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Operation Strategy of Multi-Energy Storage System Considering Power System Reliability

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***Abstract*—**As the penetration of Energy Storage System (ESS) increases in the power system due to higher performance and lower cost than ever, ESS is expanding its role to the ancillary service as well as the storage of extra energy from the intermittent renewable energy resources. For multi-ESS with different capacity and SOC level each other, it is required to make the optimal schedule of SOC level use the multi-ESS effectively. This paper proposes the energy allocation method for the multiple battery ESS with reliability constraint, in order to make the ESS discharge the required energy as long as possible. A simple but effective method is proposed in this paper, to satisfy the power for the spinning reserve requirement while improving the system reliability. Modelling of ESS is also proposed, and reliability is evaluated by using the combined reliability model which includes the proposed ESS model and conventional generation one. In the case study, it can be observed that the required power is distributed to each ESS adequately and accordingly, the SOC is scheduled to improve the reliability indices such as Loss of Load Probability (LOLP) and Loss of Load Expectation (LOLE).

***Keywords*—**Multiple energy storage system, energy allocation method, SOC schedule, reliability constraints.

I. INTRODUCTION

SINCE Paris Agreement for Climate Change, most countries have had some plans to increase the Renewable Energy Sources (RES) to replace the conventional generators in order to reduce the emission of CO_2. In this case, however, due to the intermittent output characteristic of RES, it threatens the stability of power systems, and recently, ESS attracts the attention to resolve this problem. ESS has been mainly used for obtaining stable output by connecting RES and grid between these two so as to mitigate the unstable output of RES [1], [2]. The other applications of ESS are for the ancillary service of power system such as voltage stability, frequency regulation, spinning reserve, and so on [3], [4]. According to the expansion of penetration of ESS, ESSs with different capacities and output powers spread out into the regional wide and they should be operated by the integrated control scheme to adjust their SOC (State of Charge) in specific time optimally with different capacity and output.

In this paper, when ESS is applied for the usage of spinning reserve, the optimal dispatch strategy is proposed for the adequate SOC level of each ESS in the aspect of reliability of power system.

II. OPERATION STRATEGY OF MULTIPLE ESSS

A. System Description Integrated with Multiple ESSs

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

System operator can control the system using the operation strategy which is determined by the 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 for the load up to required amount by charging and discharging procedure. However, additional operation strategy and equivalent model of ESS are required for the 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.

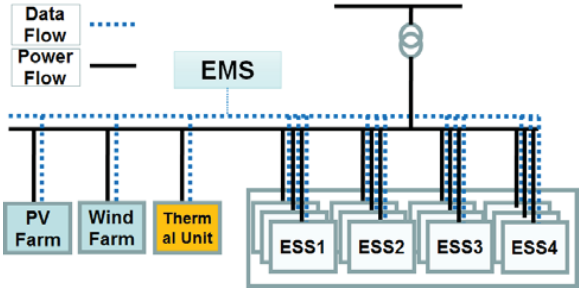

Fig. 1 Simplified Structure of EMS

B. Operation Strategy for Spinning Reserve Service

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 [5]. In the aspect of spinning reserve service, 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 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

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

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.

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

For example, let us consider the multiple ESSs consisting in four ESSs as shown Table I, where the rated capacity and the 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 by 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 values of four knee points are obtained as 9.06, 0.96, 12.28, and 13 as appeared in Table I.

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

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

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.

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

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. In addition to four knee points, power dispatches are also shown in Table I for an arbitrary required power (11 MW), and are depicted in Fig. 2 where the duration of equivalent ESS is 2.2 hour. It means that 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 the economic generation dispatch is to achieve the minimum fuel cost.

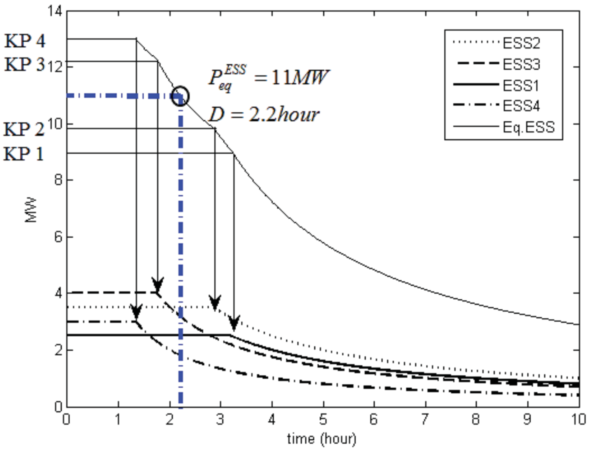

Fig. 2 Output vs duration curve of each ESS and equivalent ESS

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.

