RELIABILITY EVALUATION FOR ENERGY STORAGE SYSTEM COMBINED WITH RENEWABLE ENERGY SOURCES

Wook-Won KIM
Hanyang University, Korea
neocruser@hanyang.ac.kr

Je-Seok SHIN
Hanyang University, Korea
kjboy@hanyang.ac.kr

Jin-O KIM
Hanyang University, Korea
jokim@hanyang.ac.kr

ABSTRACT

This paper proposes the method for reliability evaluation of energy storage system combined with renewable energy sources. Time varying capacity outage probability table (COPT) calculated by convolution of probability mass function of each generator is used for evaluating proposed method. State models for conventional generators, renewable energy sources (RES) and energy storage system (ESS) are proposed for COPT. Power dispatch rule is also proposed to extend its duration for multiple ESSs. Case studies show the result of hourly loss of load probability (LOLP) and the effect of ESS capacity in each case.

INTRODUCTION

As increasing concern about energy security and climate change, renewable technologies have actively been introduced. However, it is difficult to control and operate at high penetration of intermittent renewable generation such as photovoltaic and wind generation in a power system. Also, intermittent characteristic of renewable generators decreases the reliability of power system. To enhance the reliability of the system, the study of energy storage technologies have been concentrated.[1, 2]

Energy Storage System (ESS) performs to serve the power as the function to be able to shift the load without directly generating power. However, since the amount of power generation of ESS is limited, different methods to evaluate the reliability should be used for ESS in contrast with conventional method. To do so, reliability modeling of ESS should be preceded to evaluate the reliability. In this paper, state model for various generators including ESS is proposed to reflect the characteristic of ESS. Also it is proposed the method how to distribute the required energy into each ESS among multiple ESSs with maintaining the duration as long as possible to improve the reliability. In the case study, the procedures are shown for energy distribution, change of time varying SOC, the effect of ESS capacity, and reliability indices such as hourly loss of load probability (LOLP) and loss of load energy (LOEE).

ENERGY DISPATCH FOR MULTIPLE ESSS

SystemDescription intergrated with Multiple ESSs

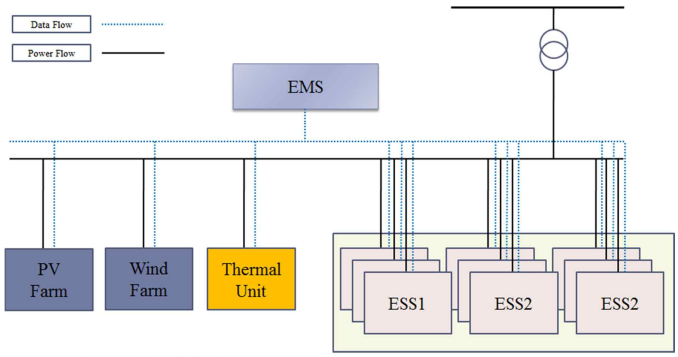

Fig. 1. Simplified Structure of Energy Management System

As shown in Fig. 1, system operator of EMS (Energy Management System) utilizes the smart grid communication and control network to receive real-time updated information and execute the operations. The received information includes load forecast, electric price, SOC of ESS, forecasted output of renewable energy sources (RES).

System operator can control the system using the operation strategy which is determined by information of generators and load. Especially, by the introduction of ESS, it can be flexible in responding to the intermittent characteristic of RES and loss of load situations. If only one ESS exists in the system, it can simply provide energy to the load up to required amount by charging and discharging procedure. However, additional operation strategy and equivalent model of ESS are required for integrated operation if multiple ESSs are introduced in the system, and optimal operation can be implemented by the equivalent model and its operation strategy according to the modes of ESS.

