Wind Power Curtailment and Energy Storage in Transmission Congestion Management Considering Power Plants Ramp Rates

Luis S. Vargas, Gonzalo Bustos-Turu, and Felipe Larraín

***Abstract*—The integration of intermittent generation in power grids, such as wind energy, imposes new challenges for transmission congestion management. In order to solve this problem, energy storage systems (ESS) have been proposed in the literature, as they provide an efficient mechanism for balancing variability while reducing operational costs. This paper presents a comprehensive analysis of the dynamic interactions between wind energy curtailment and an energy storage system (ESS) when the ramping rates of power plants are considered. An analytical framework is developed to study different mitigation measures in terms of total energy curtailed, total congestion costs, line load factor and congestion probability. This framework is tested in a real case study and a sensitivity analysis is performed to identify the influence of the main ESS design parameters in congestion mitigation performance.**

***Index Terms*—Energy storage, ramp rates, re-dispatch, transmission congestion, wind curtailment, wind energy.**

I. INTRODUCTION

EVERY day it is more recognized the large potential of renewables energies to displace greenhouse gases emissions and to achieve climate change mitigation targets [1]. Among these technologies, wind power has been the fastest growing renewable energy worldwide [2], [3]. However, there are many integration challenges regarding the impact of wind energy in both the design and operation of power systems [4], [5]. Thus, according to [6], a cost effective transition to a system with high levels of penetration of renewables, will need not only improvements in the electricity infrastructure but also fundamental changes in the philosophy of network operation and development. Special attention has to be devoted to the transmission system as new wind capacity deployment may also introduce bottlenecks in the grid. In this context, one of the most important aspects of the future integration of renewable energies is the reduction of transmission congestion while maintaining minimum impact on the reliability of the grid and the capital and operational costs of the system [7]–[9].

In general, congestion management approaches can be classified into systemic and local solutions [10], [11]. Systemic solutions involve a system-level minimization of the total operational costs, while fulfilling the network security constraints. The most common strategy for congestion management is to compensate the fluctuation of the wind energy through a re-dispatch of other power plants [9]. This approach has the disadvantage that deviates from the economic optimality, and the accuracy of the solution is directly affected by the forecasting errors in both wind generation and load [10]. In [11], a comprehensive review of different approaches for congestion management in competitive markets is presented. In [12] a real time congestion supervisor is proposed in order to reduce the re-dispatching. The deployment of this technique requires the installation of network controllers located in the transmission lines and in each generator. Besides the upgrade of the existing communication network, this congestion management approach would need the modification of the current grid codes as well.

Regarding local solutions, wind energy curtailment has emerged as a valid mechanism to deal with transmission bottlenecks [13] and excessive supply during low load periods [14]. Indeed, the results shown in [15] and [16] suggest that in order to increase the wind energy penetration, it would be more prudent to have an economically accepted level of energy curtailment, over a fixed time period, rather than additional transmission investments. Another local alternative is the use of an energy storage system (ESS) to store the excess of energy during congested periods and inject it back when the system is relieved [17]. When the ESS is located close to the wind farm, it can also increase grid efficiency. Many other benefits of ESS have been discussed in the literature. For example, for wind farm operators ESSs give additional benefits for energy trading, whereas for transmission system operators they enable a better generation management, while reducing the re-dispatch costs [9], and reduce the need for investment in system reinforcement [18]. Another local approach is the dynamic line rating [19]–[22], which allows a fine tuning of the transmission line capacity, supporting a short period overload. This represents a low cost solution requiring only an appropriate weather monitoring system to estimate the online capacity of the transmission equipment. Finally, FACTS systems can also be used to control the power flow and to improve the system security and grid flexibility. However, they present a high capital and maintenance cost [23].

Although there are many works proposing new methods, or adapting previous techniques to solve congestions, only few of them present comparative analyses. For example, in [24], four alternatives to integrate wind power in areas with trans-

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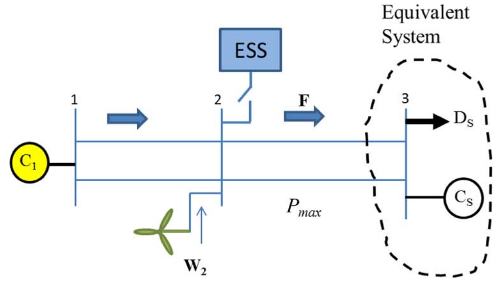

Fig. 1. Three-bus system.

mission bottlenecks are discussed. However, the discussion focuses only in a qualitative dimension without testing in a real system and no comparative analysis among these alternatives is performed. Reference [9] analyzes the effects of an ESS on the re-dispatched costs, but no study on the interactions among ESS and other possible mitigation strategies is presented. Finally, ramping rate of generating units have been included in the economic dispatch and unit commitment areas [25], [26], but there have been no studies on ramping rates and their relation to transmission congestion and wind power.

According to reference [11] the congestion management is defined as "*the comprehensive set of actions or procedures to ensure that no violations of the grid constraints occur*". By following this approach, this work proposes a comprehensive methodology to study the dynamic interactions of wind curtailment and energy storage for transmission congestion management while considering ramp-up and ramp-down rates of generating units. The methodology is applied to a real network system located in the northern part of Chile.

