Operation Strategies for Coordinating Battery Energy Storage with Wind Power Generation and Their Effects on System Reliability

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***Abstract*—The variability of wind power generation requires the allocation of a flexible energy reserve which is capable of compensating for possible imbalances between the load and generation. To reduce the variability of wind power generation and loss of load in generation deficit, we propose operation strategies for coordinating battery energy storage with wind power generation. The effects of the operation strategies on system reliability are evaluated by the developed computation model that represents the main aspects and operation limitations of the batteries. The performance evaluation of the power system is based on the composite reliability indices of loss of load probability (LOLP) and expected energy not supplied (EENS), which is calculated through sequential Monte Carlo simulation. Tests are performed by the developed model with a tutorial system consisting of five busbars and the IEEE RTS system. The results show that the use of large-scale batteries is an alternative to physically guarantee the wind power plants and to act as an operation reserve to reduce the risk of loss of load.**

***Index Terms*—Energy storage, wind power generation, power system reliability, Monte Carlo simulation.**

I. Introduction

THE Brazilian energy is undergoing with diversification, which emphasizes on the integration of renewable energy sources such as wind and solar. With a reduction in the regularization capacity of the reservoir and an increasing penetration of intermittent energy sources, the system is more sensitive to the variations in natural resources.

From the operation aspect, it is necessary to incorporate new mechanisms to provide controllability and resilience to the system against these variations. The intermittence of wind power generation requires the existence of a flexible operation reserve, which can ensure that despite variations in energy production, the load is met in both short and long terms. In Brazil, although other technologies might also be studied to address this problem, we will focus on the use of battery energy storage.

From the commercial aspect, battery energy storage may also be attractive. Wind power generation in Brazil is used to be traded by means of availability contracts, in which the entrepreneurs state the amount of energy to whom they sell annually. This value is calculated considering the forecasted annual energy production. It is also limited to a value corresponding to a probability of occurrence, which is equal to or greater than 90%. The accounting of the differences between the energy actually produced and the energy contracted is made annually when fines for the deficit could be applied or the extra remuneration could be paid for the surplus generation. In some cases, the excess or deficit could be reallocated for accounting in the subsequent year.

Recently, wind and solar start to be traded through quantity contracts, in which the entrepreneurs are exposed to greater risks of financial loss due to wind variability. With this new model, wind farm entrepreneurs may be interested in investing mechanisms to modulate the wind production and mitigate risks, avoiding fines and possibly increasing the amount of energy declared in contracts.

With standards of low greenhouse gas emission and the technology with low operation costs [1], [2], despite the high investment cost, battery energy storage is also attractive from a socio-environmental point of view.

By coordinating the operation of storage with the wind energy production, we aim to study the benefits when the batteries are installed close to the wind resource.

Different operation strategies [3] can be adopted for the use of storage systems, depending on the intended purpose such as peak load supply [4], fluctuation reduction of wind power generation and transmission deferral [5], reduction of load shedding [6], generation revenue [7]. Reliability assessment can be used to measure the system benefit for the use of batteries [8]-[10]. Other metrics may also be adopted such as power quality indices, voltage control support, etc. We present comparative proposals for energy management of batteries, aiming to reduce the variability of wind power generation or the loss of load in generation deficit.

A working model of battery energy storage is developed, addressing its main technical characteristics, lifespan and operation efficiency. Encompassing the representation of batteries and operation strategies, the developed computation model is integrated with a composite reliability assessment model [11], which evaluates the effects of integrated batteries on system performance.

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Simulations of two test systems present the benefits of using batteries to mitigate the effects of intermittent wind power generation by increasing the physical guarantee of wind power plants and acting as an operation reserve to reduce the load shedding risk.

II. Battery Storage System

The use of storage for energy management, especially in the integration of renewable resources, requires some specific attributes of the applied technology such as high charging and discharging power capacity and compatible operation time scale, i.e., continuous charging and discharging at rated power over a considerable period of time. Hence, the mitigation of intermittent generation is allowed. Among applicable technologies, batteries are preferred because they are relatively compact equipment and do not have a strong dependence on the characteristics of the installation site, which makes them flexible and adaptable.

There are different types of batteries distinguished by the material of electrodes and the electrolyte [12], [13]. The advantages of lithium-ion batteries include high efficiency (generally higher than 90%), a long lifespan in terms of charging and discharging cycles, high energy density, low occurrence of self-discharging, and the absence of memory effects. The disadvantages include the risk of explosion in the case of overloading and heating as well as the discharging influence of their lifespan. The high cost of lithium-ion battery is still one of the main obstacles, especially for the applications that require high energy storage capacity. However, according to projections from the International Renewable Energy Agency (IRENA) [14], the cost reduction of lithium-ion battery should be 61% by 2030.

The control and protection systems of batteries aim to guarantee their durability by controlling certain operation characteristics [15]:

1) Depth of discharge (DOD): percentage of storage capacity consumed during a discharge. The lifespan is directly influenced, thus deep discharging should be avoided.

