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BULK ELECTRIC SYSTEM RELIABILITY EVALUATION WITH WIND TURBINE AND ENERGY STORAGE

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This paper describes a new methodology for grid expansion planning considering the probabilistic reliability of a Bulk Electric Systems (BES) including Wind Turbine Generators (WTG) and Energy Storage System (ESS).The proposed model includes the main parameters used to create an operational history for each individual unit and transmission line unavailability. Bulk electric system reliability analysis associated with wind energy provides an opportunity to investigate the reliability benefits when large-scale wind power is injected in a BES. High wind power penetration can lead to high risk levels in the overall system reliability. The impacts of different wind turbine penetration levels on the reliability benefits from ESS are analyzed when the WTG capacity is utilized to replace the conventional generators with same total rated power capacity. The WTG and ESS capacity are installed to meet the annual growth of load demand and maintain the BES adequacy levels. The proposed method is applied to the IEEE Reliability Test System (IEEE– RTS).

KEYWORDS: *Bulk electric systems, wind turbine generator, energy storage system, grid expansion planning, reliability evaluation.*

1. INTRODUCTION

Wind power installation capacity has increased significantly worldwide in the past decades. This is benefited from the environmental and renewable energy policies. By replacing some fossil- fuel generation capacities, wind power generation can effectively reduce the greenhouse emission. However, due to the intermittent characteristics of wind power, the fluctuations of wind power generation could have negative impacts on power grid operations [1-3]. With the increase of wind power penetration in the grid, the adverse impacts of wind power fluctuations on power systems become significant. High wind power penetration can produce large power fluctuations and result in low system reliabilities. Therefore, it is urgent to eliminate the variation to promote the application of wind power in power system. Energy Storage System (ESS) has been an effective means to mitigate the generation fluctuations of intermittent power generation sources, such as wind power generation and solar energy [4]. Hence, ESS is introduced to alleviate wind power fluctuations and to maintain system reliability levels. There is a growing interest in using ESS to improve the reliabilities of power systems with wind turbines [5,6]. Reference [5] presents a technique utilizing Monte Carlo simulation for the capacity adequacy evaluation of small isolated power systems including wind power generation system (WPGS) and (ESS). Monte Carlo simulation has been considered as an effective method to analyze system generating capacity adequacy through simulating the actual process and random behavior of the system [6].

Relatively little work has been done on bulk electric system reliability analysis associated with wind energy due to the complexity associated with including detailed modeling of both the generation and transmission facilities in addition to the wind characteristics. Connecting the wind energy conversion systems without (ESS) to different locations in a bulk system can have different impacts on the overall system reliability depending on the system topology and conditions [7]. Possible transmission reinforcement alternatives in order to absorb a significant amount of wind capacity without (ESS) at a specified location are illustrated in [8]. A heuristic method is used to search for the best reliability level of a composite power system including wind turbine generators [9].

This paper describes a new methodology for grid expansion planning considering the probabilistic reliability of Bulk Electric System (BES) including Wind Turbine Generators (WTG) and Energy Storage System (ESS). The proposed model includes the main parameters used to create an operational history for each individual unit and transmission line unavailability. Reliability indices of Loss of Load Expectation (LOLE) and Expected Energy Not Served (EENS) at BES are calculated using the load duration curve (LDC). Wind power penetration levels, capacities of ESS, and the growth rate of annual peak load are studied in details to evaluate the capacity benefits of WTG and ESS. Different possible operating cases of wind farm and storage are compared and the resulting benefits are evaluated in this paper by application to the IEEE - Reliability Test System.

This paper is organized as following. In section 2, the models are presented for WTG and ESS. In section 3, the proposed method of a bulk electric system reliability evaluation is developed. The results are presented in section 4. Section 5 is conclusions.

2. PROBABILISTIC MODELLING

2.1 Conventional generating Units and Transmission Lines model

Conventional generating units can bee modeled using the two- state model under the assumption that both a line or generating unit are observed for an interval of time in which N cycles of failure and repair are noted. Let m_i and r_i be the observed times-to-failure and repair for the i-th cycle. To defend the claim that the run-repair cycle is a (renewal process), the run-repair cycles must be statistically independent and the distribution of durations stationary in time. It is also necessary that the expected values of mean time to failure (MTTF) and mean time to repair (MTTR), as shown in Eqs. (1) and (2) [12].

$$MTTF = \frac{1}{N}\sum_{1}^{N} m_i \tag{1}$$

$$MTTR = \frac{1}{N}\sum_{1}^{N} r_i \tag{2}$$

The average cycle time (T) of the failure-repair process, given by the sum of MTTF and MTTR becomes

$$T = MTTF + MTTR \qquad (3)$$

The probabilities are defined as A and U (FOR) for the operating state and the failed state, respectively as shown in Eq.(4) and Eq.(5)

$$A = \frac{MTTF}{T} \qquad (4)$$

$$U = \frac{MTTR}{T} \qquad (5)$$

2.2 Wind Turbine Generator (WTG) Model

The power output characteristics of WTG are different from those of conventional generators. The electric power output of a WTG in the operating state depends strongly on the wind speed as well as on the performance characteristics of the generator [12]. Therefore, the output of WTG can be modeled by combining the two-state model and WTG power curve, shown as in Eq.(6).

