Reliability Modeling and Control Schemes of Composite Energy Storage and Wind Generation System With Adequate Transmission Upgrades

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***Abstract*—The intermittency of wind generation and the potential need for adequate transmission expansion are the major concerns in wind generation integration to power system. One solution being considered is to build on-site energy storage with the wind farms. The idea of building such a composite system is not only to minimize the real-time variation of the composite system output, but also to optimize the transmission upgrades needed for delivery of the wind generation. A novel probabilistic reliability assessment method is proposed in this paper for determining the adequate size of on-site energy storage and the transmission upgrades needed in connecting wind generation with the power system. The practical applications of the proposed model are illustrated using the IEEE Reliability Test System (IEEE-RTS).**

***Index Terms*—Energy storage, planning, reliability, renewable, transmission upgrade, wind generation.**

I. INTRODUCTION

RENEWABLE generation has attracted much attention in recent years because of the environmental pressure and high price of natural gas and oil. Many countries have adopted an aggressive Renewable Portfolio Standard (RPS). As one of the most important resources of renewable generation, wind generation and its impact on system reliability have been extensively studied in both planning and operating phases [1]–[5]. Wind generation is an energy-limited resource such that the available energy during a given period is determined by the weather condition and is not dispatchable. In real-time operation, the intermittency of wind energy may result in large forecasting errors. A larger amount of operating reserve, therefore, has to be carried by the system as wind penetration increases in the power system [5].

Another major concern of wind energy integration is the proper transmission upgrades required to deliver the energy to the load center. Obviously, if the transmission upgrades are identified based on the nameplate capacity of the wind turbine generators, the new transmission lines will be under-utilized because of the relatively low capacity factor of the wind generators. One widely adopted practice of wind (and PV solar) integration is to determine the transmission upgrades based on the qualifying capacity of the renewable resource. The qualifying capacity is the expected average output during the study period (on-peak or off-peak) based on historical generation profile. However, such practice could result in hours of congestion when the generation is above the qualifying capacity level and exceeds what the transmission system is designed for.

Energy storage associated with wind generation has been studied from reliability [6] and economic [7] aspects. Pumped storage is the most known energy storage facility today; however, its use is limited because of the restriction of the placement. In recent years, with the progress of massive energy storage technologies, it is possible to install energy storage facilities with virtually no restrictions of location. For example, energy storage can be installed close to a wind farm so that the on-site energy storage and the wind generation share the same transmission to connect to the main grid. The on-site energy storage can be used as an alternative to transmission upgrades for wind generation integration. The need for transmission upgrades could be deferred or reduced if the energy storage can absorb wind energy when there is not enough available transmission capacity, especially during the over generation period. In other examples, energy storage can effectively participate into the power market as a provider of energy and ancillary services. It is worth noting that, the energy storage may operate either as an alternative of transmission upgrade or as a market participant, following the corresponding planning and market tariff. This paper focuses on the on-site energy storage that operates as transmission asset. As such, the paper devotes more to the reliability impact and maximizing the utilization of the available transmission capacity rather than the economic evaluation of the energy storage operation.

A probabilistic simulation method is proposed in this paper to evaluate the impacts on system reliability from the composite system of wind generation and on-site energy storage. The proposed models and methods can be used to assess the benefit of reducing transmission upgrades due to the utilization of on-site energy storage. The IEEE Reliability Test System (IEEE-RTS) is used to illustrate the developed models and the study results.

II. WIND INTEGRATION WITH ON-SITE ENERGY STORAGE

A. Transmission Upgrades for Wind Integration

Since the capacity factors of wind farms are relatively low, the transmission system may be designed to accommodate wind

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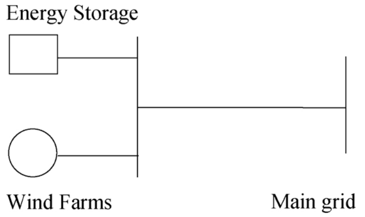

Fig. 1. Example of wind farm interconnection with an on-site energy storage.

generation at capacity level lower than the name plate ratings. One example in practice is to use the average hourly production capacity during the study period. Therefore, the actual deliverable output from the wind generation is limited by the designed transmission capacity. If the output of the wind farm and the capacity of transmission are represented by x and y, respectively, then the equivalent deliverable output to the main grid, which is denoted by z, is the smaller one between x and y

$$z = \min(x, y). \tag{1}$$

Although the transmission upgrades identified in such a manner can be used more effectively, it will compromise the utilization of green energy. The lower transmission capacity, moreover, could restrict the contribution of wind generation to the system reliability; hence, more conventional generation capacity would be needed to maintain the system reliability. Wind generation with on-site energy storage shown in Fig. 1 helps to resolve the above issues caused by lower capacity transmission upgrades.