2) State of charge (SOC): percentage of total storage capacity. The minimum SOC $SOC_{\min}$ should be kept to avoid battery wear due to the cut-off effect.

3) State of health (SOH): maximum storage capacity as a percentage of nominal storage capacity. Battery replacement is advised when the minimum SOH $SOH_{\min}$ is reached.

III. Reliability Model with Wind Power Generation and Battery System

A model is developed including the representation of batteries and operation strategies for their coordination with wind power generation. Then, it is integrated with a model for composite reliability evaluation of power systems [11]. The final model uses sequential Monte Carlo simulation (MCS) to calculate the reliability indices based on the wind power generation and time series of the load, considering the failure rates of generation and transmission assets.

The overall process of reliability assessment including battery operation can be summarized as follows:

1) At each simulation step, a new system state is sampled based on the transmission equipment and load as well as generation availability.

2) For each system state, the operation strategy of the battery is used to make decisions on whether to use the storage or not. If the decision is to store the energy in the battery, the Calculate_Charging method is triggered, and if the decision is to use the battery to inject energy into the system, the Calculate_Discharging method is triggered. During charging or discharging, the battery monitoring logic is active in an attempt to extend the lifespan and prevent the wear and tear.

3) The adequacy of the system is evaluated by calculating two reliability indices, the loss of load probability (LOLP) and the expected energy not supplied (EENS) [16]. For every state i, in which there is load shedding due to insufficient power supply or asset failures, the indices are updated according to (1) and (2):

$$LOLP = \sum_{i \in S} p_i \tag{1}$$

$$EENS = \sum_{i \in S} L_i t_i p_i \tag{2}$$

where p_i is the probability of occurrence; L_i is the amount of load shedding; t_i is the duration of system state i; and S is the total number of states with load shedding.

Considering load forecasts and costs of life cycle storage, the operation of a hybrid wind-solar-battery system has been investigated to increase power system reliability and minimize the operation costs of the overall hybrid system [17].

IV. Operation Strategies for Battery System

Three operation strategies are developed for the use of batteries with different aims. $SOC_{\min}$ of 20% and $SOH_{\min}$ of 80% are considered for the batteries.

The first operation strategy aims to reduce the intermittence of wind power generation through decentralized operation decisions. The second strategy is a variation of the first one, in which the decision process is also decentralized, but it communicates with a centralized supervisory system. The third operation strategy aims to reduce system load shedding by taking the batteries as an operation power reserve. Although the decision for energy storage can be made in a decentralized manner, the decision to discharge the batteries is centralized.

A. Operation Strategy 1: Intermittence Reduction of Wind Power Generation

This strategy aims to set the output value of wind power generation within a limited power range, eliminating sudden variations. The battery is used to modulate the output of the wind power generation. Therefore, when the power generated by the power plant is greater than a pre-determined maximum value, the excess power is stored. When it is lower than a pre-determined minimum power value, the battery discharges the power into the grid. These values represent acceptable margins around a set contract factor (CF), which is the value of annual energy production declared by the entrepreneur.

The battery works as a compensation system for wind power generation, and the power grid finds an injection of the power with smaller variations at the connection point of the "wind power plant + battery" unit. The CF values for each "wind power plant + battery" unit must be given. Note that this is a local control strategy, in which the wind power generation is considered by the decision between the charging and discharging operations, where the battery is installed.

According to (3), the generation factor (GF) relates the value of the power produced by a wind generator at a certain time-step with its nominal power.

$$GF = \frac{P_g(t)}{P_n} \tag{3}$$

where $P_g(t)$ is the power produced; and P_n is the nominal power of the wind generator.

During the operation, if GF of the wind power plant is greater than 110% of CF, the battery enters its charging mode, and the Calculate_Charging method is performed to check the viability of storing the excess power. The amount of the power available to be stored P_{in} is calculated by (4). If GF is less than 90% of CF, the battery enters its discharging mode, and the Calculate_Discharging method is executed to verify the viability of injecting the stored power into the power grid. The value of the requested power P_{out} from the battery is calculated using (5). Otherwise, the battery enters the neutral state, i.e., it neither absorbs the power nor injects the power into the grid.

$$P_{in} = \left(GF_i - 1.1 \cdot CF_i\right) P_n \tag{4}$$

$$P_{out} = \left(0.9 \cdot CF_i - GF_i\right) P_n \tag{5}$$

where GF_i is the GF set for plant *i*; and CF_i is the CF set for plant *i*.

The aim of this strategy is to ensure that as long as the battery has storage capacity, the power injected into the grid by the "wind power plant + battery" unit will be within a range of ±10% of CF, adding greater predictability and lower variability of the power injected into the system.

B. Operation Strategy 2: Intermittence Reduction of Wind Power Generation with System Restrictions

The aim of this strategy is to provide local control to reduce the variability of wind power generation that does not cause negative impacts on the performance of the system. The operative decision to store surplus energy is based not only on local measurements but also on system constraints. Thus, energy storage is only allowed if the centralized operation center of the system authorizes it.

