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Optimal network congestion management using wind farms

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SUMMARY

With the increased use of wind energy for the power generation several TSO have increasing difficulties for congestion forecasting due to the unpredictable nature of the energy source. An actual method used to deal with days-ahead congestion planning is based on an order of disconnection of the generation of the type "last generation installed, first generation limited". This paper proposes to enhance the congestion management using a real time supervisor. This supervisor is developed to perform automatic and dynamic re-dispatching using both wind and conventional generators. In order to reduce the production constraints to the minimum, the real time congestion management is based on an indicator of the efficiency of a re-dispatching on the power flowing in the overloaded line. This approach leads to reduced re-dispatching costs and increased network reliability. Actual and proposed methods are compared in the paper using Matlab/Simulink simulations of a realistic test grid. It is shown that the real-time supervisor allows maximization of renewable production during congestions while ensuring network reliability.

KEYWORDS

Congestion management; Wind farm; Power Transfer Distribution Factors (PTDF); Power system control; Active power dispatch; Variable speed wind turbines.

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I. Introduction

For several years, global warming has become a world priority. One of the solutions to solve this problem is the increased use of renewable energy for the power generation. However, the integration of such a production in the actual grid is not simple as this grid was not originally design to accept such type and localization of production. In many regions, the Transmission System Operators (TSO) are expecting an increase of line congestion in rural areas due the important increase of wind generation [1].

In the literature, many methods have been reported for congestion management. Sensitivity-based optimum generation rescheduling and/or load shedding schemes to alleviate overloading of transmission lines are proposed in [2] and [3]. These methods, based on the computation of an Optimal Power Flow (OPF) are precise techniques for congestion management in power systems as long as generation, transmission capacities are well known. Other congestion management methods are proposed in [4]-[6]. These market-based methods for congestion elimination are also very efficient as long as two areas, delimited by the congested elements can be identified and can create market structure. Furthermore, as for previously presented methods, the market-based methods are affected by errors in load and generation prediction due to element outage or random production as is wind generation.

Therefore, most European TSO's have chosen to manage separately, congestions related to wind generation [7]. This is due to the difficulties to predict exact congestion magnitude and time instant and the difficulties to increase production in high voltage distribution network. The actual used method is then to manage congestion in planning (i.e. day-ahead) by disconnection of generation on the technical and economical criteria "last generation installed, first generation limited".

The main consequence of this approach is a limitation of generation that can be more important that necessary as a precise day-ahead prediction of wind power is impossible.

This paper proposes to minimize change in generation due to congestion to the minimum using an automatic real-time congestion supervisor. This proposed method is implemented and validated using in Matlab / Simulink simulations.

In Section II, the considered test system is introduced. Then, the real-time supervisor is presented in Section III. Section IV will use simulation results to compare the proposed method with the actual one and finally, conclusions will be drawn in section V.

II. Modeling of the system under study

In Figure 1, the structure of the considered test system is shown. This system is representative of a part of the 90kV French network. This network is subjected to interregional transit flows, here represented by a load (Transit.out) and a production unit (Transit.in). Connected at node 4, a conventional generator (Gr4) is the slack bus. Wind Farms (WF) are connected to nodes 1, 2 and 3. Their nominal power is respectively 20, 50 and 70 MW.
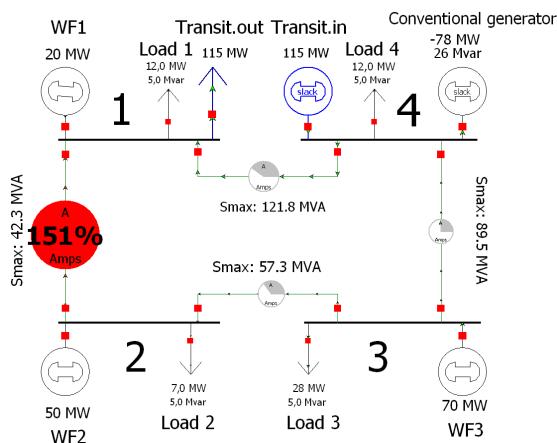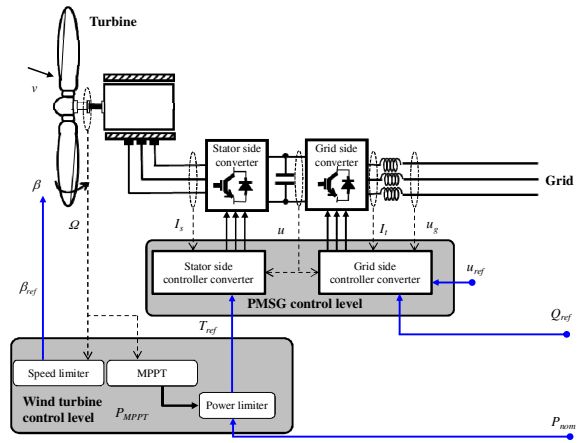