B. *On-Site Energy Storage*

The on-site energy storage and the wind generation share the same transmissions that connect them to the main grid. The idea of using on-site energy storage is to use the charge and discharge capability of the energy storage to compensate the fluctuation of wind generation output.

When the wind generation exceeds the transmission capability, the energy storage operates at the charging mode to absorb the extra wind energy. The energy storage will discharge when there is spare transmission capacity. Following this basic idea, a line-flow-control scheme can be designed for the on-site energy storage operation. This paper is not attempting to evaluate different energy storage technologies and the technique parameters; rather, a conceptual energy storage facility is used to illustrate the application of on-site energy storage associating with wind generation. The feasibility and general requirements of the on-site energy storage will be evaluated based on the system reliability requirements. For this purpose, some common characteristics of energy storage are discussed as follows:

1) Charge capacity: the maximum absorbed energy from the grid in a given period. It is the technical boundary of the energy storage in the charging state, normally in megawatts (MW).
2) Discharge capacity: the maximum delivered energy to the grid in a given period. It is the technical boundary of the energy storage in the discharging state, normally in MW.
3) Charge and discharge efficiencies: the efficiency ratios of energy transition of the energy storage. Normally they are less than one.
4) Volume of energy storage: the maximum energy volume of the storage facility, normally in megawatt hours (MWh) or gigawatt hours (GWh).

C. *Discussion of Application of Energy Storage*

The energy storage works as a flow controller when using the control scheme discussed in the earlier subsection. The main objective of such a control scheme is to reduce the need for transmission upgrades as well as to improve the system reliability. The energy storage using the line-flow-control scheme can thereby be considered as an alternative to transmission upgrades, i.e. it can be deemed as a transmission facility for the purpose of wind integration. The line-flow-control scheme can be broadly viewed as controlling flow on the critical path that may limit the output of the wind farms otherwise. The critical path can be a downstream single transmission line or a group of transmission lines that impose limitation on the delivery from the wind farms to the main grid. The wind farms used in the examples in the paper can be deemed as an aggregated model of many wind farms that are subject to the common transmission limitation. The energy storage facility is installed on the wind farm side of the transmission path.

The energy storage can also be installed at different locations in the power system, and can be used for different purposes. For example, an energy storage facility may participate in the energy and ancillary service market. Depending on the location and the purpose of applications, the interconnection of the energy storage facility may fall into different categories of power system enhancement; hence, different planning tariff and cost recovery mechanism will apply. It, therefore, may not be suitable to use a unique framework to evaluate different applications of energy storage, especially from the system economic viewpoint.

This paper proposes a reliability assessment method for determining the adequate size of the on-site energy storage and capacity of the transmission system that are needed in connecting wind generators with the power system. The system constraints can always be translated to the flow limit of the transmission line shown in Fig. 1, if needed. In practice, any decisions on the system addition will be made based on system-wide assessments. The models proposed in this paper, however, can provide boundary conditions of the size of the on-site energy storage and the transmission line for the system wide assessments, from the probabilistic reliability standpoint.

III. Reliability Model of On-Site Energy Storage

A. *Index of Probabilistic Reliability*

Different reliability indices can be used to quantify the system reliability. The energy index, Expected Energy Not Supplied (EENS), is an appropriate index for evaluating the reliability of a system including energy-limited resources. According to [8], EENS can be calculated by

$$\mathrm{EENS} = \sum_{k=1}^{n} E_k P_k \tag{2}$$

where n is the number of system capacity states; P_k is the probability of a capacity state; and E_k is the energy curtailed when the capacity is at state k. EENS has energy unit, such as MWh or GWh. The capacity states of the system can be obtained if the forced outage rate (F.O.R.) and capacity of generators are available. The detailed computation method of capacity states and associated probabilities can be found in [8].