The paper is organized as follows. In Section II the problem of congestion management is introduced and the dynamic interactions between the power plants ramp rates, wind curtailment and energy storage are discussed. In Section III an analysis framework for transmission congestion mitigation measures is proposed, including an energy storage model, and a dynamic ramp model for generating units. In Section IV the methodology is applied to a test system and results for different transmission congestion mitigation strategies are compared. Then, in Section V a sensitivity analysis is performed in order to identify the main parameters affecting the mitigation approach. Finally, conclusions are presented in Section VI.

II. DYNAMIC INTERACTIONS AMONG RAMP RATES, WIND CURTAILMENT, AND ENERGY STORAGE

To illustrate the dynamic interactions of wind power curtailment and energy storage in transmission congestion management considering power plants ramp rates, a three-bus system is used. A diagram of this system is shown in Fig. 1.

The three-bus system has one conventional thermal unit (C_1 in bus 1), a wind farm (W_2 in bus 2), and an equivalent system in bus 3 (which has an equivalent generator C_S and demand D_S). Also in Fig. 1 there is an ESS which is currently disconnected from the grid. As the focus of the analysis is the transmission congestion due to wind power, we concentrate only in the flow F between bus 2, where the wind generator is connected, and bus 3, that represents the rest of the downstream system. An additional bus 1 is used, as it captures a real situation in the northern system in Chile. Also, bus 1 may represent the rest of the upstream system in a more general case. Note that node 1 has to be a net generator as the direction of flow F is from bus 2 to 3.

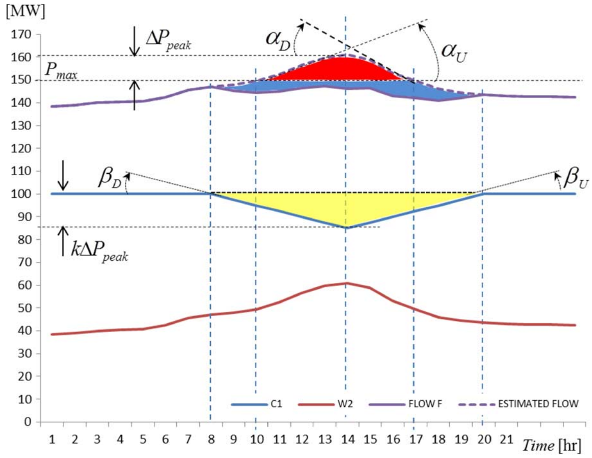

Fig. 2. Example of dynamic congestion in a three-bus system.

In order to illustrate the congestions, a numerical example of the hourly flow is presented in Fig. 2. In this graph, the real ("Flow F") and estimated ("Estimated Flow") flows through line 2–3, the generation of C_1 and the variable generation of wind farm W_2 are presented. By using a similar approach as the technique described in [27], the average ramp-up and ramp-down rates of wind power are characterized by angles α_U and α_D, respectively. Also, the ramp-up and ramp-down rates of C_1 are represented by angles β_U and β_D, respectively. In this system, when generation of wind farm W_2 increases its production, the estimated flow F grows beyond the line capacity $(P_{max} = 150\ \mathrm{MW})$ and, if no countermeasures are taken, line 2–3 becomes congested. This situation would occur between the hour 10 and hour 17 (dotted line and red area in Fig. 2), reaching a peak value $(P_{max} + \Delta P_{peak} = 160\ \mathrm{MW})$ around hour 14. Note that in this example, C_S has to represent a more expensive unit than C_1, because otherwise C_1 would be turned off due to the economic dispatch, and C_S would be fully dispatched. This, in turn, would decrease the flow F, and no transmission congestion would be observed.

A. *Redispatch Effect of Plants With Slow Ramp Rates*

Fig. 2 portraits a typical evolution when the generation in C_1 is reduced in order to allocate transfer capacity for the wind power during the (forecasted) overload period. Thus, C_1 is scheduled to decrease its power in the amount $k\Delta P_{peak}$ (k being a safety factor, 1.5 in the example) at hour 14. As unit C_1 has a slow ramp-down time when compared to the rate of increase of wind power, i.e., $\beta_D < \alpha_U$, C_1 has to start decreasing its power in hour 8, before the hour 10, in order to reach $k\Delta P_{peak}$ in hour 14. In general, if we call t^* the time of the peak, and t_0 the time when C_1 must start decreasing its power, the following relations are established

$$\tan\beta_D = \frac{k\Delta P_{peak}}{t^* - t_0} \Rightarrow t_0 = t^* - \frac{k\Delta P_{peak}}{\tan\beta_D}. \tag{1}$$

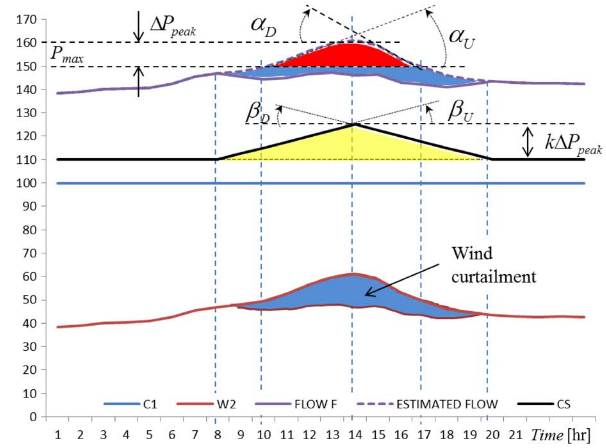

Fig. 3. Wind curtailment.