Figure 1: Test system.

Figure 2: Wind turbine model.

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Each wind farm is represented by the equivalent variable speed wind turbine model (VSWT) of Figure 2. The VSWT based permanent magnet synchronous generator (PMSG) and is fully described in [8]. The inputs of the control system are the reactive reference power (here equal to 0) and a maximum output power equal to the WF nominal power (P_{nom}). The **PMSG control level** is based on two separate controllers:

- The **rotor side converter controller** which controls the torque of the PMSG using a rotor current control loop;
- and the **grid side converter controller** which controls the DC link voltage u and the output reactive power.

The **wind turbine control level** contains three controllers:

- A **speed limiter** which uses the pitch angle (β_{ref}) to limit the blade rotating speed;
- a **MPPT (Maximum Power Point Tracking controller)** which generates the active power reference (P_{MPPT}) using rotor speed measurement (Ω) and predefined characteristics.
- a **power limiter** which generates the torque reference (T_{ref}) for the torque control loop. This torque control is performed by the rotor side converter controller of the PMSG control level. The torque reference is computed by

$$T_{ref} = \frac{\min(P_{MPPT}, P_{nom})}{\Omega} \qquad (1)$$

III. Real time supervisor

In case of line congestion, actions must be taken on the generators to reduce the power flow in the congested line and maintain the total generation at the same level to avoid frequency deviation. The problem of congestion management is then to select the two generators that will realize the re-dispatching and to define the amount of active power to re-dispatch. In order to realize these actions, an indicator which quantifies the effect of re-dispatching on congestion is used. This indicator is related to the well known Power Transfer Distribution Factor (PTDF) [9],[10] and its interpretation in the context of our study can be summarized through equation (2):

$$PTDF[\%] = \frac{\Delta P_{line}[MW]}{P_{redispatched}[MW]} \qquad (2)$$

where $P_{redispatched}$ is the re-dispatched power and ΔP_{line} is the amount of power modification in the congested line. Indeed, a same quantity of re-dispatched power via two different couples of units has not same effect on the overloaded line. This depends on the location of the power units. According to Kirchhoff's laws, PTDFs depend on the topology, parameters of the electric power system and on the operating point. However, it has been shown in [11] and [12] that the dependence with the operation point is low and that the computation of the PTDFs using DC load flow equation will give acceptable approximation. The PTDFs, computed for line L_{12} of the Figure 1, are shown in Table 1. The PTDFs magnitude will be used to define an order of efficiency of the re-dispatches which relieve congestion of line L_{12}. This order of efficiency is shown in Table 2. The re-dispatching which is number 1 in the order of efficiency is to be selected. Indeed, for a same quantity of active power reduced in line L_{12}, the re-dispatch requires the smallest amount of active power equation (2).

Table 1: PTDF related of line L_{12}.

