Contribution of ESS to Grid including Multi WTGs in Power System Reliability Aspect

Ungjin Oh, Yeonchan Lee, Duy-Phuong N. Do, Zhao Jing Feng, Jaeseok Choi+

***Abstract*--This paper proposes the aspect of power system reliability which is studied in terms of the energy storage systems(ESS) to reduce power output volatility as large penetration of wind turbine generators(WTG). In order to reduce the volatility of these WTGs and to relieve the anxiety of demand commitment in supply reliability viewpoint, the ESS is installed to the multi-wind farms, which is modeled by Monte Carlo simulation method(MCS), linking to an existing power grid. In addition, the paper is discussed more detail about method, function and model of power system reliability evaluation to assess the valuable contribution of ESS in terms of power system reliability. The reliability contribution functions developed in this study also applies to the power grids which are similar Jeju island grid dimensions.**

***Keywords*: Battery Energy Storage System(BESS), Wind Turbine Generator(WTG), Monte Carlo Simulation(MCS), Reliability evaluation, ESS reliability contribution**

I. INTRODUCTION

Since the Paris Agreement on Dec. 12, 2015, the paradigm of energy will be restructured around low carbon energy and energy efficiency globally. Because of these issues, renewable energy generators(REG), such as wind turbine generator (WTG) and solar cell generator(SCG), are expected to be rapidly integrated into existing power systems. However, in the case of REGs, the volatility of output is very high due to the uncertainty of resource supply. So the technology that is attracting people's attention now is the battery energy storage system(BESS)(referred to as "ESS" for convenience in this paper). It is expected that ESS will be installed in REGs to mitigate the output volatility of REGs through proper charge and discharge.

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In this paper, we propose a new contribution evaluation function and method that can evaluate the value of ESS when the ESS is installed in the WTG in terms of reliability using monte carlo simulation(MCS) method. Therefore, in order to verify the usefulness of the ESS contribution evaluation function, the simulation was applied to a power system model system similar to that of Jeju island in Korea. In this paper, the existing conventional generator(CG) uses probabilistic model considering forced outage rate(FOR). Also, the WTG simulates the uncertainty of the wind speed by modeling the Weibull distribution. Therefore, we used a model that is as close to realistic as possible[1-8].

II. PROBABILISTIC RELIABILITY EVALUATION OF POWER SYSTEM BY MONTE CARLO SIMULATION

A. *Probabilistic Operation Model of Generator*

The proposed probabilistic WTGs operation model postulates two states, i.e. on and off. Fig. 1 shows the operation history of a generator from the perspective of the two-state model.

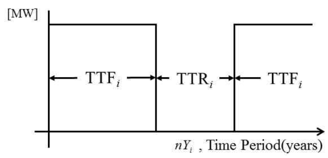

Fig. 1. Up-down-up cycle history of #*i* generator with two states

The (1) and (2) are used to yield the mean values, i.e. MTTF(Mean Time To Failure) and MTTR(Mean Time To Repair), respectively, which are shown in Fig. 2.

$$MTTF_i = \sum_{k=1}^{nY_i} TTF_{i,k} / nY_i \quad (1)$$

$$MTTR_i = \sum_{k=1}^{nY_i} TTR_{i,k} / nY_i \quad (2)$$

where,
$MTTF_{i,k}$: MTTF of the *ith* generator at *kth* state[hours]
$MTTR_{i,k}$: MTTR of the *ith* generator at *kth* state[hours]
$TTF_{i,k}$: Time to failure of the *ith* generator at *kth* state [hours]
$TTR_{i,k}$: Time to repair of the *ith* generator at *kth* state [hours]
nY_i: Actual operating year of the *ith* generator at *kth* state [hours]

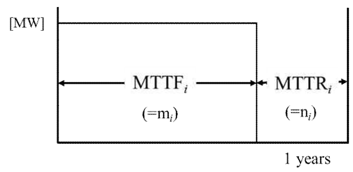

Fig. 2. Mean of up-down-up cycle of #i generator with two states.