Assuming that the wind farm output profile is given, the system load profile is modified by the given wind output profile. The remaining generators are modeled as conventional units and the system capacity states can be calculated using the method given in [8]. Then the system EENS is calculated using the modified load profile. It has been identified that wind integration may degrade system reliability [4], [5]. Addition of conventional capacity may be needed to maintain system reliability. The impact of wind integration on system reliability and the associated cost can be evaluated by the additional capacity of conventional units [5].

B. Line-Flow-Control Scheme

As noted earlier, different strategies can be employed to the operation of energy storage facilities. If the energy storage is a standalone market participant, the operation mode of energy storage facility can be decided based on the market price signals. On the other hand, the on-site energy storage discussed in this paper can be controlled by the difference between the wind generation output and a reference flow level on the critical path. The reference flow level may be static or dynamic. It can be the rating of the critical transmission path between the wind farm and the main grid, or it can be determined in real-time based on the system operating conditions.

Assume the wind generation at time T is $P_{\mathrm{wind},T}$ and will remain unchanged from T to $T+\Delta t$. The operation of the energy storage facility using line-flow control scheme can be described by the following equations:

$$\begin{aligned} E_{\mathrm{ch},T+\Delta t} = \min\big(&E_{\mathrm{volume}} - E_{\mathrm{residue},T},\\ &\min\big(P_{\mathrm{ch}}^{\max}, P_{\mathrm{wind},T} - P_{\mathrm{ref}}\big)\\ &\times \Delta t \times \eta_{\mathrm{ch}}\big), \text{if } P_{\mathrm{wind},T} \geq P_{\mathrm{ref}} \end{aligned} \tag{3}$$

$$\begin{aligned} E_{\mathrm{disch},T+\Delta t} = \min\big(&E_{\mathrm{residue},T},\\ &\min\big(P_{\mathrm{disch}}^{\max}, P_{\mathrm{ref}} - P_{\mathrm{wind},T}\big)\\ &\times \Delta t / \eta_{\mathrm{disch}}\big), \text{if } P_{\mathrm{wind},T} < P_{\mathrm{ref}} \end{aligned} \tag{4}$$

where $E_{\mathrm{ch},T+\Delta t}$ is the charged energy that the energy storage absorbed during time period Δt when the wind generation is beyond the reference flow level; $E_{\mathrm{disch},T+\Delta t}$ is the discharged energy during the time period Δt when there is spare transmission capacity. η_{ch} and η_{disch} are the charging and discharging efficiencies, respectively. E_{volume} is the volume of the energy storage; $P_{\mathrm{ch}}^{\max}$ and $P_{\mathrm{disch}}^{\max}$ are the charging and discharging capacity of the energy storage, respectively. $E_{\mathrm{residue},T}$ is the residual energy that is still stored in the energy storage at time T, which can be obtained by

$$E_{\mathrm{residue},T} = E_{\mathrm{residue},t=0} + \sum_{0<t<T} \left(E_{\mathrm{ch},t} - E_{\mathrm{disch},t}\right). \tag{5}$$

There are logical upper bounds for the charging capacity and the volume of storage. If the energy storage has a size larger than the logical upper bounds, the extra storage volume and charging capacity will never be used. If the volume of the on-site energy storage is less than its upper bound, or if the charging capacity is smaller than its upper bound, some wind energy will be spilled in high wind hours. The upper bounds in this sense for the charging capacity and the volume of storage can be obtained from (6) and (7) as follows, respectively:

$$P_{\mathrm{ch}}^{\max} \leq \frac{\max_T\left(E_{\mathrm{ch},T+\Delta t}\right)}{\Delta t \times \eta_{\mathrm{ch}}} \leq \max_T\left(P_{\mathrm{wind},T} - P_{\mathrm{ref}}\right) \tag{6}$$

$$E_{\mathrm{volume}} \leq E_{\mathrm{volume}}^{\max}, E_{\mathrm{volume}}^{\max} = \max_T\left(E_{\mathrm{residue},T}^{\infty}\right) \tag{7}$$

where $E_{\mathrm{residue},T}^{\infty}$ is the residual energy at time T when assuming there are no limits on the volume and the charging and discharging capacities.

The upper bounds are dependent on the reference flow level and the wind generation capacity. The upper bound of the volume is also dependent on the capacity factor of wind generation. If the line capacity is small and the capacity factor of wind generation is high, the volume of energy storage may have a very large upper bound. In the planning phase of the wind interconnection, these upper bounds can be estimated based on the field measurements of wind and the designed transmission capacity.

