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Operational Reliability Studies of Power Systems in Presence of Energy Storage Systems

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***Abstract*—This paper mainly focuses on operational reliability studies of modern power systems taking into consideration the effects of energy storage systems (ESSs). The aim is to develop a new evaluation tool to assess the effects of different factors such as penetration rate, operational strategies and capacities of the ESSs in determining the role of these systems as an operating reserve resource. In this regard, at first, some modifications are made to the PJM method aimed to precisely model the short-term variability in output generation of wind farms in reliability studies. Then, this algorithm is employed to examine the effects of ESSs operating strategies in operational reliability level of the system. Finally, a new formulation for ESSs scheduling problem is proposed to optimally gain the benefits of ESSs in improving the mid-term reliability level of the system. The usefulness of the proposed framework is illustrated using different case studies.**

***Index Terms*— Analytical approach, energy storage systems (ESSs), operational reliability, wind energy.**

I. Introduction

INCREASED share of renewable energy resources, especially wind power, in generation sector of power systems, imposed new challenges to power system due to their intermittent and stochastic nature. According to the World Wind Energy Association, installed capacity of wind power had 17.2% increase in the year 2015, and reached almost 435 GW worldwide [1]. However, it has been shown that the presence of this environment-friendly source of energy may cause some financial and technical issues [2]-[4]. Energy storage systems (ESSs) have been introduced as one of the potential solutions to mitigate various undesirable impacts of large scale wind power integration to power systems [2], [6].

While coordination of wind farms (WFs) and energy storage systems have been widely studied from economic aspects [7]-[11], a few works have been focused on reliability benefits of these systems especially short- and mid-term reliability studies. Investigating reliability impacts of these systems on the operational studies of power system, the following questions comes to mind: *What are the effects of WFs on short-term reliability indices of power systems and the required reserve? How utility-scale ESSs can alleviate the issues associated with operational reliability of highly wind-penetrated power systems? To what extent strategic utilization of ESSs can be effective in improving system reliability?*

To answer these questions, a power system composed of some conventional generating units, WFs and ESSs is considered in this paper, and it has been assumed that all the units are operated by a single utility. The goal is to evaluate the impacts of wind energy integration on operational reliability of power systems and to assess the advantages of ESS to these systems. We refer to this issue as *evaluating and improving operational reliability of wind integrated power system in presence of energy storage systems*.

In this paper, we treat with the problem of operational reliability studies using analytical approach for the upcoming day, in time-slots of lead time. In reliability evaluation of each lead time, we consider the variations of load, wind power, and commitment of other generating units. In addition, the operating reserve, provided by the ESS in each period, is considered. Following the previous works in this field, this paper makes the contributions as follows:

- The short-term variability and uncertainty of wind power is effectively modeled in an analytical framework. The proposed model is based on short-term wind speed data.
- We suggest a comprehensive framework to carry out the operational reliability assessment for day ahead system scheduling.
- Some modifications have been inserted in basic assumptions of PJM method in order to address system's operating conditions more accurately.
- The role of ESS as a potential operating reserve element is discussed in the paper; and its contribution to operational reliability of power system is well addressed.
- Finally, an economically optimal operating strategy for ESS is attained with the aim of improving its contribution to the system reliability.

The structure of the paper is presented as follows. A comprehensive literature review is conducted in Section II regarding energy storage studies as well as reliability models and evaluation methods in the operation phase. In Section III, the proposed methodology and modeling procedures are described. Then, the proposed reliability model and operating strategy for the ESS is explained in Section V. The case studies are presented and analyzed in Section IV, and finally

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the paper is concluded in Section VI.

II. Related Work

In recent years, many researchers have studied the exploitation of ESSs along with renewable energy resources. Most of the previous studies focus on coordinated operation of ESSs with renewable energy resources to mitigate the undesirable effects with the focus on profit or cost optimization [7]-[11]. Some address the associated variability and uncertainties, by conducting stochastic optimizations [9]-[11], yet they do not incorporate operational reliability indices into the scheduling problem. Our work differs from these in that we consider the role of ESSs as operating reserves and quantify contribution of ESSs to the system reliability. We take into account the operational reliability indices in deployment of ESSs. In such a viewpoint, [12] operates ESS to smooth out wind power fluctuations and improve supply continuity. It adopts different operating strategies for ESS and shows that the operating strategy has a significant impact on the resulting adequacy benefits of ESS. In the operational phase, [13] applies ESSs to compensate for shortage of system ramp rates when a contingency occurs. It shows that utilization of ESSs improves operational adequacy of wind integrated power systems. The authors in [14] also evaluate the capabilities of ESSs to provide energy during system shortage in terms of capacity value. Although these papers operate ESSs to mitigate system unbalances and uncertainties with the aim of reliability improvement, they are unable to propose a framework being applicable in the normal operating conditions of power systems.

In this paper, we extend the published papers to the general case of ESS scheduling with operational reliability considerations. To this end, at first it is necessary to develop an efficient method to evaluate operational reliability level of the renewable-based power systems. In this regard, the following two major steps should be taken into account:

- Reliability modeling of committed units, wind power generation, and load during the operational timeframe.
- Implementing a suitable reliability evaluation technique which perfectly represents system condition.

Considering the above procedure, the recent operational reliability studies dealing with wind power integration to power system can be reviewed as follows. A four-state Markov model based on a 180-min time-slot of wind power time series is presented in [15] and risk assessment is conducted through the basic PJM method. Reference [16] proposes time series as an efficient tool to model the dependency of wind speed at different hours; however, it neglects the intermediate variations of wind speed in period of the studies.