Therefore, the FOR_i denoting the probability of #i generator remaining off is formulated as in the (3), which is in practice used to build an FOR database(D/B).

$$FOR_i = \frac{n_i}{m_i + n_i} = \frac{\lambda_i}{\lambda_i + \mu_i} \tag{3}$$

where,

$m_i = MTTF_i = \sum_{k=1}^{nY_i} TTF_{i,k} / nY_i$ [year], $n_i = MTTR_i = \sum_{k=1}^{nY_i} TTR_{i,k} / nY_i$ [year]

$\lambda_i = \frac{1}{MTTF_i} = \frac{1}{m_i}$, $\mu_i = \frac{1}{MTTR_i} = \frac{1}{n_i}$

The two state probabilistic operation model has long been used to estimate the FOR of CGs. By contrast, when the MCS is used to assess the reliability based on the foregoing FOR, the (4) and (5) return random numbers. Thus, the two variables, viz. MTTF and MTTR, constituting the FOR of the two state operation model need be analyzed so as to reform the artificial operation history of the generators with a long history[11,12]. However, TTF should be followed by TTR in due order as part of the reformation.

$$TTF_{i,k} = -MTTF_i \ln U_k = -\frac{1}{\lambda_i} \ln U_k \tag{4}$$

$$TTR_{i,k} = -MTTR_i \ln U_k^{'} = -\frac{1}{\mu_i} \ln U_k^{'} \tag{5}$$

where,
$TTF_{i,k}$: Time to failure of the *ith* generator at *kth* state [hours]
$TTR_{i,k}$: Time to repair of the *ith* generator at *kth* state [hours]
λ_i: Failure rate of Generator *ith*, μ_i: Repair rate of Generator *ith*
U_k, $U_k^{'}$: Two uniformly distributed random number between [0,1] at *kth* state

Hence, the TG_k[MW] of a CG in the #k state is calculated for the MCS as in the (6).

$$TG_k = \sum_{i \in NG} G_{i,k} \times ISK_{i,k} \tag{6}$$

$$ISK_{i,k} = \begin{cases} 1 & k \in \Omega_{TTF_i} \\ 0 & k \in \Omega_{TTR_i} \end{cases} \tag{7}$$

where,
NG: Generator Set
TG_k : Total Generation Capacity at *kth* state [MW]
$G_{i,k}$: Capacity of the *ith* generator at *kth* state [MW]
$ISK_{i,k}$: Probability of the *ith* generator at *kth* state
Ω_{TTFi}: TTF set of the *ith* generator
Ω_{TTRi}: TTR set of the *ith* generator

B. Probabilistic output prediction model of WTG

If combining all sums of outputs(supply)($TCAP_k$=TG_k+ TW_k) from the virtual operation rewritten by considering FOR of CG and WTG and uncertainties of wind speed in order to use MCS. On the other hand, if formalizing the differences, it is as shown in (8).

$$TW_k = \sum_{i \in \Omega_{NGW}} WG_{i,k} \tag{8}$$

where,
Ω_{NGW} : WTG set(NGW : Number of WTG)
$WG_{i,k}$: output of the *ith* WTG at *kth* state [MW] [MW]

C. Estimation of reliability index by MCS

Fig. 4 shows the load given as well as the aggregate output of all states from the artificial operation reformed considering the CG's and WTG's forced outage rates and the uncertainties of wind speed based on the MCS. The overlap resulting from the load outweighing the supply indicates the supply failure.

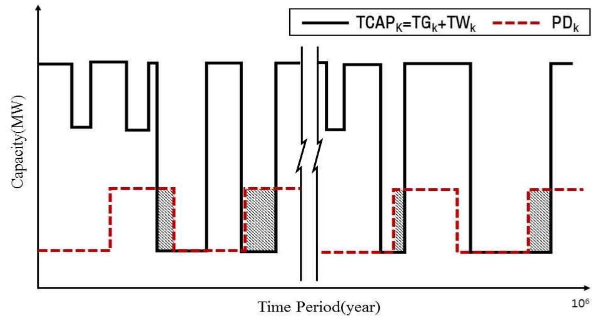

Fig. 4. An example of load combined with CG and WTG probabilistic power (TG_k+TW_k) for states

D. Reliability evaluation of power system with ESS

This paper focuses on the HLI(Hierarchical Level I)[4~13], assuming that multiple WTG complexes are present, that each complex has ESS installed, and that each adopts appropriate control system for charging and discharging.