PTDF related to power modification of line L_{12}		Decrease of generation at node			
		Node 1	**Node 2**	**Node 3**	**Node 4**
Increase of generation at node	**Node 1**		-79.8%	-50.3%	-35.0%
	Node 2	79.8%		29.5%	44.8%
	Node 3	50.3%	-29.5%		15.3%
	Node 4	35.0%	-44.8%	-15.3%	

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Table 2: Order of efficiency for line L_{12}.

Order of efficiency	Re-dispatching		PTDF
	Increase of generation at node	Decrease of generation at node	
1	Node 1	Node 2	-79.8%
2	Node 1	Node 3	-50.3%
3	**Node 4**	**Node 2**	**-44.8%**
4	Node 1	Node 4	-35.0%
5	Node 3	Node 2	-29.5%
6	**Node 4**	**Node 3**	**-15.3%**

Table 2 represents all the possible re-dispatching in the considered network in Figure 1. However as the generator of nodes 1 to 3 are wind farms working in MPPT, an increase of their power is impossible. Therefore Table 2 can be reduced to the two re-dispatching printed in bold (Node4-Node2 and Node4-Node3). This order of efficiency is used in real-time management to choose the most effective couple of nodes to use to avoid line congestion while changing as little as possible production plans.

Furthermore, the real-time supervisor for congestion management requires communication with both TSO and the production units (Figure 3):

- PTDF and line thermal limits with depends of the topology and operational policies of the electrical system are provided to the supervisor by the TSO.
- A control mode (*Mode*) signal is sent by the supervisor to the production unit to specify their participation in congestion management. There are four control *Modes*;
  If there is no congestion, then the generators can operate at power planned $P_{planned}$ (for the WF, the default planned power is the P_{MPPT}), this is the *Mode 1*. During congestion, the two generators selected by the Table 2 are asked to control their production based on a signal *L*, this is *Mode 2*. If a generator reaches its upper limit, it is asked to operate at this limit (P_{max}), this is *Mode 3*. Finally, if a generator reaches its lower limit, it is asked to operate at this limit (P_{min}) (WF for this mode is equivalent to 0MW), this is *Mode 4*.
- A dynamic control signal is (*L*) sent by the supervisor to the production units. This signal can be negative or positive to reduce or increase generation power.
- The state signal (*State*) is sent by the generation units to the supervisor to precise their dynamic availability for congestion management.
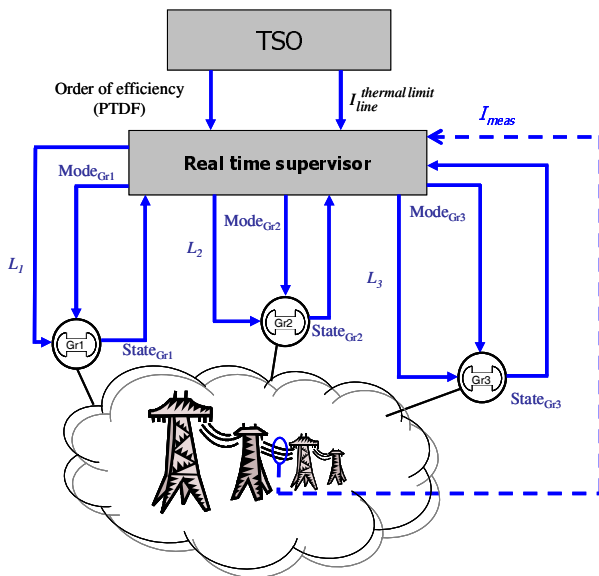

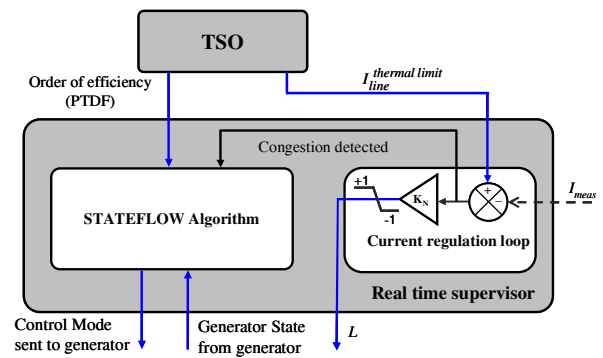Figure 3: Communication within the real time supervisor.