The authors in reference [17] obtain time varying state probabilities of generated wind power using Markov process and universal generating functions (UGFs). In spite of proposing time-varying state probabilities in this paper, utilizing a long-term Markov model of wind speed overshadows the accuracy of short-term studies. Reference

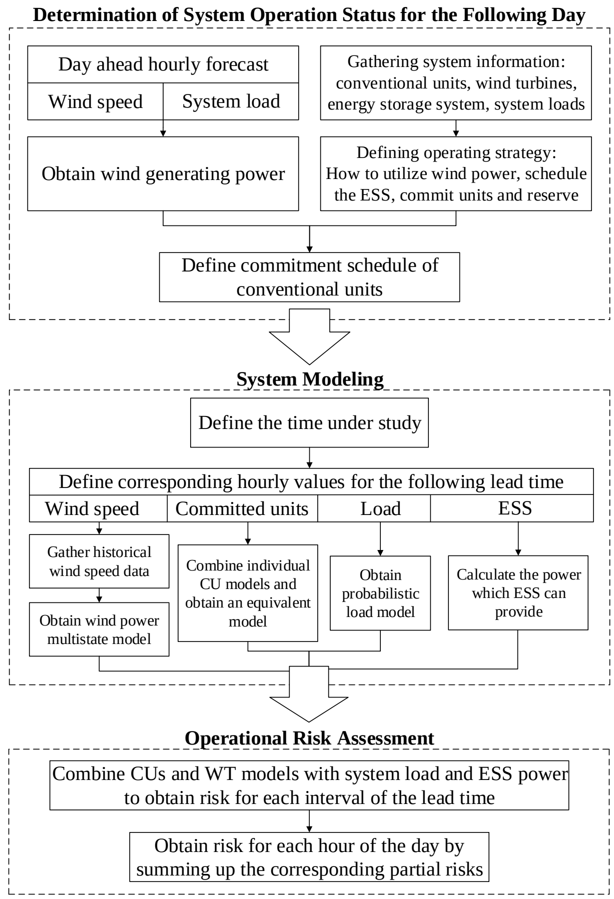

Fig. 1. General procedure of operational reliability evaluation for wind integrated power systems in presence of ESSs.

[18] utilizes the short-term wind speed modeling approach in [16] and extends the basic PJM method to consider variations of wind power more accurately. Due to the distinct wind speed fluctuations, the reviewed papers have focused primarily on modeling wind power variations, while effect of these variations on commitment of conventional units has been neglected. On the other hand, hourly load of the power system is not constant during lead time, contrary to the assumption made in operational reliability studies. Thus, this paper extends the evaluation method to consider variations of load and conventional generating units as well.

III. Methodology

A. General Procedure of the Proposed Method

The general procedure to evaluate operational risk of renewable-based power systems is presented in Fig. 1. In addition, operating strategy of ESSs with the main goal of improving system reliability is depicted in this figure. In order to evaluate the operational reliability of the system, first of all the operating condition of system and components data should be defined. To this end, basic data of the system including the forecasted hourly load and wind speed for the upcoming day should be gathered. Failure and repair rates of the conventional units (CUs), wind turbines (WTs), and ESS along with the technical constraints for system operation are the other data which are required. Using this information and

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applying a unit commitment program, the day ahead schedule of CUs would be defined. As the next step, the reliability model of committed CUs, WTs' output power, load, and ESS should be extracted. Then, equivalent operational reliability model of the whole system can be obtained by the combination of individual components' reliability models. This model can be used in the proposed procedure for evaluating operational reliability of the system. In the following, the detailed procedure of each step is explained.

B. *Reliability Model of Conventional Generating Units*

Modeling reliability of CUs is well described in [19]. Based on the method proposed in this reference, generating units are represented by multistate models with a corresponding probability associated with each state. Unlike planning studies, probability of finding a unit on an outage or derated state is not a fixed characteristic for short periods of operation. In other words, it is a time dependent parameter which its value can be determined by the value of lead time [19], calculated as follows:

$$p_i(\Delta t) = \lambda_i \times \Delta t \tag{1}$$

where, $p_i(t)$ and λ_i are the i^{th} unit failure probability and failure rate respectively, and Δt is duration of the considered time period.

C. *Wind Farms Output Modeling Procedure*

The output power of a WT at each time depends on the speed of wind. Wind speed patterns are different in accordance with the time period under study. For short-term modeling of wind power, historical wind speed data can be used to obtain probability distribution of wind speed for the time period under study (Δt) corresponding to its initial wind speed as in [16]. As a result, the wind speed distribution is converted to output power through the power curve of WT. In order to obtain a multistate model suitable for reliability studies, the well-known fuzzy c-means clustering method (FCM) is implied [21]. By means of this method, extracted wind power distribution is split up to a number of clusters with proper ranges and probabilities, considering simplicity and accuracy of the model.

The modeling procedure discussed above is applied to a WF composed of 26, 2-MW WTs with 4, 12, 25 m/s cut-in, rated, and cut-out speeds. The utilized wind speed data is the 10-min 5-year historical data of a wind site in Iran, Manjil, measured by Renewable Energy Organization of Iran [22]. The obtained multistate wind power model for two initial wind speeds of 6 and 15m/s and a lead time of 1 hour is presented in Table I.