III. EVALUATION METHOD FOR PROPOSED STRATEGY

To verify the effectiveness of introducing ESSs according to spinning reserve, reliability assessment is proceeded for the entire system including RES and ESS as well as conventional generations.

A. Generator Models

Conventional generators (CG) and RES are generally represented by two-state or derated model for the purpose of the reliability evaluation [6], [7]. and the unavailability (FOR: Forced Outage Rate) of *n*-th conventional generator is given by (5), where λ and μ are the failure and repair rates for up and down states, respectively.

$$FOR_n^{CG} = \frac{\lambda_n^{CG}}{\lambda_n^{CG} + \mu_n^{CG}} \tag{5}$$

The probability that *n*-th generator has an output of P_n^{CG} is represented by (6), and is called by the output probability mass function (PMF).

$$f_n^{CG}(x) = \begin{cases} 1 - FOR_n^{CG}, & x = P_n^{CG} \\ FOR_n^{CG}, & x = 0 \end{cases} \tag{6}$$

Similarly, PMF for various RES can be expressed by (7) using binary distribution,

$$f_t^{RES}(x) = \begin{pmatrix} N^{RES} \\ \dfrac{x}{P_t^{RES}} \end{pmatrix} \times (1 - FOR^{RES})^{\frac{x}{P_t^{RES}}} FOR^{N^{RES} - \frac{x}{P_t^{RES}}} \tag{7}$$

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

B. ESS

SOC_t of ESS is defined by the ratio of available energy to its capacity at time *t*, and the output of ESS, P_t^{ESS} [MW], can be obtained by multiplication of the initial capacity of ESS, C_0^{ESS} [MWh], and incremental rate of State of Charge (SOC) at time *t*, as given in (8)

$$P_t^{ESS} = \frac{\Delta SOC_t}{\Delta t} \times C_0^{ESS} \tag{8}$$

where

$$\Delta SOC_t = SOC_{t-1} - SOC_t \tag{9}$$

Reliability evaluation of system composed of conventional generators only is based on the rated power of generator. However, the evaluation of reliability including ESS should be estimated by the availability of generation, not the output power P_t^{ESS}, because generating amount of ESS is limited by its capacity and SOC of ESS. In this paper, generation ability of ESS, instead of output power, is newly defined as the available output power of ESS during charging/discharging time Δt, which is restrictive according to its rated power as shown in Fig. 3. Generation ability of ESS, V_t^{ESS} [MW], increases up to its maximum output and limited to its rated power, $P_{\max}^{ESS}$, as expressed as (10):

$$V_t^{ESS} = \begin{cases} C_t^{ESS} / \Delta t \times SOC_t, & SOC_t < P_{\max}^{ESS} \times \Delta t / C_t^{ESS} \\ P_{\max}^{ESS}, & otherwise \end{cases} \tag{10}$$

where C_t^{ESS} is the degraded capacity of ESS at time *t* according to its aging.

State model of ESS is represented by two states similar to the conventional generators, and PMF of ESS can be obtained by (11) as similar as (6), by using the generation ability instead of generation output.

$$f_t^{ESS}(x) = \begin{cases} 1 - FOR^{ESS}, & x = V_t^{ESS} \\ FOR^{ESS}, & x = 0 \end{cases} \tag{11}$$