For a typical WTG, the power output characteristic can be assumed in such a way that it starts generating at the cut–in wind speed V_{ci}, the power output increases linearly as the wind speed increases from V_{ci} to the rated wind speed V_R. The rated power P_R is produced when the wind speed varies from V_R to the cut–out wind speed V_{co} at which the WTG will be shut down for safety. Thus,

$$P_w(V) = \begin{cases} a + bV^m & for \quad V_{ci} \le V \le V_R \\ P_R & for \quad V_R \le V \le V_{co} \\ 0 & otherwise \end{cases} \qquad (6)$$

The constants a and b are given by:

$$a = \frac{P_R \cdot V_{ci}^m}{V_{ci}^m - V_R^m} \quad \text{and} \quad b = \frac{P_R}{V_R^m - V_{ci}^m} \qquad (7)$$

The wind speed could be treated as a random variable and assumed to be distributed as Rayleigh distribution given by following probability density function [11].

$$f(V) = \frac{2}{C} \cdot \left(\frac{V}{C}\right) . \exp\left[-\left(\frac{V}{C}\right)^2 \right] \qquad (8)$$

There is a direct relationship between scaling factor C and average wind speed $\overline{V}$ given by Eq.(9).

$$C \cong 1.128\, \overline{V} \qquad (9)$$

2.3 Energy State Model of Energy Storage System (ESS)

The major function of energy storage is to smooth out the fluctuating power sources and improve the generation system reliability. In this paper, we assume that the ESS is operated following the simple rules:

(1) the surplus energy will be stored if the sum of wind turbine generation and conventional power generation exceeds the system load.

(2) The stored energy will be used in case of generation shortage.

The ESS is defined by its energy capacity, charging and discharging rates. The relationships between energy state series of ESS and surplus power are given as follows.

$$SG(t) = WG(t) + CG(t) - L(t) \qquad (10)$$

$$ES(t+1) = \begin{cases} ES_{\min} & ES(t) + SG(t) \le ES_{\min} \\ ES(t) + SG(t) & ES_{\min} \le ES(t) + SG(t) \le ES_{\max} \\ ES_{\max} & ES_{\max} < ES(t) + SG(t) \end{cases} \qquad \text{------------} \qquad (11)$$

Where: $SG(t)$ = the surplus power generation
$WG(t)$ = the output power of wind turbine power generation
$CG(t)$ = the output power of conventional power generation
$ES_{\min}$ & $ES_{\max}$ = the minimum and maximum allowable storage levels of the energy storage system.

Therefore, the ESS model can be obtained from the load time series and the total generation time series using Eqs.(10) and (11).

3. PROPOSED METHOD

The overall procedure for bulk electric system reliability evaluation using a proposed method is briefly described in the following steps:

(1) Specify the initial state of each component (all generating units and transmission lines) using Eqs.(1-5).

(2) The capacity model for WTG units is modified to account the effect of the failure and repair characteristics using Eq.(6).

(3) Develop a suitable capacity model from the parameters of the individual generating units and transmission lines using the recursive expression for an exactly X MW on forced outage state after a unit or line of C MW and forced outage rate U is added as shown below [12].

$$P(X) = (1-U).P^*(X)+(U).P^*(X-C) \qquad (12)$$

Where $P^*(X)$ and $P(X)$ denote the cumulative probabilities of the capacity outage state of X MW before and after the unit or line addition. The above expression is initialized by setting $P^*(X) = 1.0$ for $X \le 0$ and $P^*(X) = 0$ otherwise.

(4) Create the total system capacity model by combining the capacity models obtained in steps (2) and (3).

(5) Develop a suitable load model from the given data over the period of study. In this paper, the load model is a chronological hourly load profile.

(6) The operating strategy of an energy storage system is that whenever the generation exceeds the load, the excess energy is stored and used whenever there is a generation shortage. The energy stored in the storage facility is calculated from the load time series and the total generation time series taking into consideration the charging and discharging characteristics of the storage facility using Eqs. (10) and (11).

(7) Combine the total system capacity model with the load model to obtain a probabilistic model of bulk electric system. The time reference in this paper is a year (8760 hours).