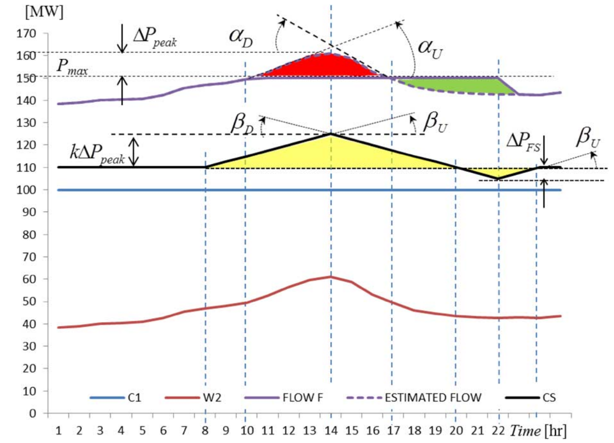

Fig. 4. Effect of ESS.

A similar situation occurs after the congestion is relieved in the hour 17. If the generation unit C_1 has a slow ramp-up time, i.e., if $\beta_{U<}\alpha_D$ as in Fig. 2, C_1 will be able to restore its normal production at hour 20. In the general case, if t_3 is the time where C_1 recovers its normal generation previous to the overload, the relations governing this operation are as follows:

$$\tan\beta_U = \frac{k\Delta P_{peak}}{t_3 - t^*} \Rightarrow t_3 = t^* + \frac{k\Delta P_{peak}}{\tan\beta_U}. \tag{2}$$

Thus, in order to avoid the overload of line 2–3 between the hour 10 and hour 17, the system reduces the energy production of C_1 (yellow area) not only in the wind excess (red area), but also in a larger amount (blue area under red area in Fig. 2) that takes into account the slow ramp rates of this unit. As a result, the system deviates from the optimal operating point in a larger interval $(\mathrm{t}_0, \mathrm{t}_3)$ (between hours 8 and 20 in the example) through a re-dispatch of a more expensive unit, such as C_S. This, in turn, produces an over cost on the system. The slower the ramp rates, the larger the over cost.

It is relevant to note that wind curtailment over cost may not only include the over cost on the system, but also a certain amount of compensation for wind generators. Grid codes around the world exhibit different criteria on this subject. In some electricity markets wind generators are compensated on wind curtailment, whereas in others there is no compensation, especially if the curtailment is required to alleviate transmission congestion. Examples of this later policy are found in the Bonneville Power Administration, Midwest ISO and New York ISO in the US, Alberta ISO in Canada, and others in Germany and New Zealand [28]. As such, and for simplicity, this penalty cost is neglected.

B. Interaction of Wind Curtailment and Ramp Rates

This case is shown in Fig. 3, where wind curtailment in W_2 avoids the transmission line overload (red area). As C_1 remains constant, the demand has to be compensated by an increase in plant C_S (yellow area), as shown in Fig. 3.

In this case, similarly as explained before, if unit C_S has slow ramp-up/down times, i.e., if $\beta_U < \alpha_U$ and $\beta_D < \alpha_D$, the curtailment has to start before and ends after the overload period. In Fig. 3 the actual wind curtailment is between hours 8 and 20, instead of between hours 10 and 17. Thus, in the general case, if t_0 and t_3 are the times between wind curtailment, the re-dispatch over cost can be estimated through the size of the yellow triangle, i.e., through the expression

$$Over\ Cost = Cop_S \times \frac{1}{2}(t_3 - t_0) \times\ k\Delta P_{peak} \tag{3}$$

where Cop_S is the variable cost of unit C_S.

C. Interaction of Energy Storage and Ramp Rates

Suppose that the ESS of Fig. 1 is now connected, so energy can be stored during the overload period. We assume that the ESS has faster charging/discharging rates as compared to the ramp rates of thermal plants and wind power. The corresponding interaction of energy storage and ramp rates is shown in Fig. 4. The ESS has the capacity to store all the wind energy produced in the overload period, which is shown as the red area between hour 10 and 17. Once the congestion disappears, the ESS injects back the stored energy into the system, highlighted as the green area between hour 17 and 23. We assume that this action is performed immediately after the overload disappears in order to keep the ESS capacity free if required. Note that flow F is kept at its maximum capacity during this period. The behavior of unit C_S between hour 8 and 20, is similar to Section II-B. However, from hour 20 on, unit C_S reduces its generation in the amount ΔP_{FS} in order to compensate the injection of energy coming from the ESS into the system (green area in Fig. 4).

Thus, between hour 20 and 24, C_S behaves similarly as case II-A. The corresponding over cost is given by

$$\begin{aligned} Over\ Cost &= Cop_S \\ &\times \left(\frac{1}{2}(t_3 - t_0) \times\ k\Delta P_{peak} - \frac{1}{2}(t_5 - t_3) \times \Delta P_{FS}\right) \end{aligned} \tag{4}$$

where t_0 is the time when C_S starts increasing its output, t_3 indicates the time when C_S reduces its injection to compensate the energy coming from the ESS, and t_5 represents the time when C_S recovers its previous generation level.

Note that if only a fraction of the energy in the overload period is stored (the green area becomes smaller than the red area), the corresponding over cost of the re-dispatch becomes larger than in the case of full storage capacity for the ESS.

D. Overall Effect of Ramp Rates

Regardless of the specific configuration, when mitigation measures are applied for transmission congestion that involve the re-dispatch of plants with slow ramp rates as compared to wind ramp rates during the overload period, the following behavior is observed:

- Re-dispatch introduces an operational over cost. The slower the ramp rates the larger the over cost.
- When using wind curtailment, there is an economic impact on the wind generator, due to the energy curtailed and not sold to the system, and also on the system, as there is an over cost due to the re-dispatch.
- When using energy storage in combination with wind curtailment the over cost effect may be reduced, but it cannot be eliminated. As in the previous case, there is an economic impact on the wind generator, and also on the system.