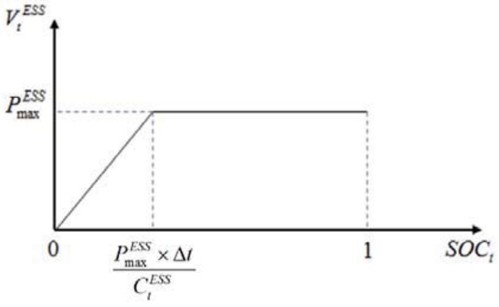

Fig. 3 Concept of generation ability of ESS

C. Reliability Assessment for Integrated Systems

This paper proposes the hybrid method that is combined with stochastic and MCS methods for the reliability assessment. Entire procedures are shown in Fig. 4. The operation strategy of ESS is decided after the amount of load and power is determined because the operation strategy depends on power-load balance. Initially, ESS is operated by the proposed strategy using chronological load and capacity model evaluated by MCS. After that, the level of SOC and generation ability is calculated. Finally, hourly reliability is evaluated by stochastic method. In order to obtain the hourly reliability, 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 the convolution of each PMF of generators as shown in (12), where the capacity of COPT is assumed to be the step of 1 MW.

$$\begin{gathered} f^{CG}(X^{CG}) = f_1^{CG} * f_2^{CG} * \cdots * f_n^{CG} \\ X^{CG} = 0,\ 1, \cdots, \sum_{i=1}^{n} P_i^{CG} \end{gathered} \tag{12}$$

where the representation of f_i^{CG} is appeared in (6).

The system COPT including all energy resources is also represented by (13), where f_t^{RES} and f_t^{ESS} are from (7) and (11), respectively.

$$
\begin{aligned}
&f_t^{CG,RES}(X) = f^{CG} * f_t^{RES} \\
&f_t^{SYS}(X) = f^{CG,RES} * f_t^{ESS} \qquad (13)\\
&X = 0,\ 1,\ \cdots\ ,\ \left(N^{RES} P_t^{RES} + \sum_{i=1}^{n} P_i^{CG} + V_t^{ESS} \right)
\end{aligned}
$$

LOLP 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).

$$LOLP_t = 1 - \sum_{X=L_t}^{P_{\max}+V_t^{ESS}} f_t^{SYS}(X) \qquad (14)$$

Output duration of ESS is limited by its capacity and SOC. It is not appropriate to evaluate only LOLP index because LOLP simply indicates the probability of loss of load, shortage of energy is not reflected. This means that the energy-related reliability indices are also contemplated. Therefore, in this paper, hourly LOEE (Loss of Energy Expectation) is also considered and given by (15).

$$LOEE_t = \sum_{X=X^{CG,RES}+V_t^{ESS}}^{L_t} (L_t - X) f_t^{SYS}(X) \qquad (15)$$

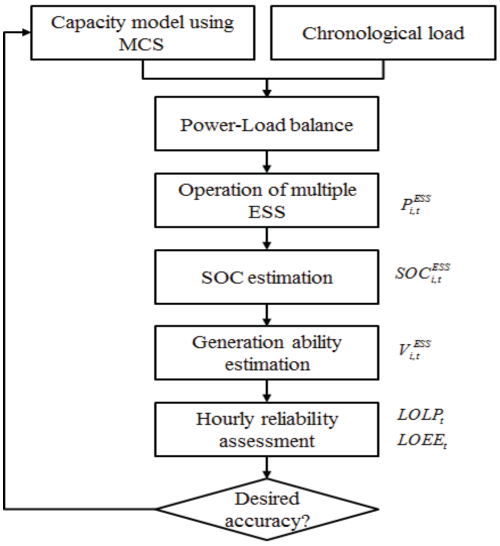

Fig. 4 Entire procedure of reliability assessment

IV. Case Study

A. Test System Data

Modified data of generators in IEEE 118-bus test system are used for the 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 are 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 assumed to be identical as shown in Table II. Output of PV and wind farm are shown in Fig. 5 with solid and dotted lines, respectively, and expected hourly load profile is shown in Fig. 6 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