The authorization is based on the verification of the balance between the load and total available generation. Therefore, if there is surplus generation to meet the load, it is allowed to store the energy in the batteries connected to the system. Otherwise, the authorization is not granted. Note that the authorization is a conditional factor, but it is not decisive for the charging or discharging of the batteries. The decision process is based on the local GF measurements of the wind power plants.

Based on the total load and generation available in the system, the value of variable signal is determined. If the available generation exceeds 5% of the load, the authorization for the storage is granted ($Signal = 1$); otherwise, $Signal = 0$. For all wind power plants installed with batteries, the decision process for charging or discharging is performed according to the GF and CF values in a manner analogous to operation strategy 1, wherein the Calculate_Charging method is executed only if $Signal = 1$.

This strategy ensures that the power injected into the grid by the "wind power plant + battery" unit will be within a range of ±10% of CF, as long as there are no restrictions imposed by the system. In addition to adding greater predictability and lower variability of the injected power, it does not have negative impacts on the overall performance of the system.

C. Operation Strategy 3: Reduction of Loss of Load

This strategy aims to reduce the loss of system load by using the existing batteries in the system as a source of operation reserve. The decision to store the energy is made based on local generation data of the plant with the authorization of the centralized control system, which is in the same manner as in operation strategy 2. The decision to discharge the battery is determined by the overall need of the system in a centralized manner and without any local influence. Note that in this strategy, the information from the centralized control system is determinative for the use of local storage. In addition to the data provided in operation strategy 2, the total energy stored in all system batteries E_{tot} is accounted for. The energy storage decision is made in the same manner as in operation strategy 2.

The process of discharging the batteries is a decision made when there is generation deficit in the system. Therefore, if the available power is less than the total load, all the batteries contribute to the power injection into the grid. The requested power of each battery is a function of its participation factor, according to (6) and (7).

$$P_{out} = PF_i \cdot \left(P_{Lsys} - P_{Gsys}\right) \tag{6}$$

$$PF_i = \frac{E_i}{E_{tot}} \tag{7}$$

where PF_i is the participation factor of plant *i*; P_{Lsys} is the total load of the system; P_{Gsys} is the total generation available in the system; and E_i is the energy stored in battery *i*.

With the participation of batteries in operation reserve of the system, there would be greater safety margins to meet the demand, smaller load shedding and better reliability indices for the system.

V. Battery Model

A. Charging and Discharging Processes of Battery

If the battery is in charging mode, P_{in} is stored in the battery within the simulated time interval ΔT, unless there is some restriction on the storage capacity. If P_{in} exceeds the maximum value that the battery can absorb $P_{\max}$, the stored energy is calculated using (8), with $\Delta P = P_{\max}$. Otherwise,

$\Delta P = P_{in}$. If the calculated value of $E_i(t)$ is greater than the maximum capacity C of the battery, a limitation occurs at the maximum value.

$$\begin{cases} E_i(t) = E_i(t-\Delta T) + \Delta P \Delta T \eta_C \\ \Delta P = P_{\max} \quad P_{in} \geq P_{\max} \\ \Delta P = P_{in} \quad P_{in} < P_{\max} \end{cases} \tag{8}$$

where ΔP is the actual power absorbed from the grid by the battery; η_C is the charging efficiency of the battery; and $P_{\max}$ is the maximum power which the battery can discharge.

If the battery is in discharging mode, the value of the energy requested by the grid P_{out} is deducted from the energy stored in the battery, except the case of any limitation. If P_{out} is higher than $P_{\max}$, the energy stored in the battery is updated using (9), with $\Delta P = P_{\max}$; otherwise, $\Delta P = P_{out}$. For the demanded power from the battery, if the charging state is lower than $SOC_{\min}$, the value of the energy stored in the battery is updated as specified in (10), limiting the power injection into the system.

$$\begin{cases} E_i(t) = E_i(t-\Delta T) - \Delta P \cdot PF_i \cdot \Delta T \dfrac{1}{\eta_D} \\ \Delta P = P_{\max} \quad P_{out} \geq P_{\max} \\ \Delta P = P_{out} \quad P_{out} < P_{\max} \end{cases} \tag{9}$$

$$E_i(t) = SOC_{\min} \cdot C(t) \tag{10}$$

where η_D is the discharging efficiency of the battery; and $C(t)$ is the storage capacity.

B. Battery Management and Protection System

The battery monitoring method is responsible for monitoring the battery SOC and DOD at each iteration, according to (11) and (12). SOC monitoring is required for the protection against deep discharging, which prevents the battery from reaching load states lower than $SOC_{\min}$.

$$SOC = \frac{E(t)}{C(t)} \tag{11}$$

$$DOD = 1 - SOC \tag{12}$$

where $E(t)$ is the stored energy.