Operation Strategy for Multiple ESSs

If multiple ESSs are participated in generation, ESSs should share the power generation. The best strategy for operating the multiple ESS is to use the available energy with the best suitable purpose during the period that the units are possible[3]. In terms of reliability aspect, if loss of load event occurs, it would be advantageous that ESS generates power as long as possible through available ESSs to decrease the loss of energy. In order to generate for the time as long as possible, it is important that the

each ESS has same duration producing output to share the power appropriately. If C_i^{ESS} and $SOC_{i,t}$ are the capacity and state of charge of *i*-th ESS, respectively, the output of *i*-th ESS at time *t*, $P_{i,t}^{ESS}$ is represented by (1) as a function of duration time *D*

$$P_{i,t}^{ESS}(D) = \frac{C_i^{ESS} \times SOC_{i,t}}{D} \qquad (1)$$
$$where \quad \frac{C_i^{ESS} \times SOC_{i,t}}{D} \le P_{i,\max}^{ESS}$$

The total output of all ESSs, $P_{eq,t}^{ESS}$, is the summation of output of individual ESS, where N^{ESS} is the number of ESS.

$$P_{eq,t}^{ESS} = \sum_{i=1}^{N^{ESS}} P_{i,t}^{ESS}(D) = \sum_{i=1}^{N^{ESS}} \frac{C_i^{ESS} \times SOC_{i,t}}{D} \qquad (2)$$

For example, let consider the multiple ESSs consisting in four ESSs as shown Table I, where rated capacity and maximum output power are given for each ESS, and the rated duration can be calculated by the ratio of these two. Then the graphs of output power of individual and equivalent ESS can be shown in Fig. 2 using (1) and (2) with the assumption of full SOC, i.e., $SOC_{i,t} = 1.0$.

As can be seen in Fig. 2, the output power of individual ESS has knee point due to the constraint of its maximum output power as calculated by (1), and consequently, output power of equivalent ESS has also knee points at the positions corresponding to the duration of individual ESS, $D_{i,rate}^{ESS}$, as many as the number of ESS. The expression of knee points of equivalent ESS is represented by (3) and as a result, the value of four knee points are obtained as 9.06, 0.96, 12.28 and 13 as appeared in Table I.

$$KP_k = \sum_{i=1}^{k-1} P_{i,t}^{ESS}(D_{i,rate}^{ESS}) + \sum_{i=k}^{N^{ESS}} P_{i,t}^{ESS}(D_{k,rate}^{ESS}) \qquad (3)$$

The piecewise inverse function of equivalent output power for the duration at time *t*, D_t , is represented by (4), which is generalized expression for any amount of output power including knee points.

$$D_t(P_{eq,t}^{ESS}) = \frac{\sum_{i=k}^{n} C_i^{ESS} \times SOC_{i,t}}{P_{eq,t}^{ESS} - \sum_{i=1}^{k-1} P_{i,\max}^{ESS}} \qquad (4)$$
$$KP_{k-1} \le P_{eq,t}^{ESS} \le KP_k \quad where\ k = \{1,\ 2,\ \cdots,\ N^{ESS}\}$$

Once the duration is obtained corresponding to the required output from multiple ESSs, output power of individual ESS can be obtained by using (1). Table I shows the amount of power dispatch to all ESSs for their knee points.

Table I. Specification of ESS

	Capacity (MWh) C^{ESS}	Output power (MW) $P_{\max}^{ESS}$	Duration (hour) D_{rate}^{ESS}	KP1 (MW)	KP2 (MW)	KP3 (MW)	KP4 (MW)	P_{eq}^{ESS} (MW)
Eq. ESS	29	13	1.33	9.06	9.86	12.28	13	11
ESS1	8	2.5	3.2	2.5	2.5	2.5	2.5	2.5
ESS2	10	3.5	2.86	3.13	3.5	3.5	3.5	3.5
ESS3	7	4	1.75	2.19	2.46	4	4	3.18
ESS4	4	3	1.33	1.25	1.4	2.29	3	1.82