In the following section, and based on the previous analysis, an analytical framework for the study of congestion mitigation measures is proposed.

III. ANALYSIS FRAMEWORK FOR TRANSMISSION CONGESTION MITIGATION MEASURES

In the previous section, a discussion of different transmission congestion strategies, considering power plants ramp rates, is introduced using a generic three-bus system. In order to simulate and analyze a real case in which the same topology can be found, a simulation analysis framework is presented in this section. The proposed framework is based on a rule-based operational model for the ESS, an iterative algorithm to estimate the re-dispatched generation considering the power plant ramp rates, and a set of indicators to assess the performance of mitigation measures.

A. Energy Storage Model

There are different ESS technologies that can be used for congestion mitigation. Due to their current stage of development at a high rated capacity (100 MW), four technologies are the most suitable for congestion management: pumped hydro system (PHS), compressed air energy storage (CAES), thermal energy storage (TES), and battery energy storage system (BESS) [29]. A generic model of an ESS that considers operational rules to deal with the dynamic congestion management is proposed. For simplicity, we assume that the ESS and the wind farm are connected to the same busbar. Note however that, in the general case, not every wind farm busbar holds a connection to an ESS. The final application of the proposed framework is described in Section IV.

The ESS stores energy from the wind farm when there is overload in transmission capacity and supplies power back to the grid when the transmission congestion is relieved. This behavior translates into a simple control strategy, where other factors like changes in the energy price, operational reserves opportunities, etc., are not considered. Fig. 5 shows the diagram of the ESS model based on reference [17], where the variables are

E_k	energy stored in the ESS in step k (MWh);
P_k^{in}	charge power input in step k (MW);
P_k^{out}	discharge power output in step k (MW);
F_k^L	power flow through the line in step k (MW).

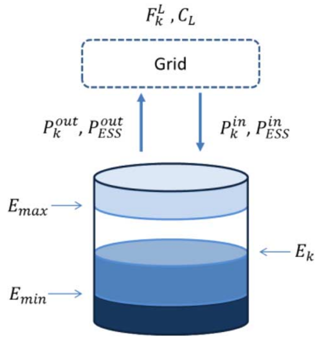

Fig. 5. ESS model used for operational analysis.

The parameters defining this model are

E_{max}	maximum energy stored (MWh);
E_{min}	minimum energy stored (MWh);
P_{ESS}^{in}	rated charge capacity (MW);
P_{ESS}^{out}	rated discharge capacity (MW);
C_L	line rated power capacity (MW).

The proposed control strategy consists of two separate operational rules for Charging and Discharging modes:

- ***Charging***: The charging rules for the charge power input in time k can be defined by the following expression:

$$P_k^{in} = \min\left\{\left(F_k^L - C_L\right), P_{ESS}^{in}, (E_{\max} - E_{k-1})/\Delta t\right\} \quad (5)$$

  The ESS will be charged only when line congestion appears ($F_k^L - C_L > 0$) with the charge rate limited by the rated charge capacity (P_{ESS}^{in}) as well as by the energy storage availability ($(E_{max} - E_{k-1})/\Delta t$).

- ***Discharging***: The ESS will be discharged only when there is no congestion ($F_k^L - C_L < 0$). The discharge rate is limited by the rated discharge capacity (P_{ESS}^{out}) as well as by the available transmission capacity ($C_L - F_k^L$) in order to avoid new congestions due to the discharged power. In all cases, the ESS discharge continues as long as stored energy is available ($(E_{k-1} - E_{min})/\Delta t$)). The previous discharging rules can be defined by the following expression for the discharge power output in time step k:

$$P_k^{out} = \min\left\{\left(C_L - F_k^L\right), P_{ESS}^{out}, (E_{k-1} - E_{\min})/\Delta t\right\}. \quad (6)$$

In the previous expressions, Δt represents the step of the simulation (in this case, it is equal to 1 h).

B. Power Plants Ramp Rates Model

In order to model the effect of slow ramp rates in power plants, an iterative algorithm is proposed as follows:

i) Let us consider P_k^j as the production of a re-dispatched generating unit j in step k. Therefore, the total re-dispatched power in step k is defined as

$$P_k = \sum_{j=1}^{S_{RR}} P_k^j \quad (7)$$

with S_{RR} re-dispatched generating units.

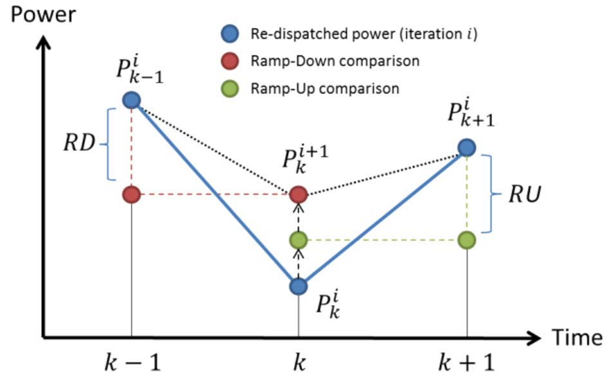

Fig. 6. Algorithm for the re-dispatch with ramp rates.

ii) In the initial state, the total re-dispatched power (P^0_k) is set equal to the wind power curtailed plus the energy stored in the ESS, calculated based on the ESS model presented previously, for each step k.

iii) Then, the re-dispatch values are updated by using recursively the following rule (which is applied at each time step k):

$$P^{i+1}_k = Max\left\{P^i_k, (P^i_{k-1} - RD), (P^i_{k+1} - RU)\right\} \quad (8)$$

where P^{i+1}_k is the updated value at step k for the total re-dispatched generation, and RD and RU the equivalent ramp-down and ramp-up rates, respectively, in MW/h.