Battery wear is also a function of the number of complete discharging cycles over the operation history. An equivalent discharging cycle is considered effective when the cumulative amount of the power injected into the network over the operation history reaches the value of the total storage capacity. At each full equivalent cycle, battery wear is accounted for by reducing the storage capacity according to (13), where the variation coefficient of storage capacity per equivalent discharging cycle Z is considered to be 0.00017 p.u. [15].

$$C(t) = (1-Z)C(t-\Delta T) \tag{13}$$

The battery SOH is calculated by (14) and can be interpreted as the degree of battery deterioration, as it reflects its loss of storage capacity over time. When the health condition reaches a value lower than $SOH_{\min}$, it is considered as the end of the lifespan of the battery. And the battery is replaced by a new one, with storage capacity equal to the nominal capacity C_{ref}.

$$SOH = \frac{C(t)}{C_{ref}} \tag{14}$$

VI. Results

The results are presented for two systems: ① a tutorial system composed of 5 busbars, for which the three operation strategies are evaluated; ② IEEE RTS system [18], for which operation strategy 3 is considered with different degrees of wind power penetration (WPP) and wind characteristics.

A. 5-busbar System

5-busbar system consists of a generation mix, including a thermal power plant with the capacity of 95 MW, a wind power plant with the capacity of 75 MW (50 wind turbines of 1.5 MW each) and a nominal load of 120 MW, which are all connected by one transmission system.

A generation availability curve is used corresponding to the average wind power generation in the northeastern region of Brazil, together with the regional hourly load curve. The average annual capacity factor of wind power generation is 54%.

As shown in (15), the average firm or minimum physical power ensures that the wind power plant should be able to meet the load. As the average wind power value cannot be lower than the one declared in the contract to avoid penalties, the value of CF can be calculated using (16), which represents the value above which the battery is programmed to modulate wind power generation (90% of the value of CF).

$$P_{wf} + P_{therm} = P_{Lsys} \Rightarrow P_{wf} = 25 \tag{15}$$

$$0.9 \cdot CF \cdot P_{wi} \geq P_{wf} \Rightarrow CF \geq 37\% \tag{16}$$

where P_{wf} is the power that the wind power plant must provide to the system according to the contract; P_{wi} is the installed power of the wind power plant; and P_{therm} is the installed power of the thermal plant.

1) Evaluation of Operation Strategy 1

Figure 1 shows the LOLP variation as CF and the installed storage capacity at the wind power plant vary without considering generator failures and load curve. When CF of less than 37% is adopted, there is an increase in LOLP when there is no storage. The largest reduction in LOLP occurs with the adoption of CF equal to 37%, indicating the optimal operation of the battery system.

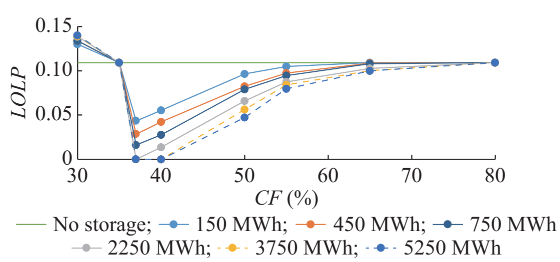

Fig. 1. Variation of LOLP with CF and storage capacity.

As CF increases, the battery remains idle most of the time because it operates in a minimum charging state. The occurrence of generation availability above CF of 110% is so rare that there are insufficient conditions for storing power when needed. Thus, the ability of battery to reduce the loss of load saturates after a certain increase in the storage capacity and also saturates with the use of high CF (above 65%).

CF of 37% is used and the generator failure and repair rates are included (4 per year and 90 per year for wind turbines [19], respectively, and 5.58 per year and 75 per year for thermal power plants, respectively). Besides, the load curve, the reliability indices and their variation without batteries are also included, as the storage capacity increases. The variation of reliability indices for operation strategy 1 is presented in Table I, where $\Delta LOLP$ is the difference between LOLP in the original system and that in the system with storage; and $\Delta EENS$ is the difference between EENS in the original system and that in the system with storage.

TABLE I
VARIATION OF RELIABILITY INDICES FOR OPERATION STRATEGY 1

Storage (MWh)	*LOLP*	*EENS* (GWh)	$\Delta LOLP$ (%)	$\Delta EENS$ (%)
0	0.0367	11.957		
300	0.0367	11.974	0	0.15
750	0.0367	11.986	0	0.25
2250	0.0367	12.012	0	0.46
3750	0.0367	12.010	0	0.45
7500	0.0367	12.010	0	0.45

It is observed that although LOLP does not vary, an increase in the value of EENS occurs after the inclusion of storage. Figure 2 illustrates the reason for this reduction in system reliability with the inclusion of the storage.

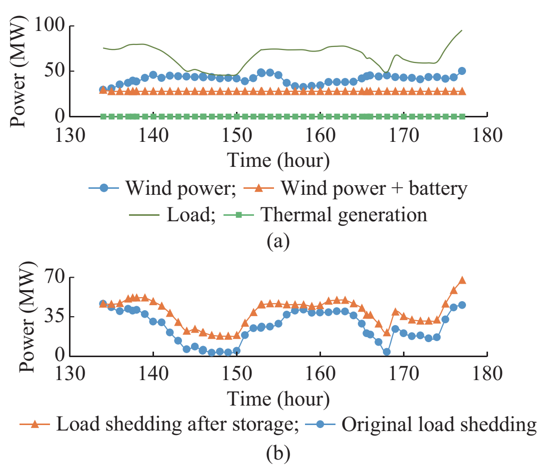

Fig. 2. Reliability worsening using operation strategy 1. (a) Power generation and system load during failure of thermal power plant. (b) Load shedding during failure of thermal power plant.