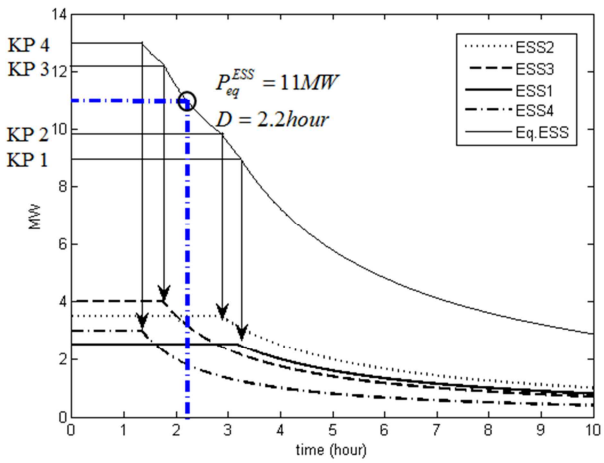

Fig. 2. Output vs duration curve of each ESS and equivalent ESS

In addition to four knee points, power dispatches are also shown in Table I for an arbitrary required power (11 MW), and is depicted in Fig. 2 where the duration of equivalent ESS is 2.2 hour. That means the equivalent ESS can produce output 11 MW up to 2.2 hours with the power dispatch of each ESS as shown in Table I. It is the procedure of energy allocation of ESS for the required amount of energy whose concept is similar with the economic generation dispatch. The purpose of ESS power dispatch is to maximize the duration while economic generation dispatch is to achieve the minimum fuel cost.

The proposed allocation method makes the ESS to discharge the required energy as long as possible as appeared in (4) when the loss of load event occurs. As a result, it enables to reduce the loss of load duration and to improve reliability, and one specific ESS would not take charge of the whole required energy but all ESSs share it adequately and uniformly and thus, it prevents the high depth of discharge and brings about the extension of life time.

RELIABILITY ANALYSIS

Model of Conventional Generator

Conventional generators (CG) are generally represented by two-state model for the purpose of the reliability

evaluation [4, 5], unavailability Forced Outage Rate (FOR) of i-th conventional generators are given by (1), where λ and μ mean failure and repair rates for up and down states, respectively.

$$FOR_i^{CG} = \frac{\lambda_i^{CG}}{\lambda_i^{CG} + \mu_i^{CG}} \tag{1}$$

The probability that i-th generator has an output of P_i^{CG} is represented by (2), and is called output probability mass function (PMF).

$$f_i^{CG}(x) = \begin{cases} 1 - FOR_i^{CG}, & x = P_i^{CG} \\ FOR_i^{CG}, & x = 0 \end{cases}$$

Model of Renewable Energy Sources

Large sized RES such as wind farm and photovoltaic system are configured with the large number individual units in the same location. Therefore, each unit of wind farm or PV has similar output characteristic. This characteristic enables simplified model of wind farm or PV system. If wind farm or PV system consists of N units which are assumed to be identical, they also have identical failure and repair rates. Therefore, state model of RES can be described as derated-state model, where the number of the states is (N+1) due to the number of failures from N units up (State 1) to zero unit up (State N+1) as shown in Fig. 1. Failure and repair rates between i state and (i+1) state are given by (3) and (4), respectively.

$$\lambda_{(i)(i+1)} = (N - i + 1)\lambda \tag{3}$$

$$\mu_{(i+1)(i)} = i\mu \tag{4}$$

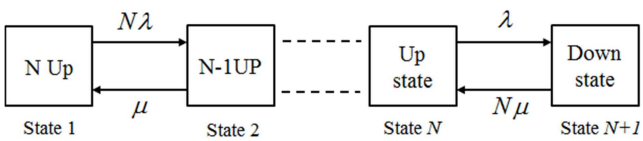

Fig. 1. Derated state model of RES

For the (N+1)-drated states of RES as stated above, the PMF of wind farm or PV is given by (5) using Binomial distribution, where N is the number of up units, N^{RES} is total number of RES, and FOR^{RES} is the FOR of individual RES as similarly as (1).

$$f_t^{RES}(x) = \binom{N^{RES}}{\frac{x}{P_t^{RES}}} \times (1 - FOR^{RES})^{\frac{x}{P_t^{RES}}} FOR^{N^{RES} - \frac{x}{P_t^{RES}}} \tag{5}$$

where $x = NP_t^{RES}$, $N = 0, 1 \ldots\ldots N^{RES}$

Model of Energy Storage Systems

Reliability evaluation of system including only conventional generators is based on capacity of generator as shown (2). On the contrary, generation ability increases up to the rated power of ESS as SOC increases, and amount of generation is limited by its capacity and SOC at that time as shown in Fig. 3, and therefore, the generation ability of ESS can be represented by (6).

$$V_t^{ESS} = \begin{cases} C^{ESS} / \Delta t & where\ \ \mathrm{SOC}_t < P_{\max}^{ESS} \times \Delta t / C^{ESS} \\ P_{\max}^{ESS} & where\ \ SOC_t \geq P_{\max}^{ESS} \times \Delta t / C^{ESS} \end{cases} \tag{6}$$