Here, X%[pu] denotes the allowable maximum output rate relative to the load imposed on WTG in any state as a constraint on WTG operation. This can be expressed as a certain rate of load in each state. The present paper sets forth three principles of operation with a view to maximizing the reliability[4~8].

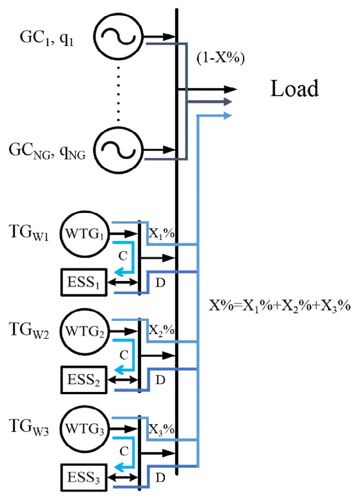

Fig. 5. Proposed Models of CG and WTG combined with Multi-ESS

1) WTG and CG operation conditions combined with ESS

The amounts of WTG which can be directly supplied for the load and which can be stored in the ESS should be calculated separately. The total outputs of WTG and CG in #k state are calculated using the MCS method. Therefore, the output of WTG that can be charged in the ESS available to the load is determined as in the (9). Also, the mandatory amount of CG(SG_{ck}) requiring the discharge of ESS is determined as in the (10). These are either '+' or '-' values.

$$SG_{wi,k} = TG_{wi,k} - X_i\% \times L_k \quad (9)$$

$$SG_{ci,k} = TG_{ci,k} - (1 - X_i\%) \times L_k \quad (10)$$

where,

$SG_{wi,k}$: WTG maximum permissible output per load of the *ith* WTG at *kth* state [MW]

$SG_{ci,k}$: CG compulsory output of the *ith* CG at *kth* state [MW]

$TG_{wi,k}$: Total capacity of the *ith* WTG at *kth* state [MW]

$TG_{ci,k}$: Total capacity of the *ith* CG at *kth* state [MW]

$X_i\%$: Percentage of a wind power dispatch restriction to power load of the *ith* WTG[pu]

L_k: Load at *kth* state[MW]

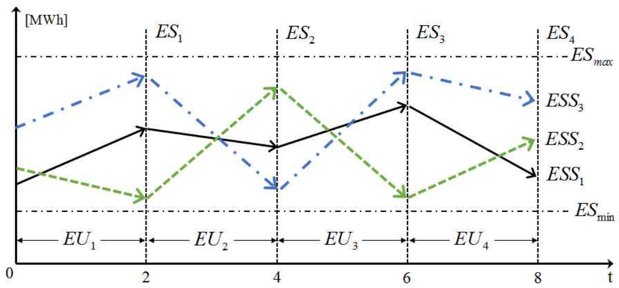

Fig. 6. ESS charge/discharge state(SOC) transition feature

2) ESS Energy State Equation

If formalizing the equation of energy state of ESS at the foresaid operating conditions of ESS, it is as shown in (11) and the state of charge(SOC) is set to satisfy the maximum and minimum energy constraints like in (12).[4,5]

$$ES_{i,k} = ES_{i,k-1} + EU_{i,k} \quad (11)$$

$$ES_{\min,i} \le ES_{i,k} \le ES_{\max,i} \quad (12)$$

where,

$ES_{i,k}$: Energy stored in ESS of the *ith* ESS at *kth* state [MWh]

$EU_{i,k}$: Energy variation of the *ith* ESS at *kth* state [MWh]

$ES_{\max,i}$: Maximum energy capacity of the *ith* ESS [MWh]

$ES_{\min,i}$: Minimum capacity of the *ith* ESS [MWh]

3) ESS control energy(EU_k)

ESS state of charge(SOC), or ES_k[MWh], and control energy, or EU_k[MWh], are calculated with the (13) and (14), respectively[4,5]. The actual EU_k, should meet the constraint conditions in the (15), (16) and (17).