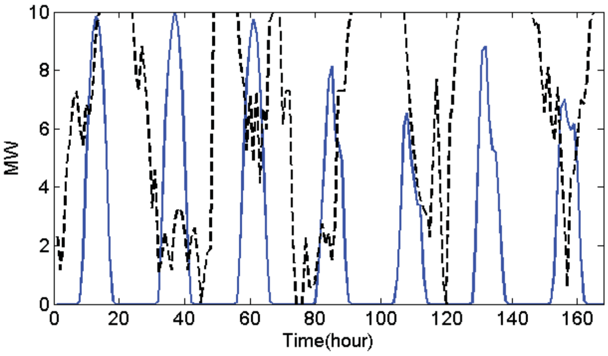

Fig. 5 PV and wind farm output

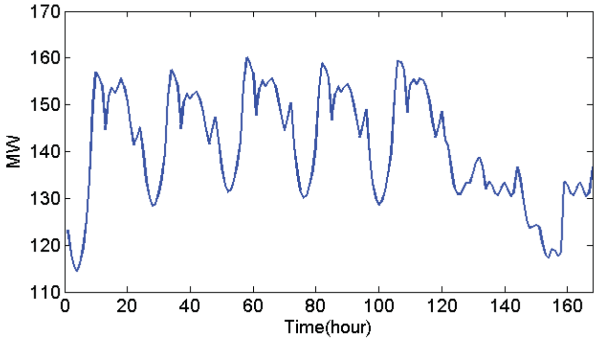

Fig. 6 Load Profile

B. Effect of Spinning Reserve Service

In the case study, in order to verify the effectiveness of the proposed method, reliability is evaluated in the three cases. Case 1 is evaluated reliability without ESS. In case 2, charging/discharging ESSs are based on its capacity in large capacity order. Case 3 is performed the charge/discharge by using the proposed method for evaluating the reliability. Fig. 9 shows the capacity model of all generators without ESS based on the COPT of $f^{CG,RES}$ appeared in (13), 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. 6) from power output (Fig. 7) during the period of only 2020 to 2060 hour for the visibility and is shown by dotted line in Figs. 8 and 9. In these figures, 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). The detailed amount of dispatched power is also tabularized in Table III during some of this period.

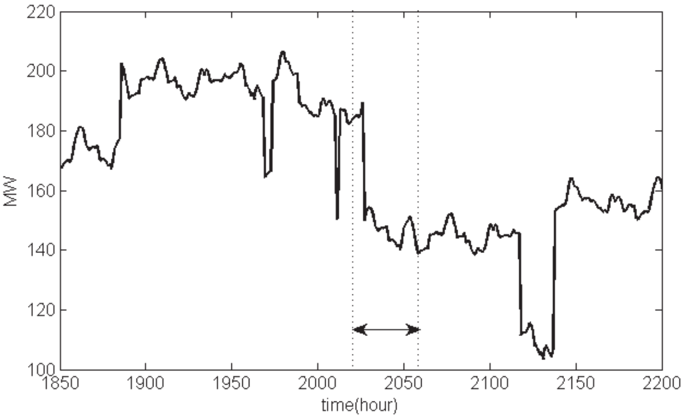

Fig. 7 Capacity model of all generators without ESS

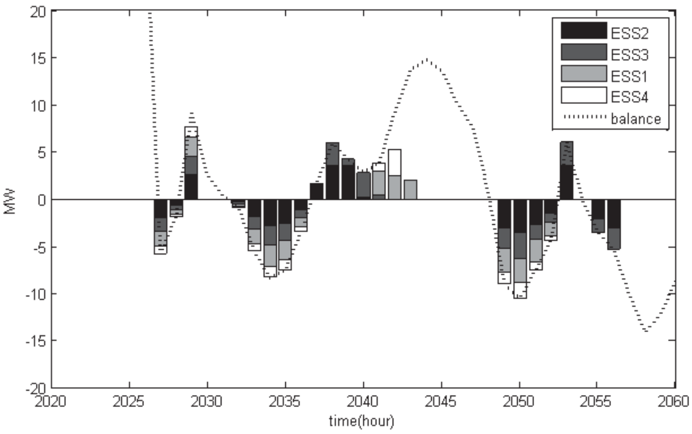

Fig. 8 Power-load balance and distributed output of ESSs

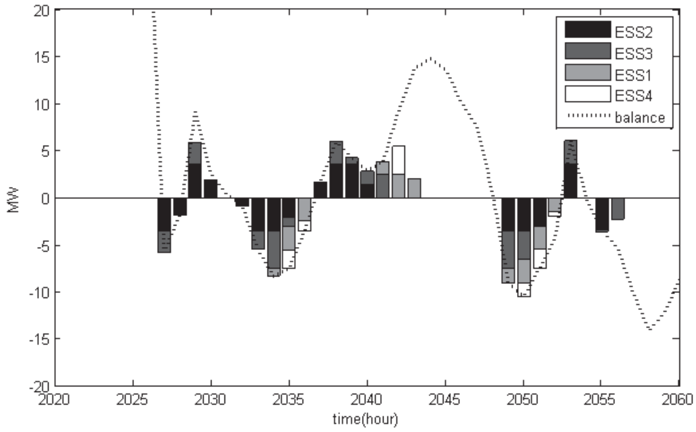

Fig. 9 Power-load balance and distributed output of ESSs (base case)