Figure 4: Structure of the central real-time supervisor.

The structure of real-time supervisor is shown in Figure 4. This supervisor contains three parts; two controllers located at a central location and a controller located at the generation site:

- A **STATEFLOW controller** to define the *Mode* of each generator. This output depends on the congested line and the PTDF of the available generator for this line. The STATEFLOW algorithm is based on a Moore machine [13], [14]. Figure 5 shows the STATEFLOW algorithm for line L_{12} considering the information of Table 2. If there is no congestion, then every generator operates in *Mode 1* (All the WF are to P_{nom} and Gr4 is to $P_{planned}$). When line L_{12} is overloaded, the WF2 and Gr4 switch to *Mode 2* and control the following signal L. When the WF2 reaches its lower limit, the WF3 and Gr4 switch to *Mode 2* and WF2 operates at P_{min} (*Mode 4*). When the WF3 is back to its higher limit, the machine returns to its previous state.
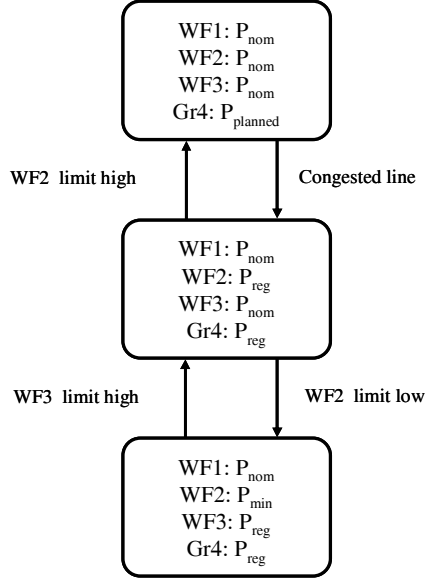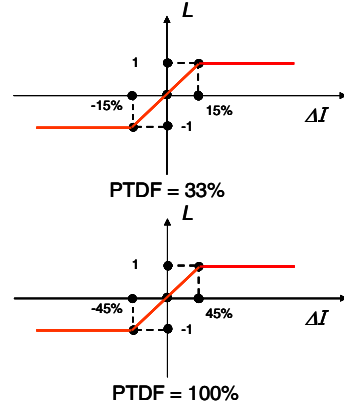

Figure 5: STATEFLOW Algorithm for line L_{12}.

Figure 6: Adjustment of the signal L based on the PDTF of the units realizing the re-dispatching and the amount of overload.

- A **current regulation loop** which generates a signal L in the range [-1,1]. If a signal $L=-1$ ($L=+1$) is sent to a generator, this generator must decrease (increase) greatly its production.

  In order to tune the parameter K_N of the control loops, an example will be considered. Using equation (1), in order to modify the power flow in line L_{12}, the couple of nodes 4-3 having a PTDF of 15.3% must re-dispatch 3 times more power than the couple of nodes 4-2 (PTDF of 44.8%) to modify the same amount of power in the line. Therefore, the signal L sent to nodes 4 and 3, representing the re-dispatch magnitude will be three times greater than the signal L sent to the nodes 4 and 2. Figure 6 and equation (3) show the cross dependence between the sent signal L, the PTDF of the couple of units realizing the re-dispatching and the overload of the congested line.