$$ES_{i,k+1} = \begin{cases} ES_{i,k} + SG_{wi,k} \times t_k & SG_{wi,k} \ge 0 \, and \, SG_{ci,k} \ge 0 \\ ES_{i,k} + SG_{ci,k} \times t_k & SG_{wi,k} \ge 0 \, and \, SG_{ci,k} < 0 \\ ES_{i,k} & SG_{wi,k} < 0 \, and \, (SG_{wi,k} + SG_{ci,k}) \ge 0 \\ ES_{i,k} + (SG_{wi,k} + SG_{ci,k}) \times t_k & SG_{wi,k} < 0 \, and \, (SG_{wi,k} + SG_{ci,k}) < 0 \end{cases} \quad (13)$$

$$EU_{i,k} = \begin{cases} SG_{wi,k} \times t_k & SG_{wi,k} \ge 0 \, and \, SG_{ci,k} \ge 0 \\ SG_{ci,k} \times t_k & SG_{wi,k} \ge 0 \, and \, SG_{ci,k} < 0 \\ 0 & SG_{wi,k} < 0 \, and \, (SG_{wi,k} + SG_{ci,k}) \ge 0 \\ (SG_{wi,k} + SG_{ci,k}) \times t_k & SG_{wi,k} < 0 \, and \, (SG_{wi,k} + SG_{ci,k}) < 0 \end{cases} \quad (14)$$

▶ Maximum constraint on charge/discharge control

$$-EU_{\max,i} \le EU_{i,k} \le EU_{\max,i} \quad (15)$$

$$EU_{\max,i} = [(ES_{\max,i} - ES_{\min,i}) / TM_{ESS,i}] \times \Delta t \quad (16)$$

where,

$TM_{ESS,i}$: Operation time from $ES_{\max,i}$ to $ES_{\min,i}$ of the *ith* ESS [hours]

▶ Maximum permissible energy constraint on charge/ discharge in line with the maximum capacity constraint of ESS

$$ES_{\min,i} \le ES_{i,k} + EU_{i,k} \le ES_{\max,i} \quad (17)$$

Therefore, if EU_k considering the constraint condition is EU_k^*, it can be smaller than (14), and if EU_k^* is in discharge mode(-) and EU_k^* is smaller than TG_{Dk}, supply failure occurs. This state set is denoted by Ω_D^-.

$$TG_{Di,k} = \begin{cases} 0 & SG_{wi,k} \ge 0 \, and \, SG_{ci,k} \ge 0 \\ -SG_{ci,k} \times t_k & SG_{wi,k} \ge 0 \, and \, SG_{ci,k} < 0 \\ 0 & SG_{wi,k} < 0 \, and \, (SG_{wi,k} + SG_{ci,k}) \ge 0 \\ -(SG_{wi,k} + SG_{ci,k}) \times t_k & SG_{wi,k} < 0 \, and \, (SG_{wi,k} + SG_{ci,k}) < 0 \end{cases} \quad (18)$$

A. Reliability Evaluation and ESS Reliability contribution Function

To calculate the reliability index, we used the MCS method. In general, the MCS-based supply reliability indices for power systems with ESS considered are formulated as (19), (20) and (21). [4,5,13].

$$LOLE = \frac{1}{NY} \sum_{k \in \Omega_D} t_k \quad (19)$$

$$EENS = \frac{1}{NY} \sum_{k \in \Omega_D} (TG_{Dk} + EU_k) \quad (20)$$

$$EIR = 1 - \frac{EENS}{TDE} \quad (21)$$

where,

NY: Years of MCS(Monte Carlo Simulation) [years]

Ω_D: A set of discharge mode

t_k: Probability of supply failure at *kth* state

NSS: Total number of samples (states)

EU_k: Discharging control energy as a negative value [MWh]

TG_{Dk}: Discharge energy indispensable for eliminating any lack of supply for load(marked as an absolute value) [MWh]

The Fig. 7 describes the process of evaluating reliability of power system including WTG and ESS.