(8) The Loss Of Load Expectation (LOLE) index as a measure of BES reliability over a period of N hours is evaluated by deducing the risk for each of these load levels and summing overall load levels as shown below [12].

$$\text{LOLE} = \sum_{i=1}^{N} P(C_i - X_i) \qquad \text{hr/yr} \tag{13}$$

Where: C_i = available capacity during hour i
X_i = forecast peak load during hour i
$P(C_i - X_i)$ = probability of the loss of load during hour i. This value is obtained from the system capacity model
N = 8760 hourly peak loads

(9) Each hourly load level is numerically equal to the energy demanded during that hour. Consequently the total energy demanded by the system is numerically given by the summation of all 8760 load levels. For each state of the capacity model C_k, k =1,2,…,N_c. The expected energy not supplied EENS is given numerically by summing all positive values of ($L_i - C_i$) where L_i is the i-th load level and i=1,2,..,N, each with equal duration ΔT= T/N, where T represents the total duration of the observation period. The expected energy not supplied is given by Eq. (14) [13].

$$EENS = \Delta T \sum_{k=1}^{N_c} E_k . P_k \tag{14}$$

Where: E_k = energy not supplied
P_k = probability of capacity state C_k

This value of EENS can be evaluated after adding each unit into the system capacity model. Hence the expected energy produced by each unit is given by the difference in EENS before and after adding the unit. The order of adding units is important and must follow a merit order table based on rearranging the units from minimum to maximum incremental production cost ($ per megawatt-hour).

4. STUDY SYSTEM

The application of the proposed method will be illustrated with the IEEE Reliability Test System (IEEE-RTS) [10]. The basic characteristic of the test system is shown in Table 1. A single line diagram of the original IEEE-RTS is shown in Fig.1.The conventional generating unit cost data for the IEEE-RTS is shown in Table 2. The load duration curve for the IEEE-RTS is shown in Table 3.

Table 1. Basic Characteristics of Test System

Characteristics	IEEE – RTS
No. of buses	24
No. of circuits	38
No. of units	32
Installed capacity (MW)	3405
Peak load (MW)	2850
Period of study (hrs)	8760

Table 2. IEEE – RTS Generating Unit Cost Data

Unit Size (MW)	No. of Units	Forced Outage Rate	Cost ($/MWH)
12 (oil 3)	5	0.02	27.60
20 (gas turbine)	4	0.10	43.50
50 (hydro)	6	0.01	00.00
76 (coal 3)	4	0.02	14.40
100 (oil 2)	3	0.04	23.00
155 (coal 2)	4	0.04	11.64
197 (oil 1)	3	0.05	22.08
350 (coal 1)	1	0.08	11.40
400 (nuclear)	2	0.12	06.00

Table 3. IEEE – RTS Load Duration Curve

Duration	0.0	0.1	0.2	0.3	0.4	0.5	0.6
Load (MW)	2850	2485	2221	2051	1909	1811	1709
Duration	0.7	0.8	0.9	1.0			
Load (MW)	1576	1453	1333	1160			

Numerical examples are studied for installing wind power in a BES with two different objectives: one objective is to replace conventional power plants with Wind Turbine Generators (WTG), and other one is installing WTG to meet the load growth and maintain the system reliability.

I. Replacing Coal –Fired Power Generators with WTG and ESS

Studies have been carried out to investigate the effects on the BES reliability of the wind energy penetration levels. The coal-fired generating units are removed one by one from the system and replaced by WTG with equal capacities as the removed units. Fig. 2, shows the LOLE increases with the increasing replacement capacity of coal-fired units 1x155MW, 2x155MW, 3x155MW, 4x155MW, (3x155MW+1x350MW) and (4x155MW+1x350MW) or increasing capacity of WTG.