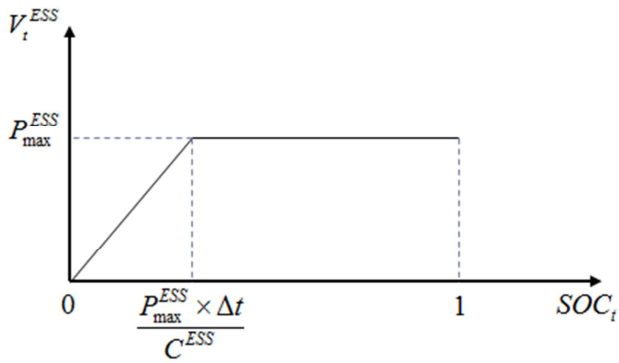

Fig. 3. Concept of generation ability of ESS

Therefore, the generation ability of ESS at UP state is time-varying dependent on SOC level as shown in Fig. 4 while conventional generators use the fixed one P_i^{CG} for reliability evaluation. The failure and repair rates of ESS are assumed to be constant and independent on the degradation.

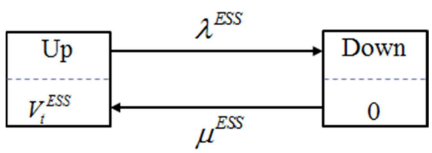

Fig. 4. State model of ESS

Finally, PMF of ESS can be represented by (7) as similar as the one of conventional generators except the time-varying capacity.

$$f_t^{ESS}(x) = \begin{cases} 1 - FOR^{ESS}, & x = V_t^{ESS} \\ FOR^{ESS}, & x = 0 \end{cases} \tag{7}$$

where $FOR^{ESS} = \dfrac{\lambda^{ESS}}{\lambda^{ESS} + \mu^{ESS}}$

Reliability Assessment for Iintegrated System

In order to obtain the reliability constraint, it is necessary to evaluate the hybrid Capacity Outage Probability Table (COPT) including RES and ESS as well as the conventional generators. Generally, COPT of

n conventional generators can be represented by convolution of each PMF of generators as shown in (8) [6], where the capacity of COPT is assumed to be the step of 1 MW.

$$f^{CG}(X^{CG}) = f_1^{CG} * f_2^{CG} * \cdots * f_n^{CG}$$
$$X^{CG} = 0,\ 1, \cdots, \sum_{i=1}^{n} P_i^{CG} \tag{8}$$

where the representation of f_i^{CG} is appeared in (2).

The system COPT including all energy resources is also represented by (9), where f_t^{RES} and f_t^{ESS} are from (5) and (7), respectively.

$$f_t^{CG,RES}(X) = f^{CG} * f_t^{RES}$$
$$f_t^{SYS}(X) = f^{CG,RES} * f_t^{ESS} \tag{9}$$
$$X = 0,\ 1,\ \cdots,\ \left(N^{RES} P_t^{RES} + \sum_{i=1}^{n} P_i^{CG} + V_t^{ESS} \right)$$

Loss of Load Probability at time t, $LOLP_t$, is defined by the probability that the power cannot afford the load at time t, L_t, and is given by (10).

$$LOLP_t = 1 - \sum_{X=L_t}^{P_{\max}+V_t^{ESS}} f_t^{SYS}(X) \tag{10}$$

CASE STUDY

Test System Data

Modified data of generators in IEEE 118-bus test system is used for case study. The system consists in 11 conventional generators, 1 wind farm, 1 PV plant, and 4 ESSs. Since there are no reliability data in IEEE 118-bus system, data of conventional generators is adopted from IEEE-RTS 24-bus as shown in Table II, where data for RES and ESS are also included in addition. Specification of four ESSs is already given in Table I, and their reliability data are assume to be identical as shown in Table II. Output of PV and wind farm are shown in Fig. 3 with solid and dotted lines, respectively, and expected hourly load profile is shown in Fig. 4 for one week.