Another parameter that may need to be considered for on-site energy storage is the discharging capacity. When the line-flow-control scheme is used, the discharging power cannot be greater than $P_{\mathrm{ref}} - P_{\mathrm{wind},T}$ when the wind power is less than the reference line flow. Depending on the storage technology, the charging and discharging capacities may be different. If the on-site energy storage is selected based on the discharging capacity, it should have

$$P_{\mathrm{disch}}^{\max} \leq \max_T\left(P_{\mathrm{ref}} - P_{\mathrm{wind},T}\right), \quad \text{for} \quad P_{\mathrm{wind},T} < P_{\mathrm{ref}}. \tag{8}$$

C. Reliability Assessment Model of On-Site Energy Storage Facility Using Line-Flow-Control

The load-modification method [9] has been proposed for the reliability assessment of energy-limited resource with volume-limited storage. This method can be used when the storage and the generation facilities compose a series connection system, such as pumped storage station and solar thermal station with thermal energy storage. In these two examples, the energy stored in the storage facility can only be transferred to the system via the generation facility. For the composite system of wind generation and on-site energy storage, however, the load-modification method proposed in [9] is not appropriate since both the wind generator and the energy storage can output to the grid in parallel. This paper proposes to use the chronological output profile of the composite system directly to modify the system load profile in the probabilistic reliability assessment. The modified load profile will be used to calculate the probabilistic reliability index, which is EENS of the system in this paper.

Assume the line-flow-control scheme is used; the output of the composite system of wind farm and energy storage at time T is

$$P_{\text{gen},T} = \begin{cases} P_{\text{ref}}, & \text{if } P_{\text{wind},T} > P_{\text{ref}} \\ P_{\text{wind},T} + E_{\text{disch},T}/\Delta t, & \text{if } P_{\text{wind},T} < P_{\text{ref}} \end{cases}. \tag{9}$$

It can be seen from (9) that the composite system of wind farm and on-site energy storage can deliver power to the main grid with minimal fluctuations depending on the capability of the energy storage facility. Since the pattern "high load and low wind" and "low load and high wind" has been frequently observed in many real systems [1], the proposed composite system model and control scheme potentially have the peak-load-shaving capability. It can be expected that the less the fluctuation on the output of the composite system, the more improvement on the system reliability.

D. Alternative Approach to the Basic Line-Flow-Control Scheme

The line-flow-control scheme is designed to maintain the line flow to the reference level as close as possible once deviation occurs. The energy in storage will be discharged right away when the actual line flow is below the reference flow level. The advantage is that the scheme is easy to implement. On the other hand, because of the limitation of the energy volume, the energy stored during the high wind periods may have been exhausted as the wind dies down before the high load hours. The peak-load shaving capability of the line-flow-control scheme, however, may be limited. The contribution of the energy storage to system reliability could thereby also be limited.

An alternative to this limitation is the valley-fill scheme, which is designed to use the stored energy to fill the next valley of wind output profile. It is expected that the valley-fill scheme improves the contribution of the energy storage to system reliability. In real-time operation, the valley-fill scheme will rely on the forecasted wind curve. As the improvement of day-ahead wind forecast, it is possible to use the stored energy to fill the wind output valleys coincident with the peak load. One implementation of the valley-fill scheme is that the stored energy is discharged to compensate the reduction of wind generation in proportion to the difference between the reference flow level and the wind generation at each time period. Equation (9) can still be used to express the proportional valley-fill scheme; however the discharged energy is different from the basic line-flow-control scheme. The discharged energy of the proportional valley-fill scheme can be calculated by

$$E_{\text{disch},T} = \min\left(E_{\text{residue},T_0}, E_{\text{valley}}\right) \times \frac{(P_{\text{ref}} - P_{\text{wind},T}) \times \Delta t}{\eta_{\text{disch}} \times E_{\text{valley}}} \tag{10}$$

where E_{residue,T_0} is the residual energy in the storage facility when the wind curve downwardly crosses the reference flow level; E_{valley} is obtained from

$$E_{\text{valley}} = \sum_{T \text{ in Valley}} \frac{(P_{\text{ref}} - P_{\text{wind},T}) \times \Delta t}{\eta_{\text{disch}}}. \tag{11}$$