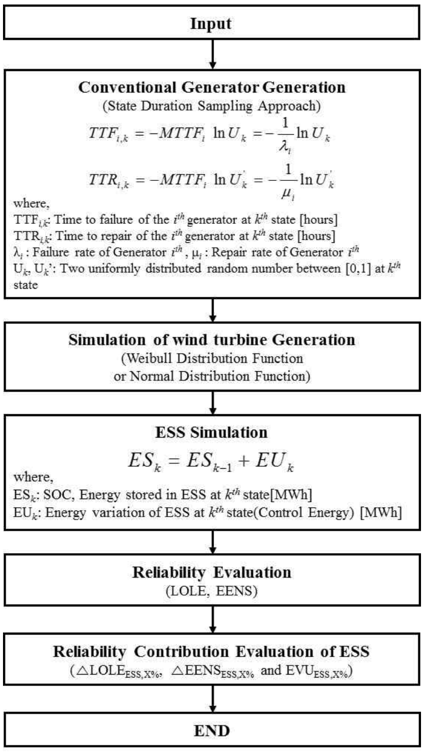

Fig. 7. Flow chart for reliability evaluation of multi WTG& ESS model proposed newly in this study

III. Case Study

In this paper, a model system including WTG and ESS is appropriately applied to a model system similar to that of the Jeju Island power system as shown in Fig. 8. And Jeju Island has wind farms in Hangwon(HWN), Seongsan(SSN), and Hanlim(HLM). Also, the Peak load is L_p=781[MW].[8]

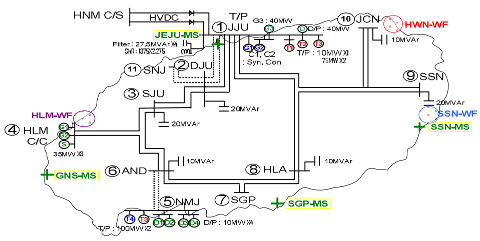

Fig. 8. Power System of Jeju Island

The Generators Data of CG and WTG is described in Table 1. Table 2 shows wind power generation characteristic and wind speed data of HWN, SSN and HLM wind farms.

TABLE 1
THE GENERATORS DATA OF CASE STUDY POWER SYSTEM

	Name	Type	Capacity [MW]	Num.	α [Gcal/ MW²h]	β [Gcal/ MWh]	γ [Gcal/ hour]	Fuel cost (f) [$/Gcal]	FOR
1	HVDC	DC	150	2	0.004	1.512	45.207	43.300	0.028
2	NMJ3	T/P	100	2	0.004	1.512	45.207	43.300	0.012
3	JJU1	T/P	10	1	0.062	2.100	5.971	43.599	0.015
4	JJU2	T/P	75	2	0.003	1.832	30.231	43.599	0.012
5	HLM1	G/T	35	2	0.004	2.401	20.320	77.909	0.013
6	HLM1	S/T	35	1	0.004	2.401	20.320	77.909	0.013
7	JJU3	D/P	40	1	0.025	0.364	28.484	43.599	0.018
8	NMJ1	D/P	10	4	0.006	1.999	1.360	43.300	0.018

TABLE 2
DATA OF WIND SEED AND WTG FOR WIND FARMS

	HWN	SSN	HLM
WTG capacity	100 MW	60 MW	40 MW
Scale Parameter	3.42m/s	3.42m/s	3.42m/s
Shape Parameter	1.85m/s	1.85m/s	1.85m/s

Table 3 shows the ESS Specification with assumption of installation in power system in this case study.

TABLE 3.
ESS SPECIFICATION

	Max. Capacity (ES_M) [MWh]	Min. Capacity (ES_m) [MWh]	Time length for charge/discharge [hours]	X% [pu]	Initial SOC of ESS [MWh]
HWN ESS_1	50	10	1	0.1	15
SSN ESS_2	30	10	1	0.1	15
HLM ESS_3	20	10	1	0.1	15

Fig. 9 shows the load variation curve (pattern) for a model system in a case study, and Fig. 10 describe variation curves of mean wind speed from 1998 to 2007 in Jeju for reference[9].