When there is a failure of the thermal plant and consequent loss of 95 MW of firm power, the wind plant is not able to fully meet the system load, leading to a loss of load. In operation strategy 1, the GF value of the wind power plant is considered to decide whether to store or discharge the batteries. When the available generation is less than the load, and the instantaneous generation of the wind power plant is greater than CF of 110%, the battery will store energy, which further increases the loss of load.

2) Evaluation of Operation Strategy 2

Table II presents the indices obtained with operation strategy 2, which is a reduction in the reliability indices of the system with an increase in storage capacity. Operation strategy 2 aims to reduce the intermittence of local generation without impairments or adversely affecting the overall performance of the power system.

TABLE II
VARIATION OF RELIABILITY INDICES FOR OPERATION STRATEGY 2

Storage (MWh)	*LOLP*	*EENS* (GWh)	$\Delta LOLP$ (%)	$\Delta EENS$ (%)
0	0.0367	11.957		
300	0.0367	11.859	0.00	–0.81
750	0.0366	11.793	–0.27	–1.37
2250	0.0366	11.752	–0.27	–1.71
3750	0.0366	11.738	–0.27	–1.82
7500	0.0366	11.738	–0.27	–1.82

Figure 3 shows that the reliability reduction problem of operation strategy 1 is eliminated with the adoption of operation strategy 2. When there is a generation deficit in relation to the load, even though GF of the wind power plant is above the specified range and there is storage capacity available on the battery, no authorization is granted for the storage of surplus energy. Therefore, the wind power plant continues to inject the power above the specified value into the grid, which supplies the load. In this operation strategy, there is no increase in system load shedding.

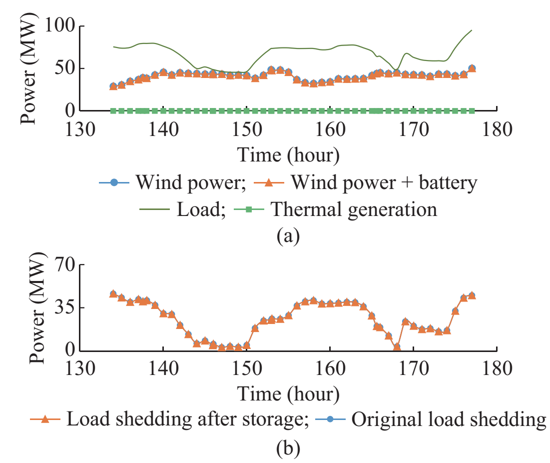

Fig. 3. Elimination of reliability worsening using operation strategy 2. (a) Power generation and system load during failure of thermal power plant. (b) Load shedding during failure of thermal power plant.

Table III presents the data regarding the battery monitoring system for increasing storage capacities. It can be observed that the increase of the storage capacity reduces the variability of the wind power generation and increases the permanence of GF within the specified range.

In addition, it can be observed that the occurence of GF below the specified minimum reduces as the storage capacity increases, implying a reduction of penalties applied to wind plants for generating below the declared value. P90 is the value of energy production with the probability of occurrence equal to or greater than 90% in a year. It is noted that P90 increases and is used to limit the maximum amount of energy traded through contracts of wind power generation availability.

TABLE III
OCCURRENCE OF BATTERY MONITORING SYSTEM

Storage (MWh)	*GF* in relation to range			Cycle per year	*SOC* (>80%)	*SOC* (=100%)	SOC_{min}
	Within	Below	Over				
0	11.6	12.7	75.7				
300	24.8	4.9	70.3	10	85.3	75.2	6.0
750	28.1	3.0	68.9	6	86.4	73.6	3.5
2250	31.6	1.4	67.0	2	86.0	71.7	1.6
3750	34.1	0.1	65.8	2	86.8	70.8	0.2
7500	34.3	0.0	65.7	1	89.4	71.6	0.0

SOC monitoring can serve as a framework for storage sizing. With the increase of storage capacity, the values of 100% SOC or SOC_{min} decrease. There is no demand for additional storage capacity with accumulated energy staying idle. Therefore, there is an inflection point after which the increase in storage capacity implies an increase in the occurrence of 100% SOC.

Considering the operation aspect, the inflection point (3750 MWh) represents the optimal storage capacity from the system perspective. Regarding the lifespan of the batteries, a good solution should have fewer average charging and discharging cycles per year and more cases with more than 80% SOC. The capacity of 3750 MWh is also a compromise solution.