IV. TEST RESULTS

A. The Test System and Basic Assumptions

The IEEE-RTS [8] system is used in this paper to illustrate the proposed models and schemes. Assume the system does not have any internal congestion. A wind farm and an on-site energy storage facility are added to the system via a transmission line as shown in Fig. 1. The effect of different transmission line capacities are first demonstrated without any storage capacity. Then different sizes of energy storage facilities are studied for different transmission capacities. The probabilistic reliability assessment method developed in this paper is used in the studies. The on-site energy storage is assumed to be a generic energy storage facility. For simplicity, it is also assumed that the charging and discharging capacities are the same. In addition, it is assumed that $\eta_{\text{ch}} = \eta_{\text{disch}} = 100\%$ first, although the charging and discharging efficiency ratios are normally different from each other and less than one. The efficiency ratio can be substituted into (3) and (4) to obtain the output profile of the composite system. The impact of lower efficiency ratio will be discussed at the end of this section.

The RPS benefit is used to illustrate the utilization of wind energy in this paper, which calculated as the wind energy that is delivered to the system divided by the total load demand for the study year. The system peak load has been assumed to be 3000 MW in this paper instead of 2850 MW as the original test system suggests. The conventional capacity is 3405 MW, same as in the original IEEE-RTS system.

B. Reliability Assessments for Different Line Capacities

The capacity of the transmission line between the main grid and the wind farm can have significant impacts on the system reliability and the wind energy utilization. Four different transmission capacities are studied to demonstrate the system reliability impacts. No on-site energy storage is modeled in the subsection. The output profile of a real wind farm with 40% capacity factor is used to represent the new wind generation in the test system.

Assume a 520-MW wind farm is interconnected to the system. The wind power that is delivered to the system via the transmission line that may have discounted capacity can be calculated by (1). The capacity state table of the existing units of the test system is created as shown in [8]. The delivered wind power is used to modify the load profile. Then the EENS is calculated by (2) using the capacity states and the modified load profile.

The study results for different capacity levels of transmission upgrades are shown in Table I. It can be seen that the RPS benefit decreases and the EENS increases when the line capacity decreases.

TABLE I
RPS AND EENS FOR DIFFERENT LINE CAPACITIES, NO ENERGY STORAGE

Line capacity (% of wind farm capacity)	RPS (%)	EENS (GWh)
100	11.12	1.790789713
85	10.78	1.792507616
65	9.44	1.809753986
40	6.84	1.907256432

TABLE II
SIZE OF ON-SITE STORAGE FOR DIFFERENT LINE CAPACITIES

Parameter	Upper bound	
	65% line capacity	40% line capacity
Charging capacity (MW)	182	312
Discharging capacity (MW)	338	208
Volume of storage (GWh)	15	146

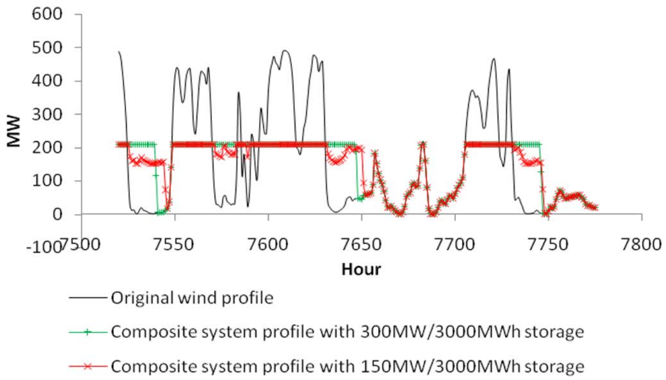

Fig. 2. Output profiles of composite system, 40% line capacity.

C. Partial Transmission Upgrade and On-Site Energy Storage

On-site energy storage can be used associated with partial transmission upgrades. The basic line-flow-control scheme of the on-site energy storage proposed in Section III is first used to assess the impacts of the energy storage on the RPS benefit and the EENS of the system. The upper bounds of the on-site storage are calculated by (6), (7), and (8) for two scenarios with different levels of transmission upgrades. The results are shown in Table II, where "65% line capacity" and "40% line capacity" mean that the line capacity is 65% and 40% of the wind farm capacity, respectively.

It can be seen that the upper bounds of the storage volume are large for both scenarios. It may not be practical to have an energy storage facility so large because of the restriction of technology and land use. Relatively small energy storages are used in this example. Meanwhile, the upper bound of the charging capacity is used to determine the capacity of the energy storage.