$$L = K_N \cdot \Delta I \ \ \text{avec} \ \ K_N = \frac{PTDF_{min}}{PTDF \cdot \Delta I_{max}} \tag{3}$$

$$\Delta I_{max} = I_{max} - I_{Line}^{Thermal\ limit} = 15\% \tag{4}$$

where ΔI_{max} is the maximum overload allowed for the congested line (equation (4)) and $PTDF_{min}$ is the minimum PDTF that guarantees not to exceed the maximum current I_{max}. The performance of the system (Current overload lower than ΔI_{max}) will be guaranteed for a $PTDF$ down to $PTDF_{min}$. The $PTDF_{min}$ value is obtained considering that the most rapid changes of line power flows in the line are 1,67MVA/s and that maximum dynamics of generators is 5MW/s. Applying equation (2) with these values, one can find a $PTDF_{min}$ of 33%.
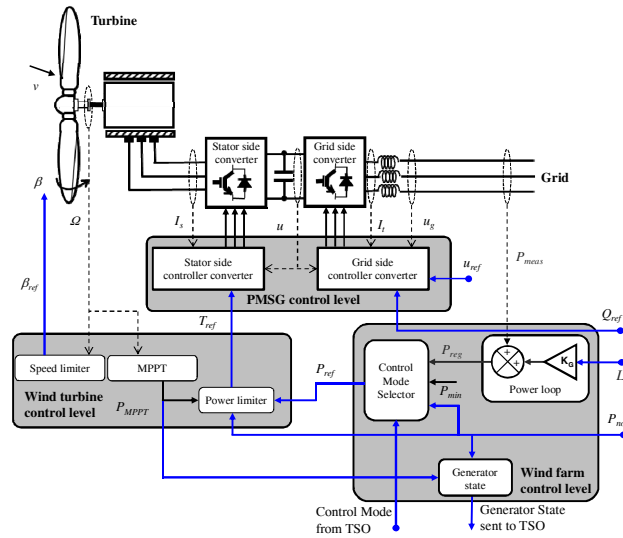
Figure 7: Wind turbine model.

- The generator side supervisor is an **active power regulator**. The goal of each generator is to convert the input signal L in a power reference which must be followed. This supervisor contains three controllers shown in Figure 7 :
  - **The power loop which** generates the active power reference (P_{ref}) according to the level L sent to TSO and the measured active power (P_{meas}). K_G is estimated to adjust the maximum dynamic response of the generator to a common value of 5MW/s. In the considered WF, a decrease of 5MW/s is observed for a signal L equal to -1.
  - **The control mode selector is** used to select the proper active power reference based on the Mode signal sent by the central supervisor.
  - **The generator state** is used to inform the central supervisor of the limits of the wind farm (limit low or limit high).

IV. Simulations and comparison

The test system shown in Figure 1 was simulated using Matlab/Simulink. Figure 8 shows the time evolution of loads and interregional transit flow. The evolution of loads represents a daily load profile, however to reduce the simulation time this profile is scaled to 900s.
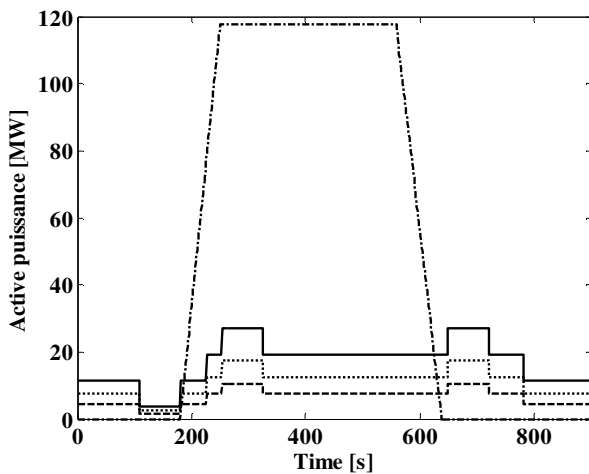