Considering the financial aspect, a cost benefit analysis must be made to define the size of the battery that best fits with the application. In this analysis, the entrepreneur must evaluate the amount of the payment to avoid the risk of generating less power than the declared value. If the entrepreneur accepts the risk of generating below the minimum up to 5% of the time, installing a 75 MW/300 MWh battery would be enough. If the ideal operation solution is adopted, the risk could be reduced to less than 1%.

Other studies [20] have been carried out to investigate optimal sizing of hybrid wind-solar-battery systems, showing that resources and load uncertainties can impact the analysis results.

Currently, it may be economically unreasonable to reduce the intermittency when observing long time scales because the high cost technology could increase the final cost of renewable energy and make it less competitive. However, considering shorter time scales and the design of energy market where the project is located, it may be economic to reduce generation variability during peak loads when energy is more expensive with profit margins. The sizing methodology could also be applied in this case.

3) Evaluation of Operation Strategy 3

With an increase in storage capacity, Table IV presents the reduction in LOLP and EENS caused by operation strategy 3. The increase in battery capacity causes a significant decrease in the reliability indices. EENS is reduced by up to 60.52% when using the optimally sized capacity.

The choice of battery capacity for the system can be made based on the amount of reduction desired for the loss of load, so that it remains below acceptable levels for the system. A cost analysis should be performed to assess the extent when it is worthwhile to invest in additional storage capacity for load shedding reduction.

TABLE IV
VARIATION OF RELIABILITY INDICES FOR OPERATION STRATEGY 3

Storage (MWh)	*LOLP*	*EENS* (GWh)	Δ*LOLP* (%)	Δ*EENS*(%)
0	0.036	11.957		
300	0.033	10.904	–9.81	–8.81
750	0.029	9.820	–19.62	–17.87
2250	0.020	6.955	–45.50	–41.83
3750	0.013	4.720	–64.03	–60.52
7500	0.005	2.053	–84.74	–82.83

Comparative analysis between the applications of batteries and thermal or hydro power plants shows that batteries are not yet economically competitive due to the high costs and limited time of continuous charging and discharging. However, its application can be desirable to comply with the Paris Protocol to reduce greenhouse gas emissions. The application of batteries can be economically attractive in electricity markets adopting shortage or scarcity pricings, i.e., electricity markets that signal higher tariffs during periods with scarce energy to supply load or even energy deficit.

A simplified economic analysis has been performed to verify the feasibility of the aforementioned application. Payback period (PBP) is the period after which the investments of installing and operating the batteries are paid at the opportunity cost without paying fines for energy deficit. PBP can be regarded as the time T after which the accumulated cash flow (ACF) becomes equal or greater than zero in (17). Profitable operation period (POP) is the period when ACF maintains a positive trend. This variable is important for monitoring since operational & maintenance (O&M) costs are considered. It implies a reduction in cash flow over time due to increased maintenance needs. Equation (18) shows how cash flow is calculated for year t F_t.

$$ACF = \sum_{t=0}^{T}\left(R_t - OM_t - I_t\right) \tag{17}$$

$$F_t = R_t - OM_t - I_t \tag{18}$$

where R_t is the cost of energy deficit avoided in year t; OM_t is the O&M costs in year t which is considered as 2% of the initial investment with escalation of 2.5% per year; and I_t is the investment made in acquisition and installation of the battery system, which is considered only in year zero.

$$R_t = \Delta EENS \cdot EDP \tag{19}$$

$$I_t = C_{ref} \cdot BP \tag{20}$$

where *EDP* is the energy deficit price; and *BP* is the battery price.

Two different battery prices are considered in the economic analysis. One is based on the values in 2019 (380 $/kWh) and the others are based on the forecasted values in 2030 (200 $/kWh) [21]. Besides, three different energy deficit prices are considered to represent three different energy market penalties. Therefore, *EDP* is equal to 3700 $/MWh in market A, 9000 $/MWh in market B, and 20000 $/MWh in market C, respectively.

Figures 4 and 5 show that the reduction of battery price is necessary to enable investment return in market A, where penalties for energy deficit are less severe and the application of batteries is not economically feasible with the prices in 2019.

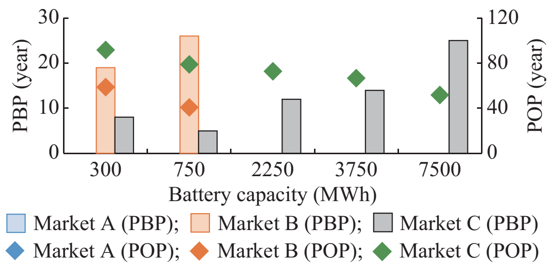

Fig. 4. PBP and POP in each market using battery costs of 2019.

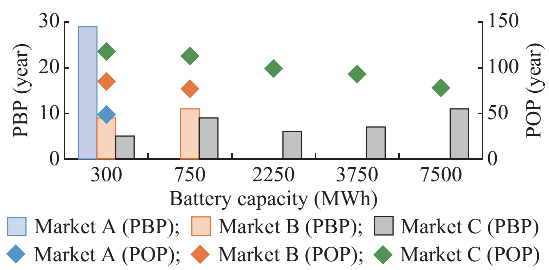

Fig. 5. PBP and POP in each market using battery costs of 2030.