TABLE II. GENERATOR DATA

Unit	Pmax (MW)	Forced Outage Rate	MTTF (Hour	MTTR (Hour)	Unit Type
1	10	0.01	0	0	Wind
2	10	0.01	0	0	PV
3	35	0.08	1150	100	Coal/Steam
4	42	0.12	1100	150	Nuclear
5	25	0.02	1960	40	Coal/Steam
6	20	0.04	1200	50	Oil/Steam
7	30	0.04	960	40	Coal/Steam
8	10	0.05	950	50	Oil/Steam
9	10	0.02	2940	60	Oil/Steam
10	8	0.02	2940	60	Oil/Steam
11	5	0.1	450	50	Oil/CT
12	3	0.1	450	50	Oil/CT
13	2	0.1	450	50	Oil/CT
14	-	-	1000	50	ESS

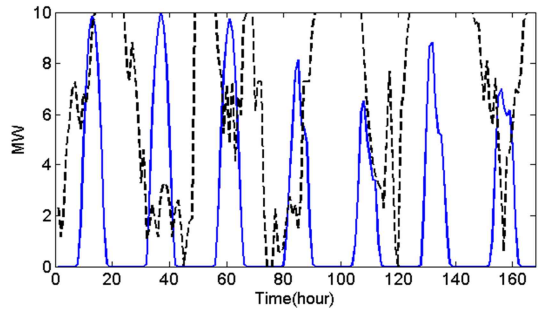

Fig. 3. PV and wind farm output

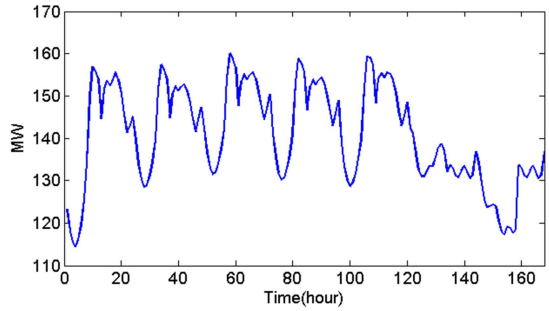

Fig. 4. Load profile

Reliability Evaluation

Fig. 5 shows the capacity model of all generators without ESS based on the COPT of $f^{CG,RES}$ appeared in (9), which is obtained by performing MCS with the reliability data given in Table II. The power balance can be obtained by subtracting the load (Fig. 4) from power output (Fig. 5) during the period of only 2020 to 2060 hour for the visibility and is shown by dotted line in Fig. 6. In this figure, charging and discharging operation of ESS occur at the periods of positive and negative balance, respectively, where power dispatches of each ESS are depicted in the bar charts based on the dispatch rule explained in (1) - (4).