TABLE I
Reliability Model of a Wind Farm for Different Initial Wind Speed

Initial Wind Speed			
6 m/s		15 m/s	
Output Power (MW)	**Probability**	**Output Power (MW)**	**Probability**
50	0.0434	52	0.9322
32.2	0.0734	42.7	0.0253
17.5	0.1318	32.5	0.0187
7.5	0.2593	12	0.0238
1	0.4922	-	-

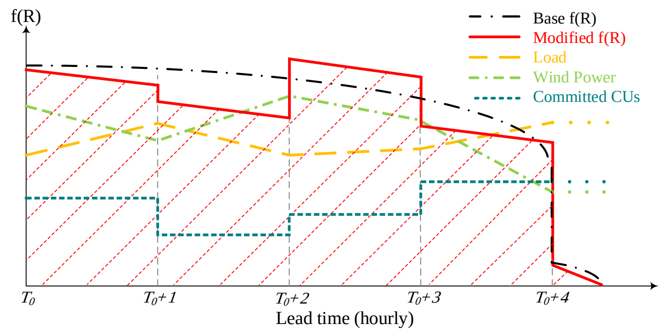

Fig. 2. Risk of power system as a function of load, wind power, and CUs.

As can be traced in Table I, for the initial wind speed of 15m/s, the maximum expected generating wind power is 52 MW (equal to the rated power of the WF) with a high probability of 93% and the obtained model has fewer states compared to the case with 6 m/s initial wind speed. This is due to the high initial speed which can be translated to higher output level of WTs and consequently reaching higher output level for wind farm. However, for the case with initial wind speed of 6 m/s, the obtained model is completely different. The maximum expected wind power is 50 MW with the probability of 4%, while probabilities of lower output powers are much higher. This can be justified due to the low value of initial speed which is close to the cut-in speed.

D. *Load Model*

In the operating stage of power system, the load is forecasted hourly for the upcoming day. The uncertainty in load forecasting can be represented by a normal distribution, divided into some discrete intervals [19]. Each interval represents a load level and probability of its occurrence.

E. *Evaluation Procedure of Operational Reliability Indices*

Traditionally, the operational reliability indices of power systems are assessed using PJM method [19]. As described in [19], PJM is considered as the most efficient and readily implementable method for evaluating operational reserve requirements, which is widely used in operational reliability studies [12],[13], and [15]-[18]. The main concept of PJM method is to evaluate probability of failing to satisfy the expected demand during lead time, when a failed generating unit cannot be replaced or repaired within this time [19], [20]. Based on this method, the commitment of different CUs is determined according to the day ahead forecasts. In addition, the basic PJM method assumes that the operating condition of system remains constant during the entire lead time, which means constant load, wind power, and committed units. However, in a wind-penetrated power system, these assumptions may not be applicable for lead times of several hours.

In order to consider all the mentioned variations in system's condition during the lead time, the concept of Area Risk, introduced in unit commitment risk (UCR) evaluation [19], is implemented. We extend the area risk concept by considering variability in load, wind power generation, and also hourly commitment schedules of CUs. In this regard, lead times of several hours are split to sub-periods with different operating conditions. Reliability index for each sub-period, called partial

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index, is extracted from the convolved reliability models of committed units and WFs with the forecasted load model. The final reliability index of the system is then calculated by summing up all the partial indices over the considered lead time. This modified PJM which considers variations within lead time is called the *n*-part PJM, where *n* defines number of sub-periods in each lead time. An illustrative figure of the proposed risk evaluation procedure for a lead time of 4 hours is presented in Fig. 2; where the lead time is split up to four different parts (4-part PJM), with exclusive load, generated wind power, and commitment schedule. The difference in evaluating procedures of the basic and modified risk functions, *f(R)*s, can be clearly observed from Fig. 2. It is also worth mentioning that this figure is only a schematic representation of change in risk function due to varying operation status of the system and it is not intended to illustrate the exact amount of the parameters.

Unit commitment risk (UCR), a probabilistic index, and expected energy not supplied (EENS), typically in MWh, are the two reliability indices used in operational reliability studies [19]. Partial UCR and EENS indices can be calculated as:

$$UCR_i = \sum_{j_L=1}^{K_L}\sum_{j=1}^{K} p^{GP}\left(L_{j_L} > GP_j\right)\times p^{L}_{j_L} \tag{2}$$

$$EENS_i = \Delta t \times \sum_{j_L=1}^{K_L}\sum_{j=1}^{K} p^{GP}\left(L_{j_L} > GP_j\right)\times p^{L}_{j_L} \times \left(L_{j_L} - GP_j\right) \tag{3}$$

where, p^{GP} and p^{L} are state probabilities of total generated power (*GP*) and load (*L*), with *K* and K_L number of states, respectively. Equivalent reliability index (*RI*) at hour $t=T_0$, for a defined lead time can be calculated as:

$$\begin{aligned} RI_{T_0} = \sum_{i=0}^{nsp-1}\Big[& RI^{+}_{T_0+i}(CU^{+}_{T_0+i}, WP^{+}_{T_0+i}, L^{+}_{T_0+i}) \\ & - RI^{-}_{T_0+i}(CU^{-}_{T_0+i}, WP^{-}_{T_0+i}, L^{-}_{T_0+i})\Big] \end{aligned} \tag{4}$$

where, *nsp* is the number of sup-periods in the lead time, and *RI* can be either UCR or EENS of each area as a function of conventional units (*CU*), wind power (*WP*), and load (*L*) at time *t*. The negative and positive signs show system condition exactly before and after the considered time. RI_t, the reliability index for each *t*, can be re-evaluated continuously through time as the status of *CUs*, *WP* and *L* change.