The output profiles of the composite system are calculated by using (3), (4), (5), and (9). The profiles during some hours for the 40% line capacity scenario are shown in Fig. 2, where two cases of 300 and 150 MW of energy storage are compared. The energy storages in both cases have 3.0 GWh of volume.

From Fig. 2, it can be seen that energy storage can shift wind energy from hour to hour based on the proposed line-flow-control scheme; hence, increase the utilization of wind energy when the line rating is lower than the maximum wind farm output. By reducing the fluctuation on the output of the composite system, the system reliability would be improved. The effectiveness of the composite system on the improvement of wind energy utilization and system reliability is reflected on the system RPS benefit and EENS, respectively, which can be seen in Table III.

TABLE III
RPS AND EENS USING BASIC LINE-FLOW-CONTROL

Line capacity	Energy storage		RPS (%)	EENS (GWh)
	Capacity (MW)	Volume (GWh)		
40%	300	1.5	7.98	1.568361879
	150	1.5	7.92	1.583080424
	300	3.0	8.47	1.504135602
	150	3.0	8.36	1.501102816
65%	150	1.5	10.36	1.681185123
	75	1.5	10.20	1.679776644
	150	3.0	10.69	1.618832673
	75	3.0	10.37	1.632773708

It can also be seen in this example that all four combinations of on-site energy storage and a transmission upgrade built to 65% of the wind farm capacity can provide similar RPS benefit to the system, compared to the scenario with the transmission upgrade built to 85% of the wind farm capacity but without energy storage as shown in Table I.

The proposed reliability modeling and analysis methods can be used to assess the benefit of on-site energy storage that operates as an alternative of transmission upgrade. In practice of transmission planning, such benefit needs to be further compared with other alternatives such as transmission upgrade, additional generation facilities, etc., in order to determine which alternative will be selected as the final solution of system enhancement [3], [10].

D. Valley-Fill Scheme of On-Site Energy Storage

The valley-fill scheme is simulated in this subsection. The upper bounds of the on-site energy storage are still the same as using the basic line-flow-control scheme. Fig. 3 shows two output profiles using basic line-flow-control and valley-fill schemes, respectively.

It is seen that the valley-fill scheme provides output profile with less fluctuation than the basic line-flow-control, given the same capacity and volume of energy storage. This improvement on the output profile is consistent with the improvement on the system reliability as shown in Table IV, which lists the results of RPS benefit and EENS when the valley-fill scheme is used.

By comparing Tables III and IV, it can be seen that two schemes result in the same RPS benefit, but the valley-fill scheme results in less system EENS. It is expected, however, that the difference between the two schemes will be reduced as the volume of storage increases.

E. Influence of Wind Capacity Factor

A wind profile that has 24% capacity factor is used to test the influence of wind capacity factor. The same wind farm capacity of 520 MW is used. Table V shows the RPS benefit and EENS for different levels of transmission upgrades when there is no on-site energy storage. Since the capacity factor is lower, the system reliability degradation is as expected.

The composite system model using the line-flow-control scheme is then simulated for this 24% wind capacity factor

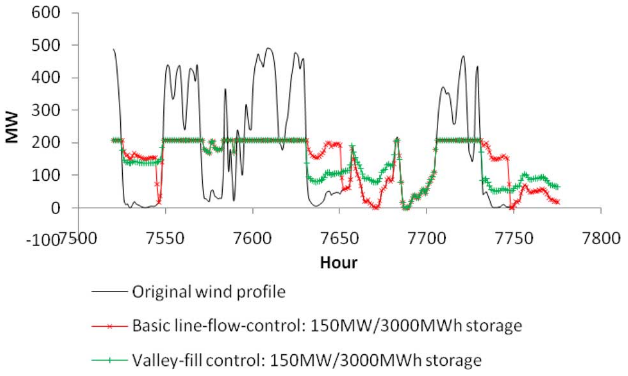

Fig. 3. Compare the output profiles using different control schemes.