In addition, markets with more rigid penalties, i.e., market C, may be attractive to investments with higher storage capacities (above 2250 MWh), which are not feasible in any of the other markets regardless of battery prices.

It can be concluded that after the reduction of battery prices in 2030, although the application of low-capacity batteries in market A becomes viable, it is not economically attractive due to the low profit margins. As the battery price decreases and the penalties for energy deficits increase, it becomes more attractive to invest in larger amounts of energy with higher profit margins.

B. Modified IEEE RTS System

With the total load of 3135 MW and the original generation capacity of 3405 MW, IEEE RTS system [18] is modified by a 10% increase in the nominal load of all busbars. Therefore, the installed power reserve of the system drops from 20% to 8.6%. LOLP and EENS indices for the modified IEEE RTS system are calculated as 0.0274 and 43.93 GWh, respectively. Cases are simulated with the gradual insertion of wind power plants in substitution of the firm power sources of the original system. The same wind power generation curve used in the 5-busbar test system is initially set for all wind power plants. Table V presents the simulated cases with different penetration degrees of wind power, highlighting the variation of EENS in relation to the purely hydrothermal system. The inadequate sizing of the operation reserve becomes more dependent on wind power. It implies an increase in the loss of load, which is not acceptable in real systems. This situation is intentionally illustrated to assess the storage capacity required to complement the pre-existing hydrothermal reserve of the system for each level of WPP.

TABLE V
MODIFIED IEEE RTS SYSTEM WITH VARYING PENETRATION DEGREE OF WIND POWER

WPP (%)	Busbar	Replacement by wind power generation (MW)	Wind power capacity (MW)	*EENS* (GWh)	Δ*EENS* (%)
10	23	351.0	351	71.26	62.21
30	18	375.0	1050	286.80	552.86
	21	375.0			
	23	300.0			
50	15	154.5	1707	1014.52	2209.40
	16	154.5			
	18	375.0			
	21	375.0			
	23	300.0			
	23	348.0			

Figures 6 and 7 demonstrate a reduction in the reliability indices with the installation in all wind power plants. The capacities of the battery banks are 12.5, 50, 100, 250, and 750 MW, respectively, and the maximum continuous charging/discharging time is four hours, which is operated according to operation strategy 3. Different values of CF are tested, where CF of 25% corresponds to the 90th percentile value (P90) and CF of 51% corresponds to the 50th percentile value (P50) of the adopted wind power generation curve.

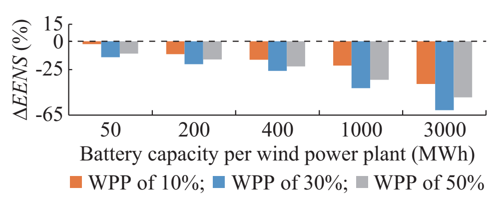

Fig. 6. Reduction of EENS index with CF of 25%.

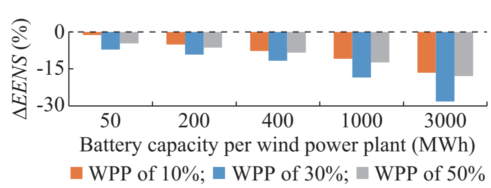

Fig. 7. Reduction of EENS index with CF of 51%.

The reduction of EENS reaches the maximum of 60.6% for a storage of 3000 MWh with WPP of 30%. However, it drops to 49.4% when the penetration increases to 50%, showing that this capacity cannot compensate well for wind power variability.

Note that in all cases, setting CF to be P90 is efficient for reducing the indices since the battery is able to store the energy for a longer time due to frequent occurrence of generation availability above this value.

1) Effect of Different Wind Profiles

Wind profiles in distinct geographic regions may be quite different. Two typical wind profiles from Northeast Brazil, coastal and inland regions, are used to analyze the storage efficiency in different regions.

A timely observation is that the inland wind power generation has greater variability, whereas the coastal wind power generation is more constant. Compared with the negative correlation between inland generation and the load, the strong positive correlation between the coastal generation curve and the load indicates that both of them follow the same growth or reduction trend most of the time.

To evaluate the effects of distinct wind profiles, IEEE RTS system is divided into two geographic regions: one with inland winds and one with coastal winds, which is in accordance with Fig. 8. The tests are performed with 10% WPP, consisting of 350 MW concentrated in a single busbar (busbar 23). The power of this plant is distributed among other busbars to verify the influence of the transmission network on the ability of supporting the load for wind power generation.