A visual image of this rule is shown in Fig. 6, where the blue dots represent the re-dispatched power in iteration i, and red and green dots represent the two values that are being compared with P^i_k for the update of the re-dispatched power.

In Fig. 6, the resulting P^{i+1}_k value is equal to $P^i_{k-1} - RD$.

The iterative process is stopped when $P^{i+1}_k = P^i_k \forall k$. Finally, the total amount of power to be re-dispatched in the grid, ΔP_{RD}, is calculated with the following expression:

$$\Delta P_{RD} = \sum_{k=1}^{Ts} P_k \quad (9)$$

where T_s is the total number of step in the simulation (in this case $T_s = 8760$).

C. Indicators for Congestion Characterization

Transmission line power flow congestions can be characterized by the *Exceedance Probability Curve*, also called *Complementary Cumulative Distribution Function*, which represents the probability of a line power flow being greater than a given value (in the x-axis). Based on this curve and the dynamic ramp model of Section III-B, four indicators are defined to quantify the congestion of a line:

— Congestion probability (CP) is the probability of a power flow over 100%.

— Line load factor (LLF) is defined as

$$LLF = \frac{\text{TET}}{\text{METC}} \quad (10)$$

where TET is the total energy transmitted through the line and METC is the maximum energy transfer capability, both calculated on an annual basis.

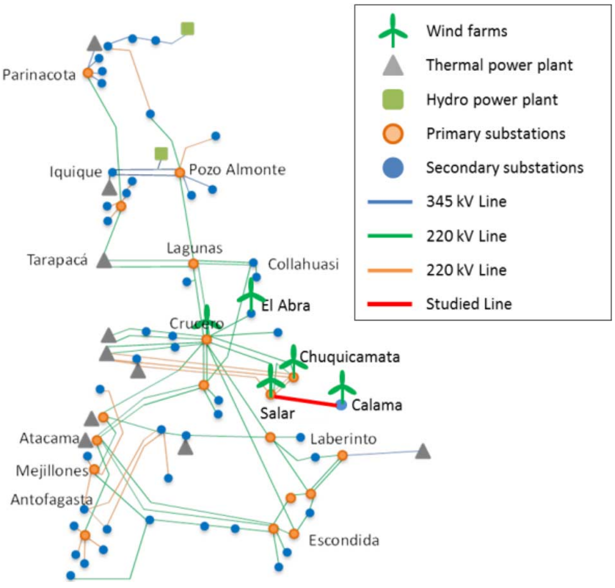

Fig. 7. GNIS diagram [30].

— Total energy curtailed (TEC) is the annual wind energy curtailment.

— Congestion cost is the operational cost produced by the necessary re-dispatch of generating units resulting from the mitigation strategies. Although re-dispatch is a way of life in running a grid, it is important to assess the over-cost as it may become a significant parameter when mitigation measures have to be selected in the operation of the system. This may be especially important for small systems where the cost of re-dispatch may affect the viability of small generating companies.

IV. TEST RESULTS

In this section, a real case is simulated in order to apply the concepts developed in Section II, and different scenarios are compared using the methodology presented in Section III.

A. Test System: Real Interconnected System

For the case study, the Chilean Great North Interconnected System (GNIS) transmission network is considered. GNIS has a low-meshed grid topology and demand is driven mainly by mining and industrial activities, which renders a rather constant and stable load profile, whereas wind resources experience a high variation during the day [30]. These conditions resemble typical congestion situations in transmission systems with high wind penetration [14], [16]. Fig. 7 shows the GNIS diagram.

In this work, a future 2020 energy scenario is considered. The demand, with hourly data, is projected by using the real values of 2011 as a baseline and by following the methodology provided by the ISO of GNIS [30]. The 2020 annual energy demand reaches 32 157 GWh, and for the conventional generation and transmission system expansion, the results of reference [31] were used. Wind power data are generated by combining stochastic weather models with typical wind turbine operating power curves, considering a total projected wind capacity of 1332 MW [31].

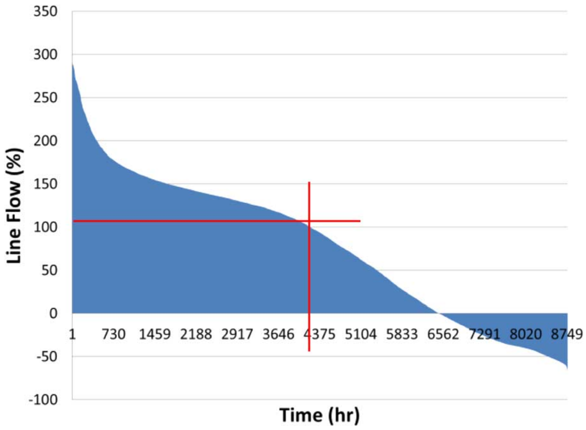

Fig. 8. Transmission line power flow duration curve.