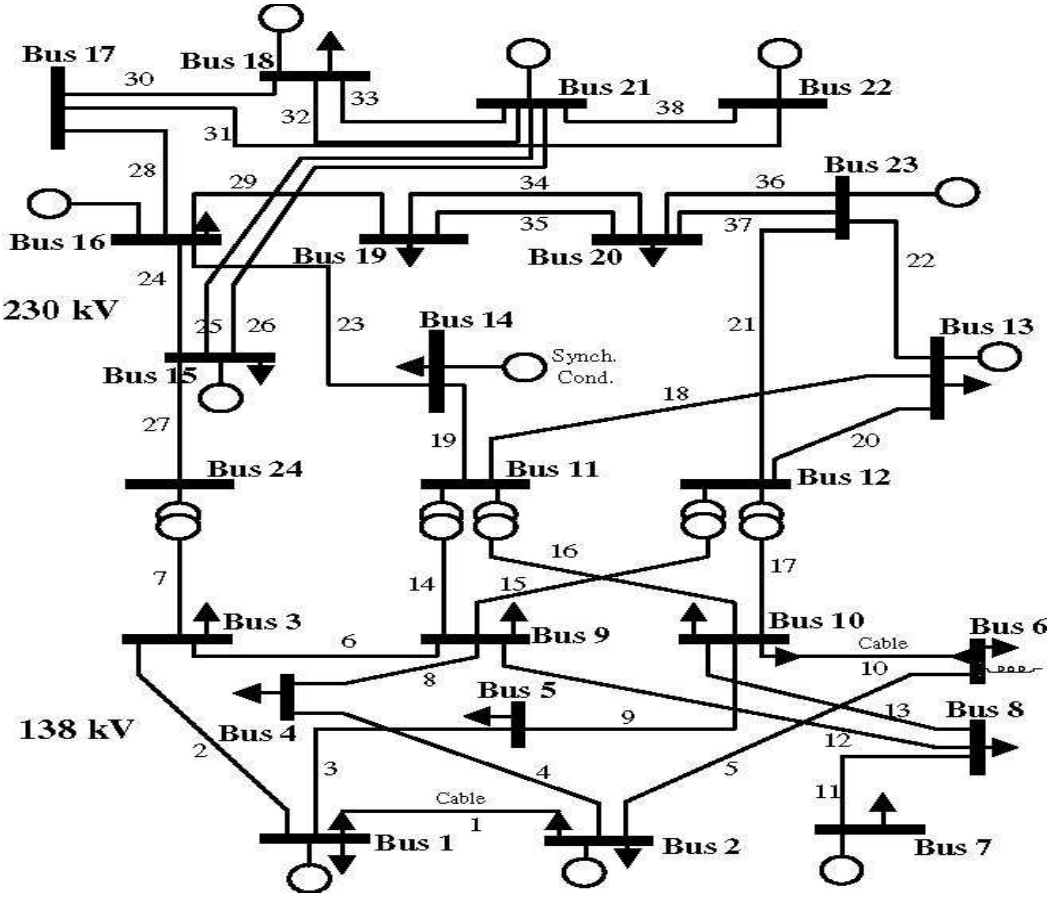

Fig. 1. Single Line Diagram of the Original IEEE-RTS

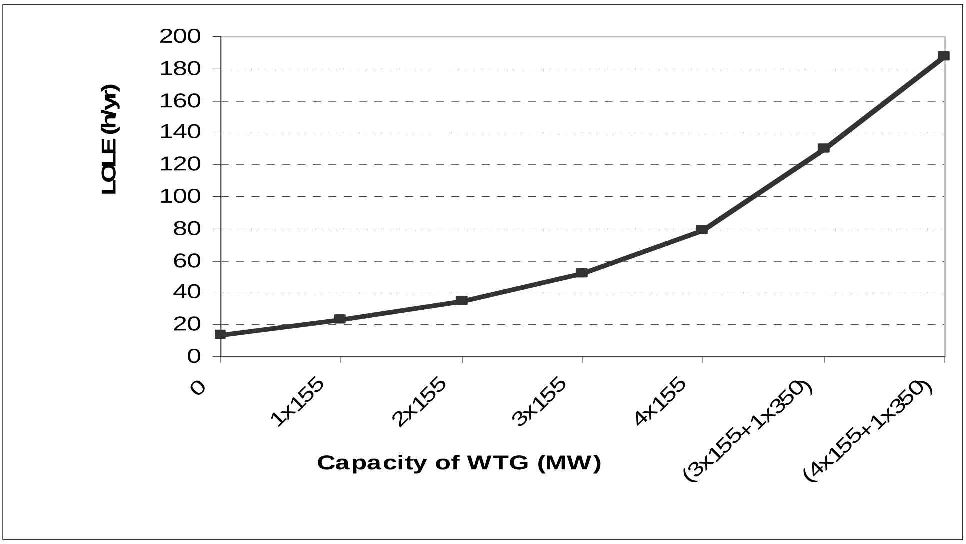

Fig.2. LOLE versus Capacity of WTG

In Fig.3, we can see that the value of EENS increases with the increasing replacement capacity of coal-fired units. The relationship of the LOLE, EENS and the WTG capacity are approximately a linear function when the wind power penetration level is lower than 20%. When the penetration level exceeds 20%, the reliability indices of the BES have an abrupt increase as shown in Figs. 2 and 3.