Figure 8: Evolution of the load and interregional transit.
Dashed line: Load 2.
Dotted line: Load 1 and load 4.
Full line: Load 3.
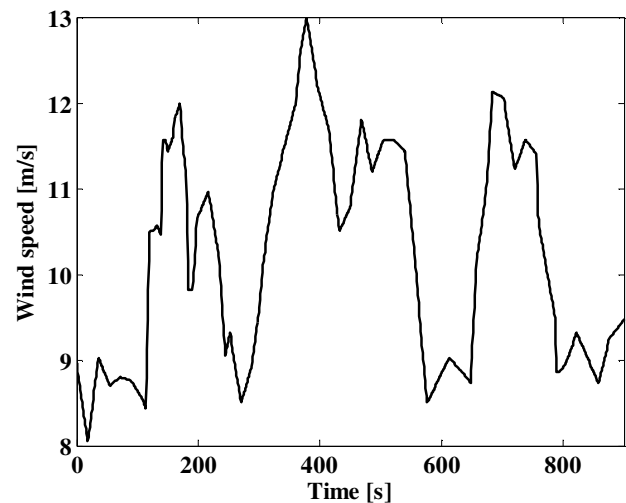**Dash-dotted line: Interregional transit.**

Figure 9: Wind speed.

The considered interregional transit flow is null at night and maximum during the day. This profile is scaled to 900s but the transition times are kept unmodified to test the supervision algorithm on realistic dynamic constraints. Figure 9 shows the wind speed for all wind farms. As before, the wind profile is not scaled to keep realistic dynamic behavior of the network. In the proposed scenario, a congestion of line L_{12} happens when both main transit flow and high winds are present.

The performance of the proposed real-time congestion management can be compared to the actually implemented method. The comparison scenario is based on the network of the Figure 1 and the profiles of the Figure 8 and Figure 9.

The actual method is used in days-ahead congestion planning. As production limits are constant they are computed for the most critical point planned congestion. In this scenario, the time instant t=380s (when interregional flow and the wind speed are high) is the most critical. Therefore limitation of the WF2 at 0MW and WF3 at 63MW are computed and applied for the congestion period t=200s to t=600s.

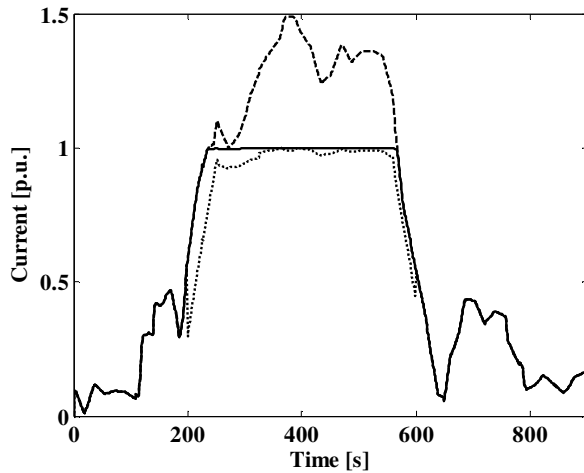**Figure 10: Evolution of the line current.**
1 p.u represents the thermal current limit.
Dash-dotted line: Without congestion management.
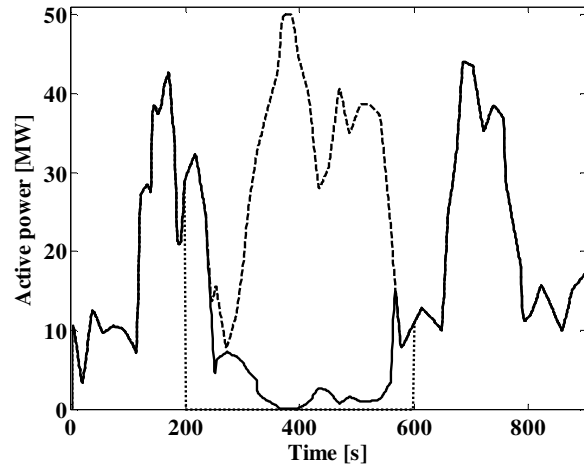**Full line: With real-time supervisor.**
Dotted line: With actual method.