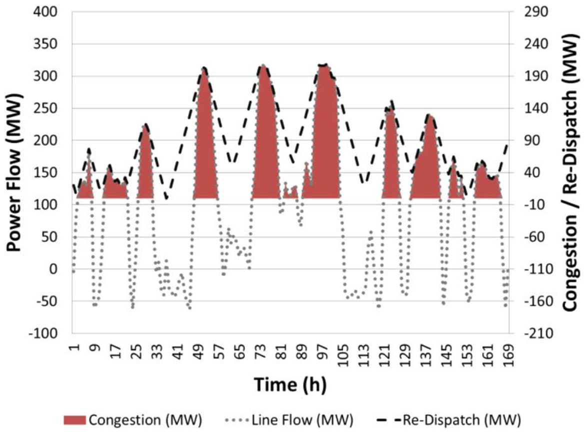

Fig. 9. Transmission congestion and re-dispatch.

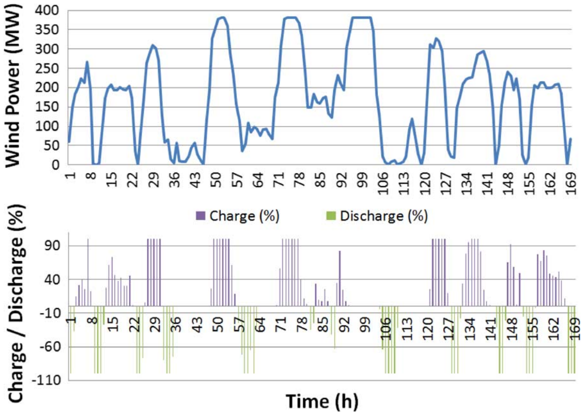

Fig. 10. Charge/discharge of the ESS and wind power generation.

With these data, the power flows through the transmission system are calculated and situations of congested lines are identified. The main congested lines are Calama-Salar, Crucero-El Abra, Crucero-Chuquicamata, and Chuquicamata-Salar. As the congestion management strategies are similar for all lines, in the remainder of this section only the Calama-Salar line case (highlighted in Fig. 7) is discussed as it shows the highest congestion levels. In this simulation a ramp rate of 0.25 MW/min (up/down) was assumed for old thermal plants.

B. Operation Simulation

The system model is implemented in the power system simulation tool DIgSILENT. An optimal power flow (OPF) is performed for each of the economic dispatch scenarios. To establish the base-case, network constraints and power plants maintenance schedule were not considered. In addition, the wind farm operation costs are assumed null; therefore the wind farm will always be dispatched while there is wind available.

Results show that total wind energy produced during the year 2020 at Calama busbar is 1260 GWh, with a load factor of 38%. Fig. 8 shows the corresponding duration curve for the transmission power flow (positive from Calama to Salar). In this figure, it can be seen that most of the time (6500 h approximates to 75% of time), the power flows from Calama (where the wind farms are located) to the main grid (Salar busbar). Moreover, the congestions appear only in that direction.

C. Dynamic Congestion Mitigation Strategies

a) Wind Curtailment Only: In absence of any ESS, during the 4213 hours of line congestion (see vertical red line in Fig. 8), the surplus of wind energy in bus Calama has to be curtailed in order to operate the line within its limits (110 MW). This curtailed energy has to be compensated re-dispatching more expensive thermal power plants, as was explained previously in Section II. A sample of one week simulation is shown in Fig. 9, where the line power flow, line congestion, and the re-dispatch are shown.

It can be seen from Fig. 9 that the re-dispatched energy (dotted line) is larger than the overloaded energy alone (red area in Fig. 9). As explained in Section II-A, this is due to the effect of the slower ramp rates of power plants.

b) Wind Curtailment with ESS: In this subsection, an ESS is included in the operational analysis to evaluate the congestion management. Assuming a typical value of 70% for the round trip efficiency [29], the energy stored can be estimated using the ESS model developed in Section III-A. The main parameters for the dimensioning of the ESS are its power capacity and the charging/discharging time. In this application, congestion probability, the line utilization and the wind energy curtailment are used as indicators to assess the ESS performance. Based on a sensitivity analysis, shown in detail in the next section, a reasonable sizing is around 5 to 6 h for charging/discharging time and between 70 to 80 MW for the power capacity. Thus, an ESS of 70 MW and 5 h of charging time is selected for the tests in this section.

Results for the simulation are shown in Fig. 10, which shows that the ESS charging and discharging patterns are correlated with the wind power generation, i.e., the energy is stored when there is surplus of wind and it is injected back to the grid when wind decreases.

In order to illustrate the overall effect of the ESS, Fig. 11 shows the relation between the congestion, curtailment and energy stored in the ESS. The congestion/curtailment curve is presented in terms of percentage related to the line capacity. It can be seen that the ESS is charged when the congestion occurs, if there is energy capacity available in the ESS to charge it. When the storage capacity of the ESS is reached, the surplus

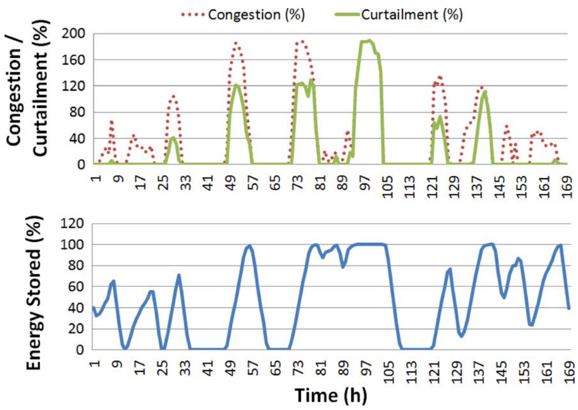

Fig. 11. Congestion and energy stored.