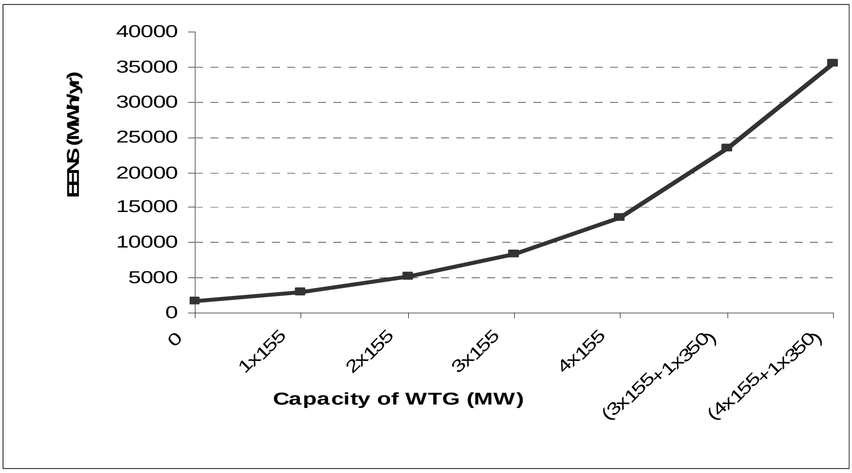

Fig.3. EENS versus Capacity of WTG

Electric power from a WTG unit is intermittent and nondispatchs able as the outputs of these non-conventional generating units depend strongly on the penetration level. This effect can be further examined by replacing different units in the IEEE-RTS by the required number of WTG units while maintaining a specific reliability criterion. The system LOLE in the original IEEE-RTS is 13.04 hours/year.

One of the 155MW coal-fired units is removed from IEEE-RTS and replaced by WTG units. Table 4, shows the WTG capacity required to maintain a LOLE of 13.04 h/yr and the corresponding penetration levels. Fig. 4 shows the variation in the LOLE as a function of the added WTG capacity.

Table 4. Expected Energy Not Supplied, LOLE, when 155MW Coal-Fired Unit is Replaced with WTG Capacity Added for Different Penetration Level

WTG Capacity (MW)	Penetration Level (%)	EENS (MWh/yr)	LOLE (hrs/yr)
0	__	1668.71	13.04
155	4.55	2998.82	22.69
355	9.85	2323.02	17.49
555	14.59	2170.57	16.24
755	18.85	2143.88	15.98
955	22.71	2139.61	15.94
1155	26.22	2138.94	15.93
1355	29.42	2138.79	15.93
1555	32.36	2138.73	15.93
1755	35.06	2138.77	15.93

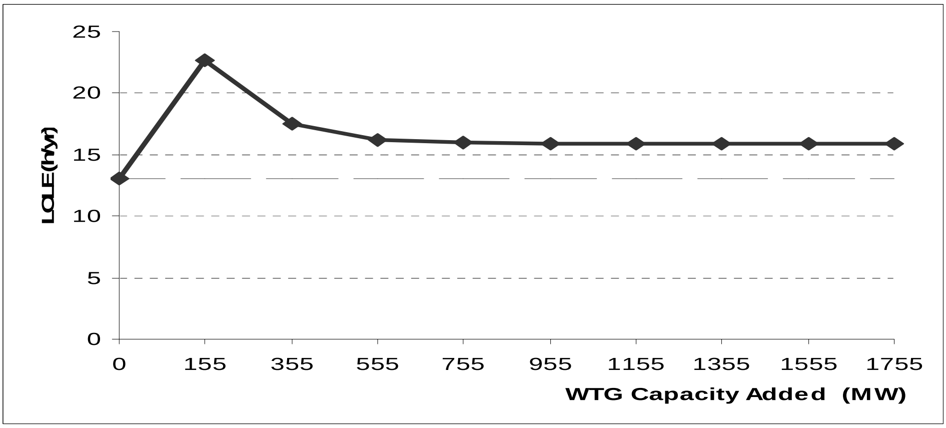

Fig.4. LOLE versus Total WTG Capacity Assuming a 155MW Coal-Fired Unit is Removed from the IEEE-RTS

The results presented in Table 4, show that the LOLE increases from 13.04 h/yr to 22.69 h/yr after the 155MW coal-fired unit is removed. Fig. 4 shows that the LOLE decreases with increasing WTG capacity. It can be seen from Table 4 and Fig. 4 that there is a reliability benefit from WTG capacity. The changes in the LOLE are significant in the beginning and tend to saturate when more WTG are added while the decreases in the LOLE are relatively flat with the increases in WTG capacity and the LOLE is not restored to 13.04 h/yr but the LOLE is 15.93 h/yr.

As noted earlier, the available energy from wind is intermittent and variable. In order to use these energy sources as viable power generation, energy storage is often incorporated in BES applications to match the power supply with the instantaneous power demand. The Energy Storage System (ESS) was added in the system to mitigate the adverse effect of WTG on the system reliability. The ESS is installed with the target to maintain the original level of system reliability (LOLE= 13.04 h/yr).

Table 5, compares the two basic reliability indices for the six different system configurations with and without energy storage when the coal-fired units (1X155MW), (2X155 MW), (3X155 MW), (4X155 MW), (3X155 MW + 1X350 MW) and (4X155 MW + 1X350 MW) are replaced by WTG with equal capacities as the removed units.