IV. ESS Incorporation in UCR Studies

A. ESS reliability model

This section discusses the role of ESSs as operating reserve in mitigating the operational risk of wind-penetrated power systems. Among different technologies of ESSs pumped hydro storage (PHS) and compressed air storage (CAS) have been proven to be the most suitable as operating reserve, due to their fast response and high energy capacity [5]. However, this functional feature of these systems has not been well studied. The main contribution of an ESS as an operating reserve depends on its energy level at the time under study, and also its maximum discharging power. In order to obtain reliability model of the ESS, we assume that whenever the power system encounters a contingency and fails to satisfy the expected

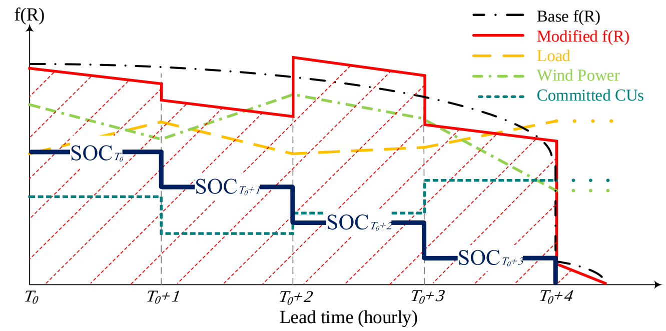

Fig. 3. Modeling ESS in operational reliability studies.

load, due to failure of units or generation deficiency, any charging schedule is cancelled. Instead, the ESS is ready to discharge with maximum power, until the power system is recovered or the minimum energy level of the ESS is reached. This is the common assumption in studying ESS as operating reserve due to its fast response rate and low operating cost [23]. Nevertheless, in addition to deficiency in generation, the system may encounter generation surplus, when the expected load is smaller than the generated power. In this situation, downward reserve, wind curtailment, and storing the extra power by charging storage unit can be utilized in order to balance generation and load. Application of ESS for storing the surplus generation and avoiding/minimizing wind power curtailment is one of the potential benefits of ESS. This concept is addressed by indices as expected energy not used (EENU) in [13], which are useful in capacity credit evaluations of wind power similar to that of [14]. However, in reliability studies and the associated indices, only deficiency in generated power and unsupplied energy is taken into account and storing the surplus energy by the ESS have no effect on the value of related indices.

In order to quantify the contribution of ESS as an operating reserve in reliability studies of power system, first we define the maximum amount of power that ESS can provide to the system until its energy reaches the minimum extent. This concept is schematically illustrated in Fig. 3. The number of sub-periods that ESS can help the system during the lead time can be calculated as:

$$N = \frac{SOC_t}{P_D^{\max} \times dsp} \tag{5}$$

where, SOC_t is the energy level of ESS at time *t*, P_D^{max} is the maximum discharge power, and *dsp* represents duration of sub-periods in hour. Based on the obtained *N*, contribution of the ESS can be different. If *N* >= *nsp*, all the sub-periods can be provided by the maximum discharge power:

$$P^{ESS}_{sr_i} = P_D^{\max} \quad i = 1,\dots,nsp \tag{6}$$

For 1 < *N* < *nsp*, the provided power by the ESS to each sub-period will be different, as:

$$P^{ESS}_{sr_i} = \begin{cases} P_D^{\max} & i = 1,\dots,\lfloor N \rfloor \\ \left(N - \lfloor N \rfloor\right) P_D^{\max} & i = \lfloor N \rfloor + 1 \\ 0 & i = \lfloor N \rfloor + 2,\dots,nsp \end{cases} \tag{7}$$

Where, $\lfloor N \rfloor$ is floor of *N*, representing the number of sub-periods in which the ESS can provide full power. In addition,

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if N < 1, the ESS can only help the system in the first sub-period with:

$$P_{sr_i}^{ESS}=\begin{cases} N\times P_D^{\max} & i=1 \\ 0 & i=2,\ldots,nsp \end{cases} \tag{8}$$

The power P_{sr}^{ESS} (in MW), which is provided by ESS during the lead time, is considered as a negative load. As a result, system load should be modified for risk calculations, that is,

$$L_{t+i}^{*}=L_{t+i}-P_{sr_i}^{ESS} \tag{9}$$

The new modified load is then used in (2)-(4) to find the operational reliability level of power system in presence of ESS units. It is worth mentioning that providing this power to the system depends on the availability of the ESS. Just like the CUs, the ESS is exposed to failure with a corresponding probability. The probability of finding an ESS in failure mode during the lead time can be calculated as in (1), if its failure rate (λ_i) is available.

B. Operating Strategy of ESS

As discussed in the previous part, contribution of ESSs to operational reliability level of power system mainly depends on its energy level. Fig. 4 represents a sensitivity analysis on the operational reliability of power system for different energy levels of an ESS. In order to conduct this sensitivity analysis, operating status of the parameters *L*, *WP*, and *CU*s is considered to be known for each hour, and the only variable parameter is *SOC*, which takes different values for each hour. Based on the general procedure for evaluating operational risk, presented in Fig. 1, the desired reliability index is evaluated during the day for different *SOCs*. In the sensitivity analysis of Fig. 4, EENS has been chosen as the *RI*. As shown in this figure, different energy levels of the ESS at various hours of the day can considerably affect the system reliability level. Taking into consideration hour 6 as an example, it can be seen that high energy level of the ESS can greatly reduce the EENS and improves reliability of the system. In contrast, some operating hours are reliable by their own and do not require additional assist from the ESS. Thus, high level of energy in ESS, loses its effectiveness and it is not necessarily required.

For an ESS in practice, the energy level at each hour is defined by its charging and discharging schedule. Accordingly, this schedule greatly determines contribution of ESS to the reliability of power system.

Considering this attribute in the ESS scheduling can significantly improve its contribution to the operational reliability studies. However, little attention has been paid to this issue in reliability studies of ESSs. Studying the application of ESS as operating reserve as well as energy arbitrage purposes is the main contribution of this part.