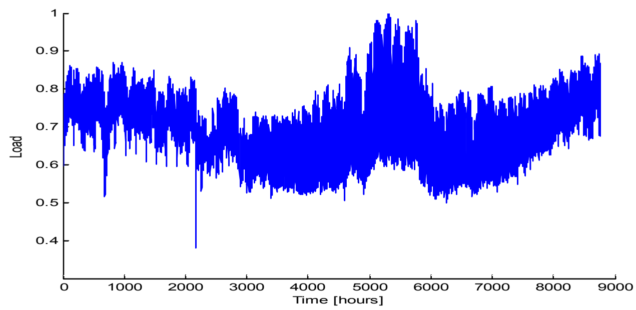

Fig. 9. The load variation curve (pattern) of power system

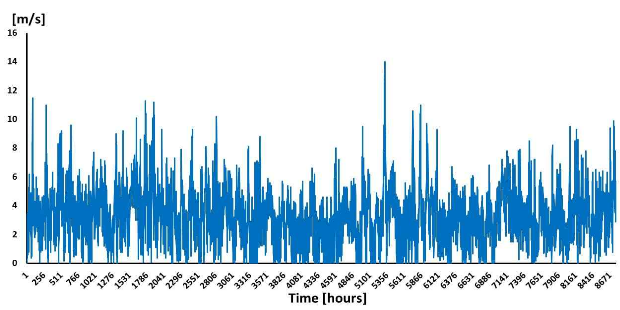

Fig. 10. The wind speed variation curve (pattern) of power system (α=3.42, β=1.85) (1998~2007)

1) Comparison of Reliability indices when WTG combined with ESS (X%=0.2)

In order to examine the effect of the installation of Multi-ESS variously in terms of reliability, three model systems were assumed. Table 4 shows the reliability evaluation.

TABLE 4
RELIABILITY EVALUATION RESULT OF MODEL SYSTEM

	System A (With WTG Without ESS)	System B (Without WTG+ESS)	System C (With WTG+ESS)
Total Capacity [MW]	1045	845	1145
LOLE [Hours/day]	47.33	83.51	0.504
EENS [MWh/day]	2292.0	4220.4	15.2
EIR	0.99956	0.9991899	0.9999971

The following three cases are considered:
- System A: Conventional Generator and WTG without ESS
- System B: Only Conventional Generator
- System C: Conventional Generator and WTG with ESSs

A. *Comparison of WTG and Single-ESS combined power system*

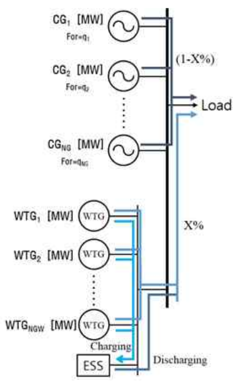

Fig. 11. Model System of Single-ESS

To delve into the effects of multi-ESS on the reliability where an ESS is installed for each of multiple WTG sources, the multi-ESS is compared with the single-ESS where an ESS is installed for multiple WTGs as in Fig. 11. Table 5 compares the calculated results from these two model systems. The multi-ESS proves to be 64 times more reliable than the single-ESS[8].

TABLE 5
RELIABILITY COMPARISON BETWEEN SINGLE-ESS AND MULTI-ESS

	Single-ESS	Multi-ESS
Total Capacity [MW]	1145	1145
LOLE [Hours/day]	32.694	0.504
EENS [MWh/day]	1864.8	15.2
EIR	0.999642	0.9999971

IV. CONCLUSIONS

This study proposes new methodology to evaluate the contribution to supply of reliability. The proposed method can be used to predict the effects of ESS from the aspect of supply of reliability if ESS is installed to a WTG to reduce output variability. It is expected that the sources of new renewable energy generation such as a wind turbine generator with a high output variability will be penetrated highly into the power system rapidly in near future.

The models and methods developed in this study are expected to be the basis for developing a technology to relieve the current circumstances of fears and constraints significantly by incorporating the sources of new renewable energy generation into the power system because the variability in output is very high. In particular, as it is expected that sources of new renewable energy generation worldwide are incorporated into the power system more rapidly from the Paris Agreement on Dec. 12, 2015, this study is considered to be a starting point for further multifaceted researches.

4) ACKNOWLEDGMENT

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