Table 5. Reliability Indices for the Different Systems with and without ESS

Cases	**Pen. Level %**	**EENS (MWh/yr)**		**LOLE (h/yr)**	
		ESS = 0	**ESS =1500MWh**	**ESS = 0**	**ESS =1500MWh**
Base Case	_____	1668.71	______	13.04	_____
1x155 MW	4.55	2998.82	978.62	22.69	7.52
2x155	9.10	5123.20	1777.09	34.50	13.55
3x155	13.66	8390.24	3104.33	51.85	21.93
4x155	18.21	13502.87	5197.37	78.96	33.96
3x155+350	23.93	23475.19	9343.56	130.26	60.34
4x155+350	28.49	35562.34	14990.27	187.97	88.98

It can be seen from Table 5, that the BES reliability with energy storage is significantly higher than that of the systems with no energy storage. The relationships between ESS capacity and LOLE for the six different systems shown in Table 5 and the wind power penetration levels, are simulated and shown in Fig.5.

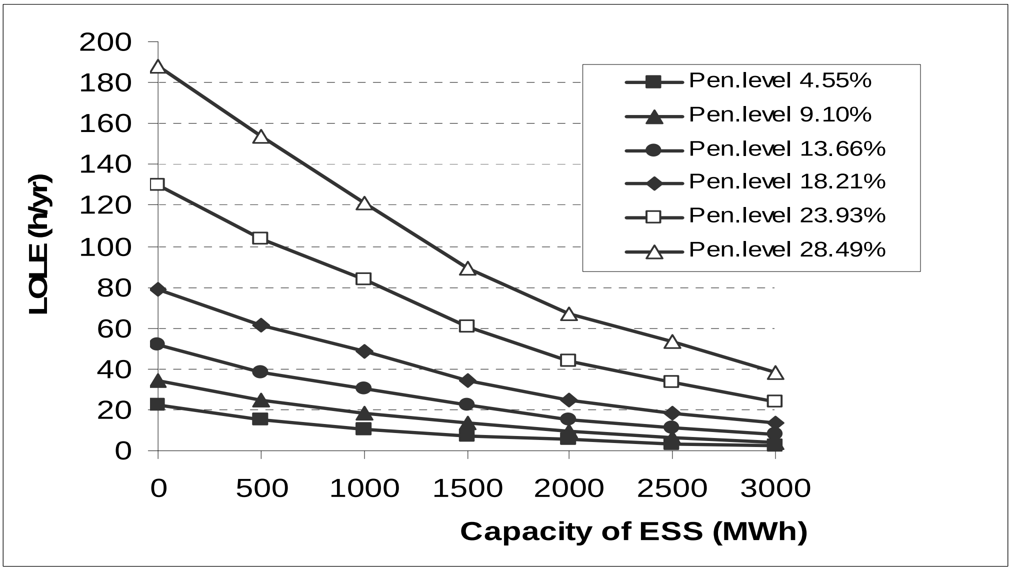

Fig.5. LOLE versus Capacity of ESS for Different Penetration Levels

As shown in Fig.5, adding ESS can significantly improve system capacity adequacy. However, the improvement tends to be saturate, when the capacity of ESS reaches specific threshold. When the wind penetration level reaches 4.55%, 9.1%, 13.66% and 18.21%, approximate threshold values of ESS capacity are 1500MWh, 2000MWh, 2500MWh and 3000MWh, respectively. Therefore, the capacity of ESS should be less than the threshold value, to avoid saturation and maximize the benefits of ESS.

The desired capacity of ESS with respect to wind penetration level has also been studied for six basic system configurations. In order to appreciate the impact of ESS capacity on the adequacy of BES, the above four basic system configurations were studied using variable size storage facilities. The corresponding EENS were determined as a function of the ESS capacity for the four basic system configurations as shown in Fig. 6.

It can be seen from Fig. 6, that the addition of a suitable ESS significantly improves the reliability of BES. The studies conducted show that minimal incremental benefit is obtained if the capacity of the energy storage exceeds a certain value. In this case it is approximately 1500 MWh for penetration level (P. L.) 4.55% and 9.1% and 2500 MWh for P. L. 13.66% and 18.21%. In order to further illustrate this effect, the expected energy supplied (EES) by the energy storage facility was determined as a function of the energy storage capacity for the four basic configurations and is shown in Fig. 7.

It can be seen from Fig. 7, that the incremental benefit due to the expected energy supplied become minimal when the energy storage capacity exceeds 1500 MWh for P.L. 4.55% and 9.1% and 2500 MWh for P.L. 13.66% and 18.21%.