C. Main Assumptions of ESS Scheduling Problem

In this paper, it has been assumed that the utility implements the ESS for two applications of energy arbitrage and operating reserve. The utility conducts ESS scheduling in a day ahead with the aim of maximizing arbitrage benefits. In addition, in the advent of any contingencies due to failure of generating units, reduction in wind power generation, or increase in load, we assume that any charging plan for the ESS is cancelled and instead the ESS discharges its maximum power to the system until the contingency is resolved or physical limitations of the ESS are reached. The problem formulation of the proposed operational strategy for the ESS, which aims to maximize its arbitrage profit along with improving its contribution to the system reliability, is presented in the following.

D. Problem Formulation

ESS scheduling defines its charging or discharging power for 24 hours of the following day. In this scheduling problem, the following constraints should hold for all times:

$$-P_{disch}^{\max}\le P_t^{ESS}\le P_{ch}^{\max} \tag{10}$$

$$SOC^{\min}\le SOC_t\le SOC^{\max} \tag{11}$$

where, P_t^{ESS} is the power that ESS receives from the power system. If ESS discharges power to the system, P_t^{ESS} takes a negative value. SOC_t is energy level of the ESS at time t in MWh, which is defined with regards to its previous energy level and power:

$$SOC_t=SOC_{t-1}+P_{t-1}^{ESS} \tag{12}$$

Energy stability during a scheduling period should also be considered. This requires equal energy levels at the initial and final hours, which can be formulated as:

$$\sum_{t=1}^{24}P_t^{ESS}=0 \tag{13}$$

Daily schedule of the ESS is then obtained by maximizing the total energy arbitrage profit during the period:

$$\begin{aligned}&\max\left(\sum_{t=1}^{24}P_t^{ESS}\times C_t^{E}\right)\\ &s.t.\quad (10)-(13)\end{aligned} \tag{14}$$

where, C_t^E is the hourly energy price, assumed to be forecasted.

In order to investigate the effect of ESS schedule on its reliability contribution, a reliability constraint is also considered. This constraint is based on a sensitivity analysis similar to that of Fig. 4, which demonstrates changes in system reliability based on different energy levels of the ESS. Based on this analysis, the minimum required energy level (SOC_t^{limit}) to reach the desired reliability index (RI^{desired}) is obtained for each hour of the day. This is done through intersecting the desired reliability level and the obtained curve of sensitivity analysis. Energy levels at points where the

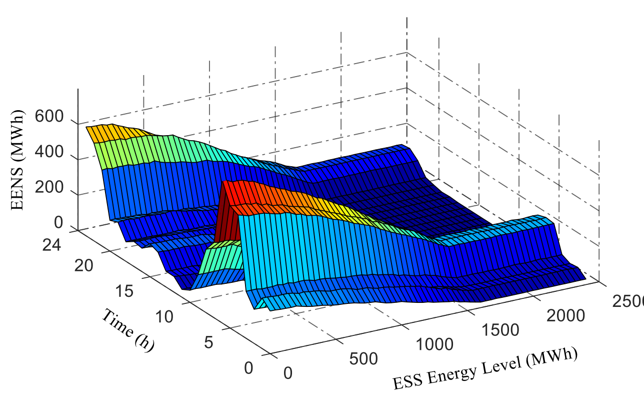

Fig. 4. Sensitivity analysis of EENS for different energy levels of the ESS.

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obtained risk curve meets the $RI^{desired}$, are considered as SOC_t^{limit}. However, due to the physical limitation of the ESS, this constraint may not be applicable at all times. Therefore, this limit is met as long as the ESS energy capacity (SOC^{max}) allows:

$$SOC_t \geq \min(SOC_t^{limit}, SOC^{max}) \tag{15}$$

When the required SOC^{limit} is larger than SOC^{max}, SOC_t is limited to SOC^{max} and it means that the ESS is not able to fully provide all the required operating reserve. Therefore, more spinning reserve is required to fulfill the reliability requirement of the system. In other words, while we can utilize the ESS to improve operational reliability, we cannot expect it to provide all the operating reserve that we need to reach our desired reliability level.

It is noteworthy that the proposed scheduling strategy leads to a linear multi-period optimization problem that can be solved by any linear programming approaches.

V. Case Studies

A. Test System under Study and Main Assumptions

The proposed reliability evaluation technique is implemented on the modified IEEE-RTS [24]. System load is scaled according to the overall installed generating capacity including WF capacity. Different integration levels of wind power are defined as the ratio of WF capacity to the initial installed generating capacity of the system. Lead time is assumed to be 4 hours according to the fastest cold start time of generating units. In addition, due to the lack of reliability data, it has been assumed that the considered ESS is fully reliable. It is worth mentioning that this assumption is somehow realistic, since failure rates of hydro plants are low compared to that of CUs [19], which leads to nearly zero failure probabilities in short intervals of operational studies.

B. Operational Reliability Analysis– without ESSs

The proposed evaluation method based on the modified PJM method was applied on the test system and the obtained results were compared with the basic PJM method. The result of this analysis, conducted for different penetration rates of wind power, is presented in Table II. As can be seen in this table, once there is no wind power installed in the system, the assumption of constant operating condition during lead time, in the basic PJM, is still valid. Consequently, no significant difference can be observed among the results of the three methods. As the considered sub-periods in the lead time increase, variations in load, wind power, and commitment of units are better captured, which results in more accurate results; especially in the high penetration of wind power with increased variability in the net load and committed units.