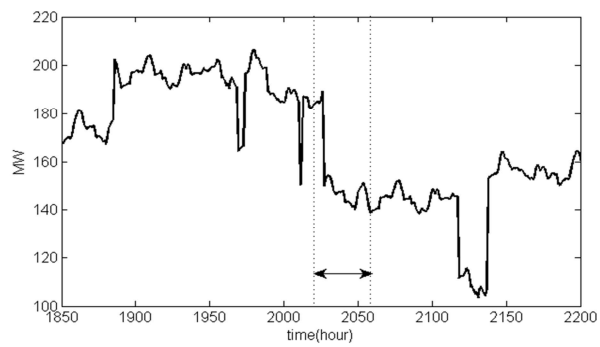

Fig. 5. Capacity model of all generators without ESS

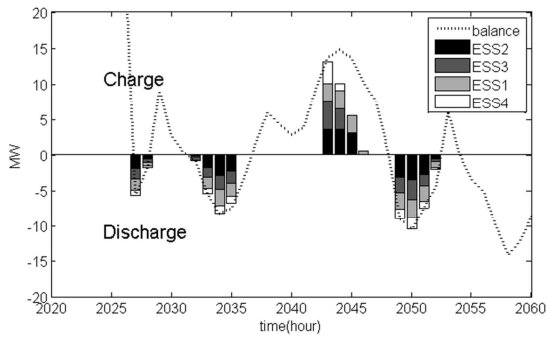

Fig. 6. Power-load balance and distributed output of ESSs

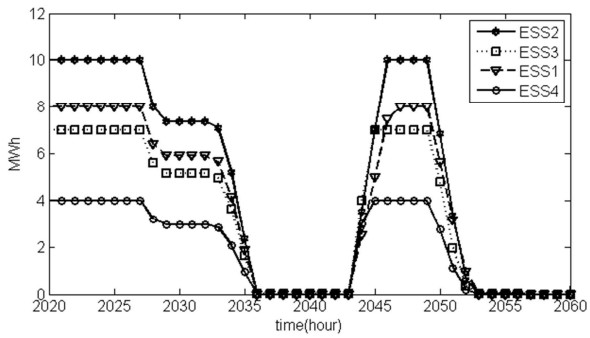

Fig. 7. Change of SOC

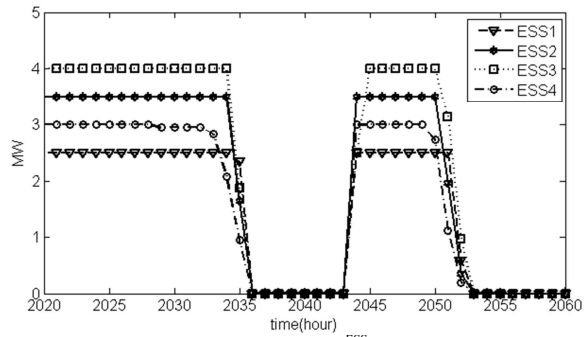

Fig. 8. Generation ability(V_t^{ESS}) of each ESS

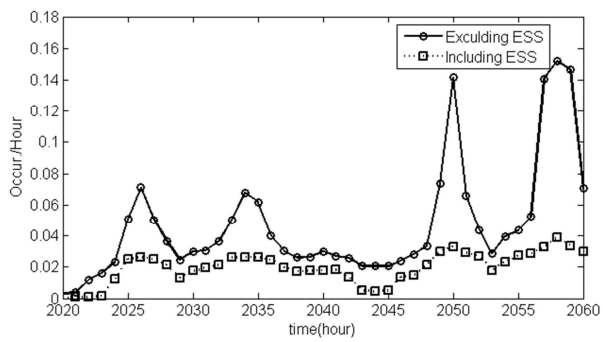

Fig. 9 Hourly LOLP

The SOC levels of each ESS are varied as shown in Fig. 7, where increase and decrease of SOC level are coincident with the charging and discharging periods, respectively. The generation abilities of each ESS are also varied with the change of SOC level as explained in (6) and Fig. 3, and are shown in Fig. 8. Finally, hourly LOLP can be obtained by (10) as shown in Fig. 9 with the cases with and without ESS. It can be observed that the LOLP is improved significantly with ESS.

CONCLUSION

In this paper, the state models for various generators including RES and ESS are proposed, which are used for time-varying COPT calculated by convolution of probability mass function of each generator. Also power dispatch rule for multiple ESSs is proposed to extend its duration to produce the required power for charging and discharging periods. Whit this dispatch rule, reliability index LOLP is evaluated at the case study by using the data of 14 generating units including RES and multiple ESSs, and the efficiency of the proposed methods was demonstrated.

REFERENCES

[1] P. Hu, R. Karki, and R. Billinton, 2009, "Reliability evaluation of generating systems containing wind power and energy storage," *IET Generation, Transmission & Distribution,* vol. 3, 783-791.

[2] X. Yixing and C. Singh, 2014, "Power System Reliability Impact of Energy Storage Integration With Intelligent Operation Strategy," *IEEE Transactions on Smart Grid,* vol. 5, 1129-1137.

[3] R. N. Allan and J. Roman, 1989, "Reliability assessment of generation systems containing multiple hydro plant using simulation techniques," *IEEE Transactions on Power Systems,* vol. 4, 1074-1080.

[4] R. Billinton and R. N. Allan, 1992, *Reliability evaluation of engineering systems: concepts and techniques*, 2nd ed. Plenum Press, New York.

[5] R. Billinton and R. N. Allan, 1996, *Reliability evaluation of power systems*, 2nd ed. Plenum Press, New York.

[6] R. N. Allan, A. M. Leite da Silva, A. A. Abu-Nasser, and R. C. Burchett, 1981, "Discrete Convolution in Power System Reliability," *IEEE Transactions on Reliability,*, vol. R-30, 452-456.