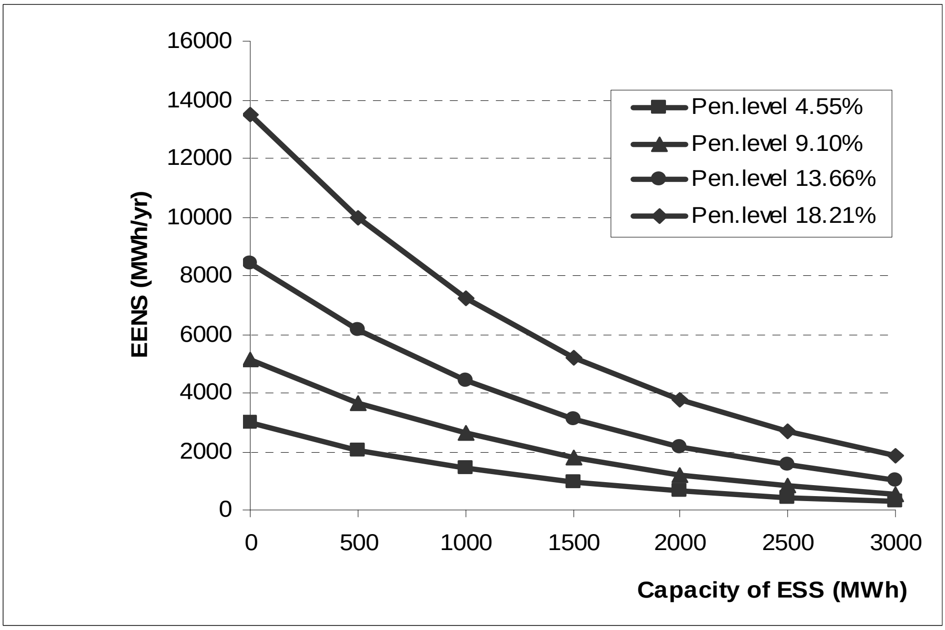

Fig.6. EENS versus Capacity of ESS for Different Penetration Levels

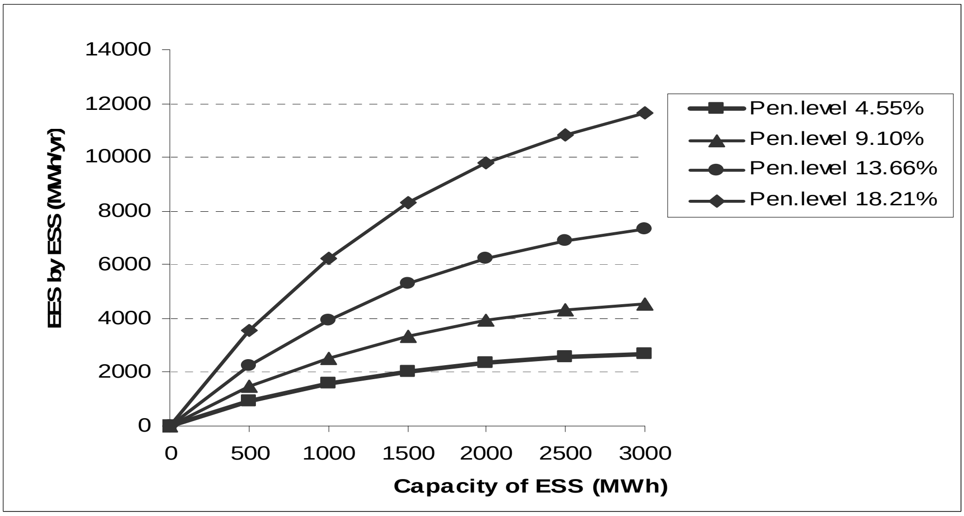

Fig.7. EES by ESS versus Capacity of ESS for Different Penetration Levels

II. Installing WTG and ESS to Meet Annual Growth of Load Demand

In this case study, the system data is almost the same as the original IEEE-RTS. Thus the EENS and LOLE of the base system are 1668.71 MWh/yr and 13.04 h/yr. The installed capacity of system is 3405MW and the annual peak load is 2850MW. The annual load growth is represented by the growth of annual peak load in this work. Three growth rates 1%, 3%, and 5% are tested.

Three expansion cases of the generation system are also studied to meet the load growth and maintain the system reliability. No generation capacity is added in case 1, while the added capacity of WTG equals to the growth of annual peak load in case 2. The WTG and ESS capacity are added in case 3. The BES reliability indices of different expansion plan is calculated and shown in Table 6.

Table 6. EENS and LOLE of Different Expansion Plan with Different Growth Rate of Peak Load

Growth Rate (%)	Load Growth (MW)	EENS (MWh/yr)		LOLE (h/yr)	
		Case 1	Case 2	Case 1	Case 2
1	28.5	2015.20	1796.41	16.24	14.11
3	85.5	2899.48	2125.78	20.88	15.68
5	142.5	4084.47	2595.85	31.36	20.16

Table 6, shows that adding WTG capacity could improve the system reliability when peak load growth. It may also been seen from Table 6, that the difference between case 1 and case 2 becomes significant as the peak load growth rate increase.