In order to assess operational reliability of wind integrated power systems, system risk during a whole day, for different

Table II
UCR of Different Cases Based on Different PJM Methods

Wind Penetration	UCR		
	Basic PJM	2-part PJM	4-part PJM
0%	0.00010	0.00006	0.00003
20%	0.02074	0.02957	0.04957
40%	0.06268	0.10318	0.18277

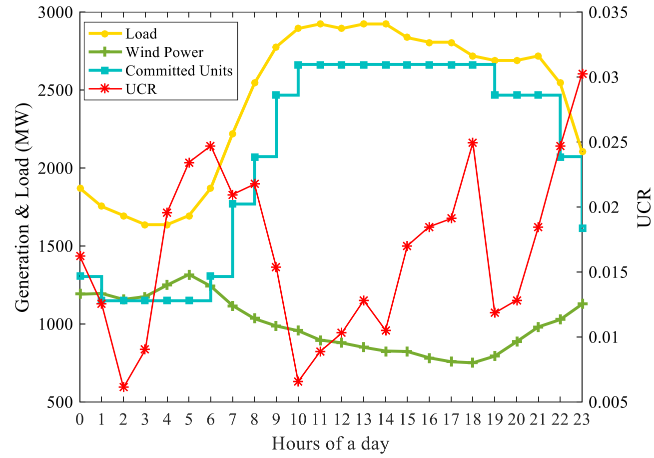

Fig. 5. Operating condition of power system and its associated UCR based on the proposed 4-part PJM method.

operating conditions has been evaluated. This evaluation method utilizes the proposed PJM method based on the 4-part lead time and the results are shown in Fig. 5. At the first hours of the day, when the generated wind power and commitment states of CUs are constant and the load is falling to its off-peak state, system risk decreases and reaches its minimum extent. As the share of wind power increases in serving load at hours 3 to 6, the value of system risk increases. Rising to the peak load hours, the number of committed CUs increases and consequently the wind power generation share decreases. Operational risk of the system diminishes significantly in this situation, which indicates the importance of the ratio between wind power and CUs' generation.

As Fig. 5 shows, there is raising trend in system risk during hours 10 to 18 due to the gradual decrement in wind power generation. Contrarily, the increment in wind power generation in hour 19 and 20 concurrent with the reduction in load causes reduction in the risk of system. However, the increase in the ratio of wind power to conventional generation in the following hours raises the risk again.

Generally, the high amounts of risk obtained in study (Fig. 5) is due to considering a fixed amount of reserve for the whole scheduling period, regardless of the system operating condition. The required spinning reserve to obtain the desired reliability level, is investigated in the following.

The required spinning reserve for the system to work at specified risk level of 0.001, considering different wind

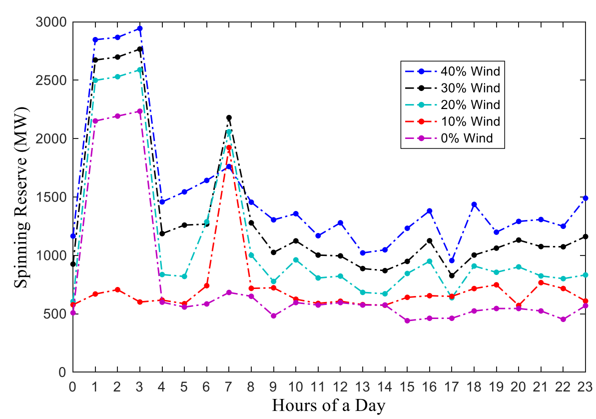

Fig. 6. Required spinning reserve under various conditions.

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penetration levels has been shown in Fig. 6. It illustrates different requirements for spinning reserve at various operating conditions. The amount of required spinning reserve is a function of load, the number and characteristics of committed CUs and also the wind speed variations. As Fig. 6 depicts, increasing wind power penetration, increases the need for spinning reserve most of the time, but it is not always the case. For example, at first hours of the day, the 10% wind penetration helps the system reliability and leads to less required spinning reserve compared to the case without wind power usage.

C. Operational Reliability Analysis– with ESSs

In order to assess the abilities of ESS in improving operational reliability of the system considering the scheduling problem defined in previous part, several case studies are provided in this part. First of all, we assess different penetrations of ESS and wind power from arbitrage and reliability point of view. Then, we examine the effect of various factors such as charging and discharging power, stored energy capacity, initial energy level, and operating strategy on the ESS contribution to system reliability. Finally, we study a whole scheduling period analyze effects of aforementioned factors altogether. The ESS units under study are selected based on the operational PHS projects worldwide, which their main application has been introduced as operating reserve and energy time shifting [25].

First of all, we evaluate effect of different ESS penetrations versus several wind power integrations. Different levels of ESS power are considered as a percentage of the installed generating capacity in the system as shown in Table III. It is assumed that the ESS units are fully charged at the beginning of the scheduling period.

For the case that ESS is scheduled to maximize arbitrage profits without any reliability constraints, the obtained results are presented in Table IV. As the ESS penetration increases, i.e. ESS with higher power and energy capacity, the profit from energy arbitrage increases accordingly. Moreover, for high penetration of wind energy, profitability of the ESS becomes much more. These results confirm the beneficiary of integrating the ESSs to power system for energy arbitrage under various conditions. However, this is not the case for the ESS as an operating reserve. As the obtained EENS results in Table IV reveal, increasing penetration of ESS cannot necessarily improve operational reliability level of the system. This is due to the fact that beneficiary of ESS units as an operating reserve depends on different factors such as charging and discharging power, energy capacity, operating strategy, and initial energy level of these units. In what follows, we carry out an in-depth analysis of the effects of these factors on system reliability.

Charge and discharge schedules of ESS have different effects on the system's operational reliability. While implementing ESS in discharging mode can considerably help the system operator in contingency events, it acts as a load in charging mode, which can worsen the situation for generating units. For instance, in the no wind case with different ESS penetrations, various impacts of the ESS can be observed on the system's EENS (Table IV). When the ESS penetration is low (1%) and its power is not significant (34MW), it improves the operational reliability. Increasing the ESS penetration (5%-7%) with higher charging and discharging power (170MW-238MW), results in lower reliability improvements. While for the 10% ESS penetration, its EENS exceeds that of the case without storage. This adverse effect of ESS on system reliability is due to not considering reliability aspects in scheduling strategy and shows the undeniable role of its charge and discharge power.