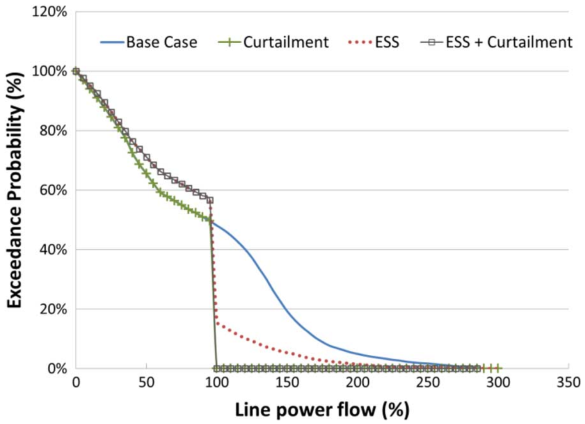

Fig. 12. Transmission line exceedance probability with ESS.

of energy cannot be stored anymore and energy curtailment has to be applied to avoid transmission congestion.

c) Comparative Analysis: In this subsection, the two congestion management strategies analyzed previously are compared. Fig. 12 shows the exceedance probability of the line power flow for all cases: Base case (blue line), Wind curtailment (green line), Energy Storage only (red line), and the ESS with Wind Curtailment (purple line). Base Case data was taken from Fig. 8.

From Fig. 12 it can be seen that when using wind curtailment alone or in combination with the ESS, the line overload is completely suppressed. However, when the ESS is used alone, it is not enough to relieve the overload, as the capacity of the storage device is limited to 70 MW. In order to eliminate all overloads in the line it would be necessary to increase the storage capacity to nearly 190 MW (see Fig. 8), which becomes economically unfeasible. It can also be seen that for power flows lower than 100%, the exceedance probability increases with the ESS operation, allowing an increment in the line load factor. For power flows between 100% and 250%, this probability decreases, avoiding scenarios of congestion and reducing the wind curtailment. Power flows over 250% do not seem to change significantly their occurrence due to the limited capacity of the ESS.

TABLE I
PERFORMANCE INDICATORS

Case	(CP) [%]	(LLF) [%]	(TEC) [GWh/year]
Base case	48	94	0
Curtailment	0	70	239
ESS	16	81	0
ESS + Curtailment	0	74	65

Using the same key performance indicators presented in Section III-C, the four cases are compared in Table I. Congestion costs are analyzed separately in the Section V-A.

From Table I it is clear that the use of a 70 MW ESS reduces the congestion probability from 48% (Base case) to 16%. When the curtailment is combined with an ESS, there is no congestion in the line and the total energy curtailed becomes 65 GWh. If curtailment is used alone, it is necessary to increase the load shedding dramatically to 239 GWh in order to eliminate the congestion. Finally, in cases where the overload is completely removed, the line utilization increases with the use of an ESS from 70% to 74%.

V. SENSITIVITY ANALYSIS

As the performance of the congestion mitigation measures depend on the ramp rates and the size of the ESS, in this section a sensitivity analysis of these parameters is presented.

A. Ramp-Up/Down Sensitivity

To analyze the influence of ramp rates in congestion costs, it is assumed the ramp-up and ramp-down values are equal. The re-dispatch costs (or congestion costs) were estimated by using an average operational cost of 145 [USD/MWh] [30]. Fig. 13 shows the re-dispatch generation and costs for different ramp-rates. The green line represents the total energy to be compensated when using wind curtailment only (see Section II-B). The red line represents the case with ESS as additional mitigation measure. It can be seen that the total re-dispatched generation tends to be equal to the energy curtailed when there is no ESS in the system (239 GWh/year from Table I). This means when faster power plants are used in the re-dispatch, the total re-dispatched generation becomes equal to the energy curtailed, and no effects of ramp rates are observed. However, when slower plants are used, the re-dispatched energy increases due to the effect explained in Section II-B. On the other hand, the use of an ESS reduces the re-dispatch of conventional generation, as there are moments where the energy stored is re-injected to the grid. This in turn leads to a reduction in the total operational costs as well (blue dotted line in Fig. 13). Finally, it is clear that the slower the ramp rates the larger the over cost, as it was pointed in Section II-D.

B. ESS Parameter Sensitivity

In this Subsection a sensitivity analysis is performed to analyze the effect of the variation of two parameters (ESS power capacity and charging/discharging time) on three different indicators (congestion probability, line utilization and wind energy curtailment). In the case of power capacity, it is varied up to 110 MW as this is the transmission line capacity. For each indicator curves showing the effect of parameters variations are

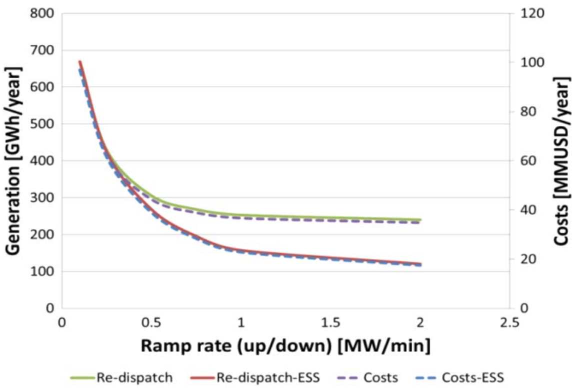

Fig. 13. Re-dispatch generation and costs with the use of an ESS.