In order to maintain the original level of system reliability, sufficient generation was added into the system. The required capacity of generating unit in case 2 and case 3 are also shown in Table 7.

Table 7. Capacity of WTG and Capacity Combination of WTG and ESS with Growth Rate of Peak Load

Growth Rate %	Growth of Peak Load (MW)	Capacity WTG (MW)	Capacity	
			WTG (MW)	ESS (MWh)
1	28.5	50	20	140
			40	40
3	85.5	190	50	500
			100	270
5	142.5	Not satisfied	200	460
			400	190

As shown in Table 6, when the growth rate is 5%, adding WTG capacity (case 2) can significantly improve system reliability. However, the improvement tends to be saturated, when the capacity of WTG is 800MW and the wind penetration level reach to 19%. Therefore, the WTG capacity could not satisfy the growing load demand of 5% to maintain the original level of system reliability as base case. In this case, we must add the ESS with WTG capacity to satisfy the base case reliability.

If the ESS is introduced (case 3), the required wind turbine capacity would be greatly reduced due to assistance of ESS. In order to decrease the required capacity of WTG and maintain the system reliability level, the desired ESS capacity with respect to different peak load growth rate is shown in Table 7.

Comparing the results presented in Table 7, we can see that adding ESS could effectively decrease the needed capacity of WTG. As shown in the growth rate 5%, 190 MWh ESS could save the WTG capacity up to 400 MW.

5. CONCLUSION

This paper presents a new method for grid expansion planning considering the probabilistic reliability of a Bulk Electric System (BES) with wind turbine generators (WTG) and Energy Storage System (ESS). An analytical procedure is presented in this paper to analyze the impacts of energy storage on reliability of BES with wind turbine generators. The Expected Energy Not Supplied (EENS) and the Loss of Load Expectation (LOLE) indices are used to investigate the impacts of ESS and WTG on system reliability by using a study system of the 24-bus the IEEE-RTS. The following points may be noted from these studies:

1- The EENS and LOLE increase along with increasing the replaced capacities of coal-fired units, when the coal-fired generators are replaced by the WTG with equal capacities as the removed units.
2- The reliability indices of the BES has an abrupt increase, when the wind penetration level exceeds 20% (Figs. 2 and 3). Results indicate that the suggested wind penetration level is lower than 20%.
3- In order to maintain the original level of system reliability, adding WTG capacity can significantly improve system reliability. However, the improvement tends to be saturated, when the capacity of WTG reaches a specific threshold and the required reliability criterion is not satisfied (Table 4 and Fig.4).
4- The provision of energy storage can have significant positive impacts on the system reliability performance. These impacts can be quantitatively evaluated using the model and the procedure described in this paper.
5- The studies conducted show that minimal incremental benefit is obtained if the capacity of the energy storage exceeds a certain value (Fig. 7).
6- The WTG capacity required to maintain a given reliability criterion will, however, be considerably higher than that normally associated with a WTG and ESS capacity (Table 7).
7- Installing WTG can improve the system reliability when the peak load grows (Table6). However, WTG could not economically satisfy the growing load demand by itself, because of the load-carrying ability of WTG is weaker than WTG and ESS (Table 7).
8- A specific reliability criterion could not satisfy when installing WTG capacity to meet annual growth of load demand when the peak load growth rate increased (Table 7).
9- The required capacity of WTG can be greatly decreased by ESS at different growth rate of peak load. Therefore, economical capacity combination of WTG and ESS, in terms of BES adequacy could be figure out in the future study.
10- This work could assist power system planners and utility managers to evaluate the minimal incremental benefit of WTG and ESS.

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حساب اعتمادية منظومة التوليد و النقل مع تربينة الرياح و الطاقة المخزنة

يقدم هذا البحث طريقة جديدة لتخطيط شبكة ممتدة أخذين في الأعتبارحساب الأعتمادية لمنظومة من التوليد و النقل شاملا مولدات رياح و نظام طاقة مخزنة، النموذج المقترح في هذا البحث يشمل المعطيات الأساسية المستخدمة في تمثيل عدم الأتاحية للمولد و خط النقل. إن تحليل اعتمادية المنظومة مع طاقة الرياح ، قد يعطينا عائدا للنفع عند إمداد المنظومة بقدرة كهربية ناتجة من تربينات الرياح. إن ازدياد طاقة الرياح في المنظومة قد يؤدى إلى مستوى عالي من المخاطرة في أعتمادية المنظومة، لذلك لأبد من استخدام نظام الطاقة المخزنة مع طاقة الرياح لتحسين أعتمادية المنظومة. كما إن الدراسة شملت إضافة طاقة الرياح مع الطاقة المخزنة لتحقيق النمو في الحمل مع المحافظة على مستوى اعتمادية محدد. وقد تم تطبيقا الطريقة المقترحة على نظام اختبار (IEEE- RTS) .