TABLE III
LEVELS OF ESS POWER FOR DIFFERENT WIND PENETRATIONS (MW)

Wind \ Storage	1% (1h)	5% (5h)	7% (7h)	10% (10h)
0%	34	170	238	340
10% (340 MW)	37	187	262	375
20% (681 MW)	40	204	286	409
40% (1362 MW)	48	238	334	477

TABLE IV
EENS AND ARBITRAGE PROFIT FOR DIFFERENT WIND AND ESS PENETRATIONS – WITHOUT RELIABILITY CONSTRAINT

EENS (MWh)					
Wind \ Storage	0%	1%	5%	7%	10%
0%	0.03	0.01	0.02	0.02	0.04
10%	0.00	0.03	0.26	0.27	0.15
20%	30.14	7.06	10.19	8.13	4.20
40%	296.21	81.20	73.17	60.35	48.86
Arbitrage Profit ($)					
Wind \ Storage	0%	1%	5%	7%	10%
0%	0	1006	5032	7044	10063
10%	0	1059	9786	14207	20019
20%	0	1200	10734	15499	21957
40%	0	1412	12628	18082	25832

While wind power integration improves the installed capacity in generation sector, this may worsen the operational reliability level of the system due to its variable and uncertain nature. As shown in Table IV, in extreme case of 40%, the operational reliability level of the system has remarkably decreased. In this case, it can be observed that implication of ESS units, even in small sizes, contributes significantly to system reliability. Nevertheless, based on the diverse results obtained in Table IV, one can conclude that just implementing ESS cannot guaranty reduction in operational risk of the system and it is important to employ an effective operating strategy to fully exploit the potential of ESS.

In order to assess the impact of ESS operating strategy on the operational reliability, the provided reliability constraints, i.e. equation (15), is applied to the optimization problem. The obtained results are presented in Table V. The attained results for system EENS confirm that this constraint can amplify the reliability impacts of ESS units. It also affects arbitrage profit in most of the cases. This observation is due to the fact that stored energy in ESS is maintained at high levels in order to provide the power system with operating reserve. On the other hand, for some cases in addition to providing sufficient operating reserve to the system, the ESS participates in energy arbitrage and obtains profit. It shows the high potential of the ESS for energy arbitrage in addition to serving operating reserve to the system in these cases.

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TABLE V
EENS AND ARBITRAGE PROFIT FOR DIFFERENT WIND AND ESS PENETRATIONS - WITH RELAIBILITY CONSTRAINT

EENS (MWh)					
Wind \ Storage	0%	1%	5%	7%	10%
0%	0.03	0.01	0.01	0.01	0.01
10%	0.00	0.03	0.01	0.00	0.01
20%	30.14	5.48	2.22	0.20	0.00
40%	296.21	81.19	47.35	27.58	37.92
Arbitrage Profit ($)					
Wind \ Storage	0%	1%	5%	7%	10%
0%	0	0	0	0	0
10%	0	0	0	0	17078
20%	0	0	0	0	0
40%	0	944	0	0	22008

Another controlling factor in operation of ESS is its initial energy level. For all the aforementioned cases, the ESS has been assumed to be fully charged at the beginning of the scheduling interval.

In order to investigate the impact of this factor on the effectiveness of the ESS, a sensitivity analysis is conducted for different initial energy levels of the ESS. Table VI presents the results of this analysis when the reliability constraint is applied. The implemented constraint forces the ESS to rise or keep up its energy level as far as possible. According to the obtained results, initial energy level has little impact on the EENS index; since the reliability constraint keeps the EENS at its minimum attainable value. The arbitrage profit, however, considerably changes regarding to initial energy level. For lower levels of initial energy, the ESS has the chance to participate in energy arbitrage as it charges to increase its energy level and reach the reliability constraints. Therefore, the initial energy level plays an important role in ESS performance for operational timeframes.

In order to investigate the overall effects of ESS on the operational reliability, hourly schedule of this unit is obtained for two cases of I) normal operation and II) reliability-constrained operation. In these cases, wind penetration is considered 40% and the ESS under study is utility-owned 400 MW Yards Creek Pumped Storage with 6 hours of operation at rated power, located in the United States [25]. The main application of this PHS is to provide energy regulation and supply reserve capacity. The ESS is assumed to be fully discharged at the beginning of the scheduling period. For the whole scheduling interval, the hourly charge and discharge schedule, energy level, and EENS of the system are depicted in Figures 7-9. As it can be traced in these figures, the ESS with higher energy level can provide more operating reserve to the system during lead time. However, this operating reserve is limited to the discharging power of ESS and system lead time. Consequently, the maximum effective energy level in an ESS is limited to:

$$SOC_{eff}^{\max} = LT \times P_{dis}^{\max} \tag{16}$$

TABLE VI
EENS AND ARBITRAGE PROFIT FOR DIFFERENT ESS PENETRATIONS AND INITIAL ENEGRY LEVELS

EENS (MWh)					
Storage \ $SOC_{ini.}$	0%	25%	50%	75%	100%
1%	81.31	81.40	81.29	81.14	81.19
5%	54.11	49.62	49.02	47.58	47.35
7%	40.94	34.72	29.82	28.52	27.58
10%	45.14	36.55	33.31	31.22	37.92
Arbitrage Profit ($)					
Storage \ $SOC_{ini.}$	0%	25%	50%	75%	100%
1%	88	66	44	22	994
5%	4426	2509	1156	332	0
7%	10970	6196	2618	619	0
10%	38420	31688	26632	25306	22008

Scheduled power of ESS for energy arbitrage also affects the hourly EENS. When ESS is scheduled to charge, the load of system raises and more generating units are committed. In this situation, if a failure occurs, charging schedule of the ESS is cancelled and the ESS discharges its power to the system as far as its physical limitations allow. In addition, generating units, which have been planned to charge the ESS, are able to provide operating reserve to the system. Accordingly, charging schedule of the ESS results in a reduction in EENS.

