and solar radiation profile respectively.

TABLE V
CAPACITY CREDIT OF WIND AND SOLAR POWER

Wind penetration (%)	Wind capacity credit (%)	PV capacity credit (%)
10	27	13.7
20	17.7	9.17
30	10.39	6

It should be noted that the capacity benefit is a function of climatic condition and is not fixed for any source. A location having higher average solar radiation value can have high capacity contribution than the presently calculated value.

VII. CONCLUSION

This work gives an account of adequacy evaluation of variable energy sources which are likely to be largely utilized in the near future. Study is mainly focused on the effect of increasing penetration level on the multi-state model and the capacity credit value. The contribution of the work can be summarized as follows:

1. The increasing penetration level on the multi-state model is studied. Study showed that more number of states are required at higher penetration level. Results also indicated that WTG requires to be modeled with higher number of states than SCG for a particular penetration level.

2. The calculated capacity credit values also showed that with increasing energy penetration relative capacity benefit reduces.

VIII. REFERENCES

[1] Nick Jenkins, Ron Allan, Peter Crossley, David Kirschen, GoranStrbac, "Embeded Generation", 2000, pp. 31-38.

[2] Liang Wu, Jeongje Park, Jaeseok Choi, A. A. EI- Keib, "Probabilistic Reliability Evaluation of Power Systems Including Wind Turbine Generator Considering Wind Speed Correlation", Journal of Electrical Engineering and Technology, vol. 4, no. 4, pp. 485-491, 2009.

[3] Rajesh Karki, Dinesh Dhungana, Roy Billinton, "An Appropriate Wind Model for wind integrated Power System's Reliability Evaluation Considering Wind Speed Correlation", Applied Science, vol. 3, no. 1, pp. 107-121, 2013.

[4] R. Billinton, Hua Chen, R. Ghajar, "Time Series Models for Reliability Evaluation of Power Systems Including Wind Energy", Microelectronic Reliab., Vol.36, No.9,pp.1253-1261, 1996.

[5] Rajesh Karki, Po Hu, "Wind Power Simulation Model for Reliability Evaluation", Electrical and Computer Engineering, Canadian Conference, pp. 541-544, 2005.

[6] Mohamed Shaaban, M.D. Usman, "Risk Assessment of Wind Generation Dispatch Using Monte Carlo Simulation", International journal of Smart Grid and Clean Energy,vol. 2, no. 2, pp.258-263, May, 2013.

[7] L. T. Wong, W. K. Chow, "Solar Radiation Model", Applied Energy, vol. 69, pp. 191-224, 2001.

[8] J. Park, Taegon Oh, kyeonghee Cho, Jaeseok Choi, Sang-Seung Lee, JunzoWatada, A.A.El-Keib, "Reliability Evaluation of Interconnected Power System Including Wind Turbine Generators", International journal of Innovative Computing, Information and Control, vol.8, pp.5797-5808, 2012.

[9] J. Park, W. Liang, J. Choi, A. A. EI-Keib, R. Billinton, M. Shahidehpour, "A Probabilistic Reliability Evaluation of A Power System Including Solar/ Photovoltaic Cell Generator", IEEEPower and Energy Society General Meeting, pp. 1-6, July, 2009.

[10] R.Kakri, Po Hu, "A Simplified Wind Power Generation Model for Reliability Evaluation", IEEE, vol. 21, June 2006, pp.533-540.

[11] R.Karki and R. Billinton and A. Alferidi, "Reliability modelling for Evaluating the Contribution of Photovoltaics in Electric Power Systems ", Photovoltaic Specialists Conference, IEEE, June, 2011, pp. 001811-001816.

[12] Roy Billinton, GuangBai, "Generating Capacity Adequacy Associated With Wind Energy", IEEE Transaction on Energy Conversion, vol. 19, no. 3, 2004.

[13] A. A. Choudhury, "Reliability Model for Large Wind Farms in Generation System Planning", IEEE, vol. 2, July, 2005, pp. 1926-1933.

[14] Gautam Kumar, A. Pachauri, "Reliability Modelling for Evaluating the Contribution of Photovoltaics in Electric Power System", International Journal of Innovation in Engineering Research and Management, pp. 1-7, June, 2014.

[15] R. Billinton, R. N. Allan, "Reliability Evaluation of Power System", 2nd Edison, Plenum Press, New York, 1996.

[16] R. Billinton, S. Kumar, "A Reliability Test System for Educational Purpose- Basic Ideas", IEEE Transaction Power System, vol. 4, no. 3, pp. 1238-1244, Aug, 1989.