Figure 11: Power of the WF2.
Dash-dotted line: Without congestion management.
Full line: With real-time supervisor.
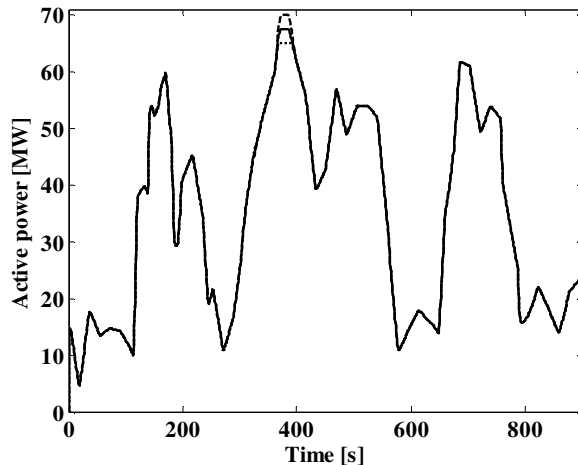**Dotted line: With actual method.**

Figure 12: Power of the WF3.
Dash-dotted line: Without congestion management.
Full line: With real-time supervisor.
Dotted line: With actual method.

Table 3: Produced energy by WF.

% maximum energy	WF2	WF3	WF2+WF3 +WF1
Without congestion management	100%	100%	100%
With real-time supervisor	57.3%	99.8%	84,7%
With actual method	46.6%	99.7%	80,8%

The current in the congested line with real-time supervisor (full line), with actual method (dotted line) and without congestion management (dash-dotted line) is shown in Figure 10. In Figure 11, the power (P_{WF2}) of the WF2 is shown, the dash-dotted line represents the maximun power that can be obtained from the wind by the WF (MPPT). In Figure 12, the power (P_{WF3}) of the WF3 is shown. The STATEFLOW controller selects the most efficient the available couple of generation to avoid the line

overload with a minimum of re-dispatch effort; from t=300s to t=365s, this couple is WF2-Gr4; the WF2 decreases its production while the conventional generator Gr4 increases its production of the same amount.

At t=365s, the WF2 is in lower limit (here P_{WF2}=0MW) and the STATEFLOW controller selects the second couple (WF3-Gr4) and sets the WF2 to constant minimum power operation (0MW); from t=365s to t=395s.

At t=395s, the WF3 is back to its higher limit (here P_{WF3}=P_{MPPT}) and the STATEFLOW controller selects the first couple (WF2-Gr4) and sets the WF3 to operate in normal operation; from t=395s to t=570s.

From 570s, the line is no more onverloaded; WF2 operates back to P_{MPPT} and Gr4 to $P_{planned}$. Figure 10 shows the ability of the real-time congestion management to avoid the congestion by limiting the current in the line equal to its thermal limit. In addition, the Figure 10 shows that the management can make the minimum re-dispatching.

For the actual method, limitations of the WF2 and WF3 allow the current line L_{12} not to exceed the maximum current as shown in Figure 10. By comparing the full line and the dotted line of Figure 11 and Figure 12, the real time management reduces the time and quantity of the limitation imposed to the WF2 and WF3. Table 3 shows that the real time management allows more energy to be produced than with the actual method. The real time management allows therefore the reduction of the energy loss for the wind producers. Besides, by comparing the full line and the dotted line of Figure 10, the real time management allows ensuring the safety of the network. This is possible thanks to the real-time regulation of current in the line.

V. Conclusion and future work

This paper presents a method for real-time congestion management of power grids. Through simualtion results, it is shown that this method avoids the congestion of the lines while reducing the production constraints to the minimum. Therefore, it provides a solution for congestion management in present of weakly predictable production. However, the implementation of this real-time congestion management will require the development of the existing communication systems as well as the modification of the actual grid codes. The proposed method leads to the reduction of the re-dispatching costs and an increase of the network reliability.

Future work will present the real-time management when congestions are due to element loss (n-1 operation) and will present an automatic construction of the STATEFLOW algorithm.

Acknowledgements

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