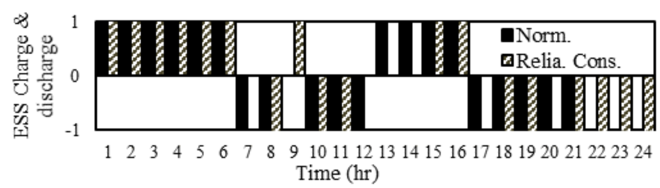

Fig. 7. ESS hourly charge and discharge schedule for two cases of normal operation and reliability constrained operation.

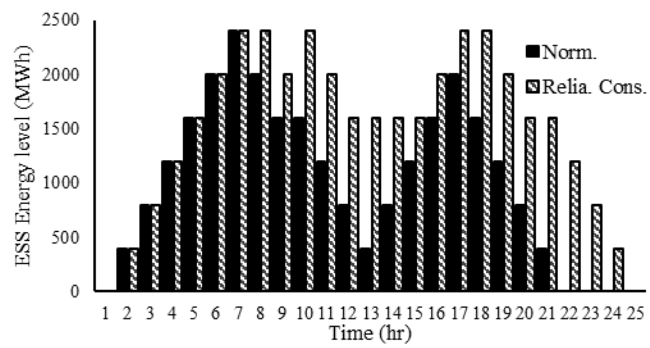

Fig. 8. Hourly energy level of the ESS during a day for two cases of normal operation and reliability-constrained operation.

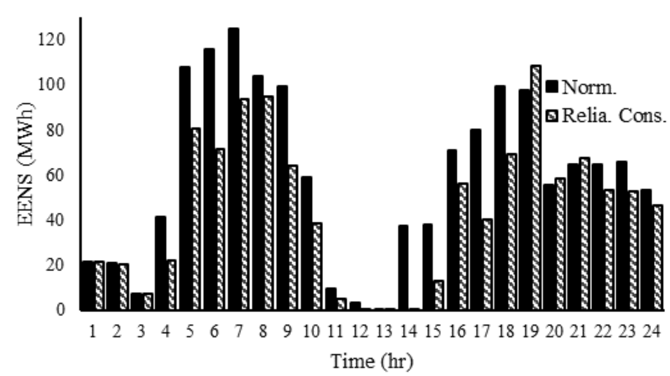

Fig. 9. Hourly EENS index schedule for two cases of normal operation and reliability constrained operation.

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When the ESS is planned to discharge, it serves some of the system load as a generating unit and replaces CUs. Therefore, in the advent of a failure, fewer generating units are available to provide operating reserve. Moreover, the ESS cannot offer operating reserve while it is in discharging mode. Consequently, the ESS unit in discharging mode cannot improve the reliability significantly. In the idle mode, however, the ESS can provide the system with operating reserve until its energy level allows.

As Fig. 8 depicts, energy level of the ESS is kept higher for the reliability-constrained case than the normal case, in order to improve the system reliability. This also leads to different charge and discharge intervals of the ESS for these cases (presented in Fig. 7). The average EENS reduces from the 62.64 MWh in the normal operation, to 47.67 MWh for the reliability-constrained case. Changes in the ESS operation also overshadow the arbitrage profit. In the reliability-constrained case, the obtained arbitrage profit decreases to 384200$ compared to that of 48080$ in the normal case.

As shown in Fig. 7, during hours 1 to 6, for both cases schedules of the ESS are the same. With these charging schedules, energy of the ESS increases to its maximum level. In addition, it stores energy with low price, which can be sold in high price intervals. By changing the schedule of hour 7 from discharge to idle mode, in the reliability constrained case, more CUs are committed to serve the load; thus, energy of the ESS can be served as operating reserve to the system. This leads to a reduction in EENS of hour 7 and the associated previous hours which have hour 7 within their lead time. The difference in the schedule of hours 9 and 12 has also the same effect on the EENS. Moreover, it maintains the energy level of the ESS above its effective threshold. For this system with lead time of 4 hours and power capacity of 400 MW, the maximum energy level, useful as operating reserve, is 1600 MWh. As a result, with energy level of 1600MWh or more, the ESS can offer its maximum capacity as operating reserve for the following hours. In the case that operational reliability of the system is still below the desired level, more operating reserve should be committed in the system in order to guarantee the same operational reliability during the whole scheduling period.

VI. Conclusions

This paper has presented an analytical framework for operational reliability studies of power systems taking into account different penetration rates of wind energy and ESSs. The obtained results indicated that new evaluation frameworks should be developed to assess the operational risk of highly-wind penetrated power systems. Therefore, a modified version of the PJM method is introduced in the paper to more accurately evaluate the reliability level of power systems in short- and mid-terms time frames. These results also confirmed that while wind power integration improves the installed capacity in generation sector, this may worsen the operational reliability level of the system due to its variable and uncertain nature. In response, the role of ESSs in providing the required operating reserve of renewable-based power systems was put under investigation. Different case studies defined in the paper revealed that operating strategy of ESSs can considerably determine the benefits of these systems in improving the reliability of system. The focus of reliability-constrained operation on the application of the ESS as operating reserve other than energy arbitrage, demonstrates that the operating strategy is a matter of great importance both for maximizing the ESS profit and its role in improving operational reliability. Therefore, in scheduling the ESS, it is important to consider the application of which the ESS has been utilized for.

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