Same energy is spent in both case 2 and case 3 during same period. However, in case 2, loss of load is occurred during 4 hours, while only 2 hours in case 3. These result show that the proposed method has competent for suppling ability more than case 2.

The SOC levels of each ESS are varied as shown in Figs. 10 and 11, 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 (10) and Fig. 3, and are shown in Fig. 12. Finally, hourly LOLP and LOEE can be obtained by (14) and (15), and shown in Figs. 13 and 14 with the cases with and without ESS. It can be observed that the reliability indices are improved significantly with ESS.

TABLE III
POWER DISPATCH OF EACH ESS

		Charge (-), Discharge(+)									
Hour		2049	2050	2051	2052	2053	2054	2055	2056	2057	
Demand requirement		7.5	6.5	9.5	5	-	0.1	3.6	5.3	10	
Case1		-	-	-	-	-	-	-	-	-	-
	ESS1	0	0	2.5	2.5	0	0	0	2.5	0.5	8
	ESS2	3.5	3.5	3	0	-3.5	0.1	3.4	0	0	10
Case2	ESS3	4	3	0	0	-2.5	0	0.2	2.3	0	7
	ESS4	0	0	3	1	0	0	0	0	0	4
		7.5	6.5	8.5	3.5	-6	0.1	3.6	4.8	0.5	
	ESS1	2.07	1.79	2.50	1.49	-1.65	0.03	1.00	0.78	0	8
	ESS2	2.59	2.24	3.33	1.67	-2.07	0.03	1.24	0.96	0	10
Case3	ESS3	1.81	1.57	2.33	1.17	-1.45	0.02	0.87	0.67	0	7
	ESS4	1.03	0.90	1.33	0.67	-0.83	0.01	0.50	0.39	0	4
		7.5	6.5	9.5	5	6	0.1	3.6	2.8	0	

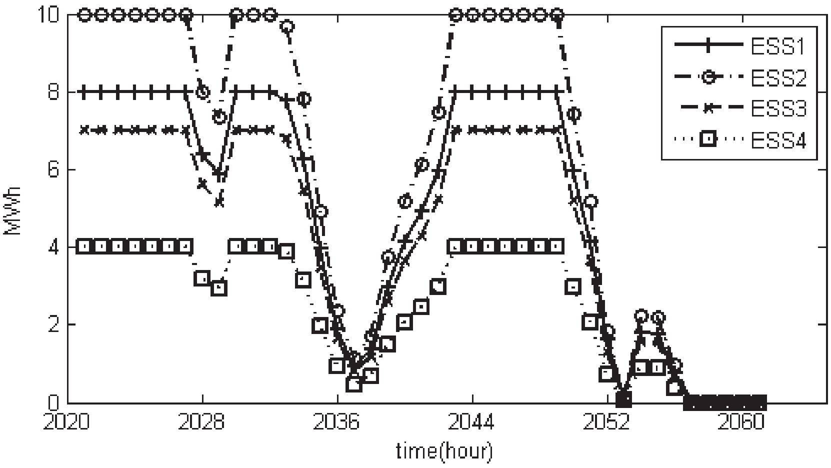

Fig. 10 Change of SOC

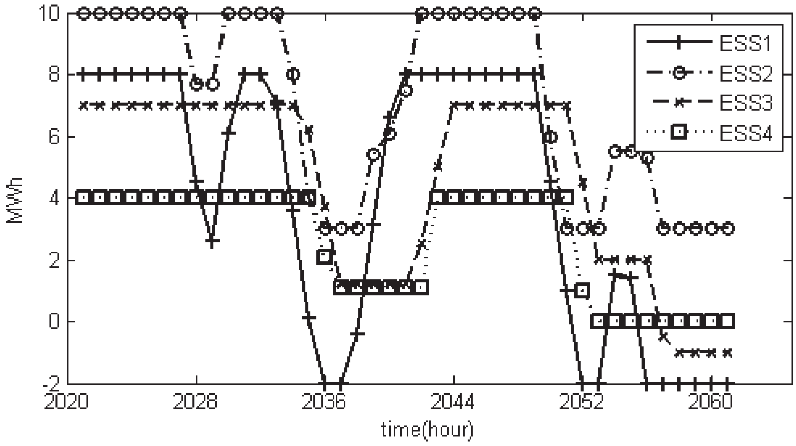

Fig. 11 Change of SOC (base case)