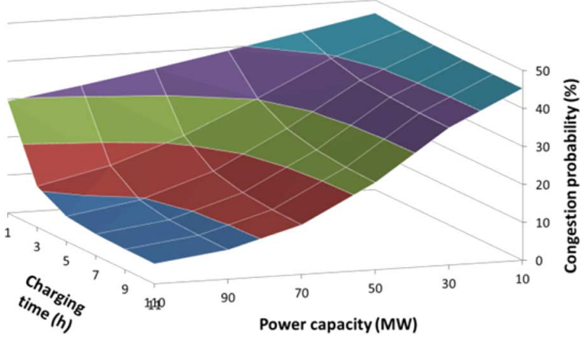

Fig. 14. Sensitivity analysis for congestion probability.

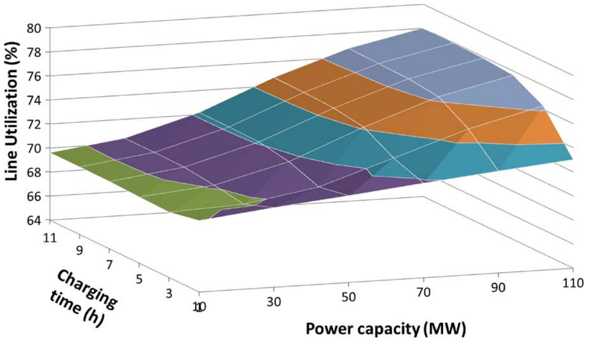

Fig. 15. Sensitivity analysis for line utilization.

built. Thus, by analyzing the curves, particularly their extremes values, it is possible to identify the best values for each parameter. Fig. 14–16 show results for congestion probability, the line utilization, and the wind energy curtailment, respectively.

Fig. 14 shows congestion probability decreases as charging time increases and no significant improvements are obtained beyond 5 to 6 h. Similarly, congestion probability does not improve significantly with power capacity beyond 80–90 MW. The minimum congestion probability is 5.2% with an ESS size of 110 MW and a discharging time of 11 h.

Fig. 15 shows that line utilization is more dependent on the power capacity of the ESS than on the charging time. This result is in line with Table I, where the LLF experiences a small change (from 70% to 74%) when ESS is applied together with the wind curtailment. Overall, it was found that the maximum line utilization is around 78%.

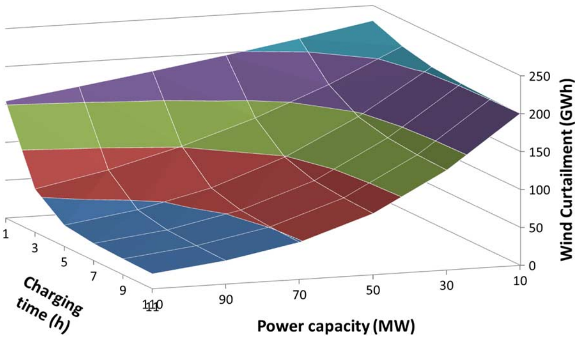

Fig. 16. Sensitivity analysis for wind energy curtailment.

Fig. 16 reveals that wind curtailment remains almost constant when charging time goes beyond 5 to 6 h. Also, ESS power capacity seems to affect strongly the wind curtailment in the range up to 70–80 MW. Beyond that range, no major improvements are obtained when increasing ESS power capacity. It was found that wind curtailments can be reduced to a minimum of 19 GWh.

C. *About the Economic Feasibility of BESS*

The investment cost of the proposed ESS is not trivial and, at present costs, it might be comparable with building a transmission line. In fact, a comprehensive economic analysis should consider all possible revenue streams with a positive impact on the operational income. These include not only energy arbitrage and transmission congestion relief, but also the provision of frequency regulation, operational reserves and peak shaving, among other ancillary services. Moreover, a unified economic framework is required to accurately compare the economic value of different congestion mitigation strategies from an overall system perspective. Otherwise, it might lead to either underestimate or overestimate the overall economic value of each strategy. For example, although wind energy curtailment has no capital costs, it produces a negative economic impact on wind generators, as it decreases their operational revenues. This may be relevant at power systems with grid codes that include renewable portfolio standards.

VI. CONCLUSIONS

In this work, wind power curtailment and energy storage as transmission congestions mitigation measures are analyzed, considering power plants ramp rates. It is found that there is a dynamic interaction that introduces an over cost when slow power plants are re-dispatched. Congestion mitigation measures are compared in terms of congestion probability, line load factor and total energy curtailed. Results indicate that if the re-dispatched power plants have ramp rates slower than the wind ramp rates, the following behavior is observed:

- Re-dispatch introduces an operational over cost. The slower the ramp rates the larger the over cost.
- When using wind curtailment, there are two effects. There is an economic impact on the wind generator, due to the energy curtailed, not sold to the system. Also, there is an over cost on the system due to the re-dispatch.

— When using ESS in combination with wind curtailment the over cost effect may be reduced, but it cannot be eliminated. As in the previous case, there is an economic impact on the wind generator, and also on the system.

Results of the sensitivity analysis show that with the use of an ESS, congestion probability, wind energy curtailment and re-dispatch costs are reduced. Also, transmission line utilization is increased due to the operational rules of the ESS.

Further research is needed in order to accurately assess the profitability of an ESS when compared to alternative projects such as line enhancement, power re-dispatch and wind/load curtailment. It should explore not only energy costs, but also ancillary services, peak shaving, unserved energy costs, etc., in order to properly assess BESS investment benefits.

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