TABLE IV
RPS AND EENS FOR 40% WIND CAPACITY FACTOR USING VALLEY-FILL CONTROL

Line capacity	Energy storage		RPS (%)	EENS (GWh)
	Capacity (MW)	Volume (GWh)		
40%	300	1.5	7.98	1.524526822
	150	1.5	7.92	1.542855333
	300	3.0	8.47	1.425429264
	150	3.0	8.36	1.448612575
65%	150	1.5	10.36	1.618860338
	75	1.5	10.20	1.624946093
	150	3.0	10.69	1.526908287
	75	3.0	10.37	1.577581407

TABLE V
RPS AND EENS FOR 24% WIND CAPACITY FACTOR AND WITH DIFFERENT LINE CAPACITIES; NO ENERGY STORAGE

Line capacity (% of wind farm capacity)	RPS (%)	EENS (GWh)
100	6.79	2.114851849
85	6.78	2.114893333
65	6.63	2.116906641
40	5.44	2.143813254

TABLE VI
SIZE OF ON-SITE STORAGE FOR 24% WIND CAPACITY FACTOR

Parameter	Upper bound	
	65% line capacity	40% line capacity
Charging capacity (MW)	182	312
Discharging capacity (MW)	338	208
Volume of storage (GWh)	3.7	55

case. As shown in Table VI, the upper bounds of the charging and discharging capacities for the 24% capacity factor case do not change from the 40% capacity factor case in Table II since the capacity of wind farm does not change. The upper bound of the storage volume, however, reduces significantly, compared to Table II. This indicates that there is a potential risk in selecting the volume of energy storage based on a relatively high wind capacity factor. If the wind capacity factor decreases due to weather change year to year, energy storage may not be fully utilized if the volume is originally selected close to the upper bound based on high capacity factor.

TABLE VII
RPS AND EENS FOR 24% WIND CAPACITY FACTOR USING LINE-FLOW-CONTROL

Line capacity	Energy storage		RPS (%)	EENS (GWh)
	Capacity (MW)	Volume (GWh)		
40%	300	1.5	5.87	2.112709516
	150	1.5	5.87	2.107633413
	300	3.0	6.08	2.068605359
	150	3.0	6.07	2.065748440
65%	150	1.5	6.75	2.109148606
	75	1.5	6.74	2.086529643
	150	3.0	6.78	2.080898762
	75	3.0	6.76	2.079239966

TABLE VIII
RPS AND EENS FOR 24% WIND CAPACITY FACTOR USING BASIC LINE-FLOW-CONTROL AND ASSUMING 0.7 EFFICIENCY RATIO FOR STORAGE

Line capacity	Energy storage		RPS (%)	EENS (GWh)
	Capacity (MW)	Volume (GWh)		
65%	150	1.5	6.71	2.111309798
	75	1.5	6.69	2.099542399
	150	3.0	6.72	2.101372463
	75	3.0	6.70	2.099413477

Table VII shows the results of the RPS benefit and EENS when the line-flow-control scheme is used for the 24% wind capacity factor case. By comparing Tables VII and III, it is seen that the reliability and RPS benefits of the on-site energy storage decrease, although the capacity and volume of energy storage are the same, when the wind capacity factor decreases from 40% to 24%.

F. Influence of Storage Efficiency

The efficiency ratio is another factor to be considered in the assessment of the benefit of on-site energy storage. Assuming both charge and discharge efficiencies are 0.7. The RPS benefit and system EENS are calculated on the same example as in the previous subsections. Only the scenario that the line capacity is 65% of the wind farm capacity is studied for simplicity. The results are shown in Table VIII. Compared with Table VII, where the efficiency ratios are assumed at 1.0, both the RPS benefit and the system reliability decrease, although not significantly.

V. CONCLUSION

On-site energy storage, as an alternative of transmission upgrade, associated with wind generation has been analyzed in this paper. A line-flow-control scheme of on-site energy storage is proposed such that the power flow on the transmission line between the wind farm and the grid does not exceed a predefined reference level. Operation constraints of the on-site energy storage have been investigated. A framework of analyzing the effect of the on-site energy storage is presented.

The upper bounds of the volume of storage and the charging and discharging capacities of the on-site energy storage are analyzed. The paper also demonstrates that the on-site energy storage using the line-flow-control scheme can reduce the need for transmission upgrades. Meanwhile, the green energy can be used effectively and the system reliability can be improved. The influence of wind capacity factor has been investigated. It is observed that the benefit of using on-site energy storage will decrease as wind capacity factor decreases. Also investigated is the impact of the efficiency ratios of energy storage. Both utilization of wind energy and system reliability degrade when the efficiency ratio of energy storage reduces.

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