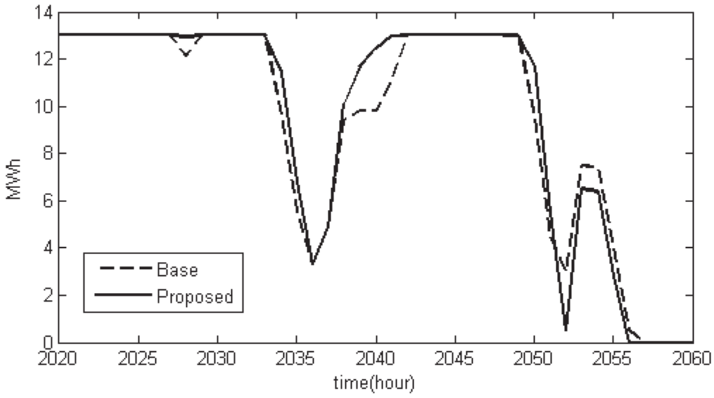

Fig. 12 Difference of total generation ability(V_t^{ESS})

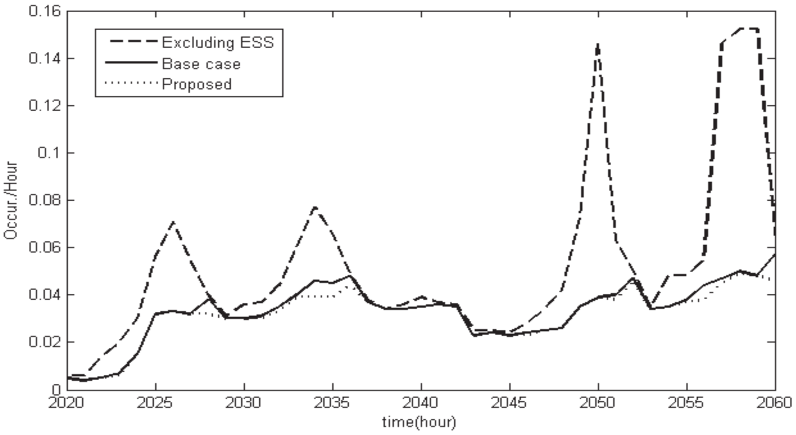

Fig. 13 Hourly LOLP

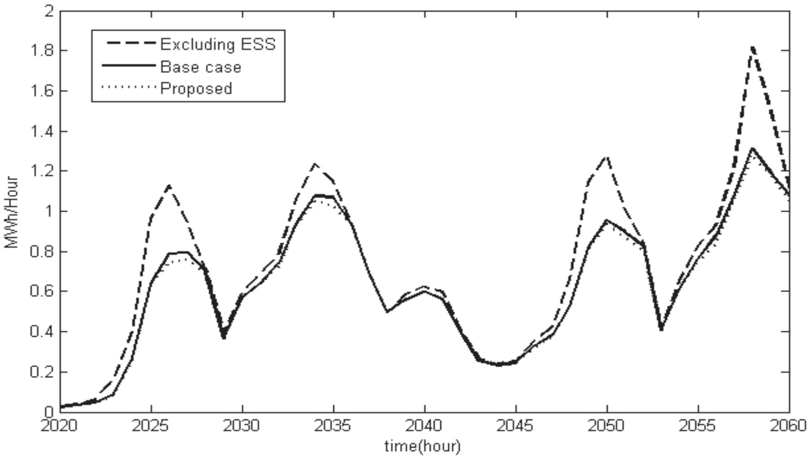

Fig. 14 Hourly LOEE

V. 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 and to produce the required power for charging and discharging periods. With 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.

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