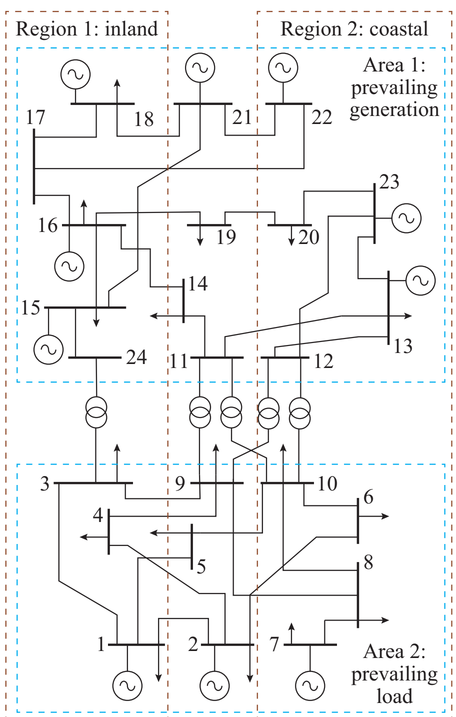

Fig. 8. IEEE RTS system of two regions with different winds.

In this case, failure and repair rates are associated with each transmission line and transformer to allow composite reliability analysis. In each simulation step, the system state is calculated by an optimal power flow algorithm with the objective function of minimum load shedding subject to DC power flow constraints. The simulated cases and their respective EENS indices are reported in Table VI.

Results show that the characteristics of the transmission grid are also relevant. Busbars 13 and 23 in the coastal region have a lower dependence on the local grid to supply the load since they are closer to the transformation that connects the predominant generating system (area 1) to the load center (area 2). Busbars 16 and 18 in the inland region have strong dependence on the transmission grid to outflow its generation to the load center.

TABLE VI
DISTRIBUTION OF WIND POWER BY REGION WITH 10% PENETRATION

Wind power dispersion	Busbar of wind power generation	Location	*EENS* (GWh)
1 busbar	18	Inland	84.9
	23	Coast	
2 busbars	13	Coast	91.2
	23	Coast	
	16	Inland	
	18	Inland	

Therefore, the lack of robustness of the local transmission to outflow the generation of busbars 16 and 18 makes the concentration of wind power generation more favorable than its distribution. However, depending on the wind regime and the robustness of the local transmission, it may occur that the distribution of generation is preferable to the concentration of generation at a weaker point of the system and with less favorable winds.

2) Battery Dispersion Effect

Batteries are allocated to the wind power plants in a granular manner, as described in Tables VII and VIII.

TABLE VII
DISTRIBUTION OF BATTERIES (1 BUSBAR)

Region	Battery capacity of busbar (MW)		Total capacity (MW)	*EENS* (GWh)	Δ*EENS* (%)
	18	23			
Inland	100	0	100	76.2	–10.2
Coastal	0	100	100	77.9	–8.3
Both	100	100	200	57.2	–32.6
Inland	250	0	250	67.6	–20.3
Coastal	0	250	250	68.1	–19.8
Both	250	250	500	58.3	–31.3
Inland	750	0	750	64.7	–23.8
Coastal	0	750	750	61.3	–27.7
Both	750	750	1500	50.6	–40.4

From the analysis of the results, it is not possible to identify a region that is more favorable for battery installation. The installation of batteries only inland generates a greater reduction in EENS, and sometimes, the installation only at the coast is more beneficial.

For all the storage capacities, the installation of batteries distributed over the two regions is more effective than the concentrated installation in just one region. For example, the total installation of 200 MW for each region causes a greater reduction in the loss of load than the installation of 250 MW only inland or only at the coast.

TABLE VIII
DISTRIBUTION OF BATTERIES (2 BUSBARS)

Region	Battery capacity of busbar (MW)				Total capacity (MW)	*EENS* (GWh)	Δ*EENS* (%)
	18	16	13	23			
Inland	50	50	0	0	100	79.8	–12.4
Coastal	0	0	50	50	100	84.3	–7.6
Both	50	50	50	50	200	74.5	–18.3
Inland	125	125	0	0	250	76.6	–16.0
Coastal	0	0	125	125	250	80.5	–11.7
Both	125	125	125	125	500	65.4	–28.3
Inland	375	375	0	0	750	66.0	–27.6
Coastal	0	0	375	375	750	69.0	–24.3
Both	375	375	375	375	1500	45.8	–49.7

VII. CONCLUSION

This paper presents 3 operation strategies for the use of storage in systems with high penetration of wind power generation, which differ from each other for applications. The use of storage is efficient to ensure the supply of firm power of the "wind power plant + battery" unit. However, the operation strategy does not consider the generation and load balance of the system, which increases the risk of load shedding.

For the entrepreneur, the increase of P90 for wind power plants is beneficial. It allows for the commercialization of higher amounts of power via contracts in addition to reducing the payment of fines for generating below the declared value of the contract. For the system operator, establishing a guaranteed firm energy from wind power generation is a tool to mitigate the problems of short-term generation forecasting and reduce the occurrence of deficits in the dispatched power.

As a flexible operation reserve, the use of batteries provides a significant reduction of load loss of the system. Although the use of batteries is not yet economically competitive, it is attractive in adverse environmental situations and electricity markets with scarcity pricing. The technological limitations and costs are the determinant factors for the wide commercial application of batteries in power systems.

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