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# Real time grid congestion management in presence of high penetration of wind energy

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## Keywords

« Power management », « Power transmission », « Energy system management », « Wind energy », « Variable speed drive »

## Abstract

With the increased use of wind energy the power generation several Transmission System Operators (TSO) have increasing difficulties for congestion forecasting due to the unpredictable nature of the energy source. 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. The simulation of the supervisor and the test grid is realized using by the EUROSTAG [1]. It is shown that the real-time supervisor allows maximization of renewable production during congestions while ensuring network reliability.

## 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 TSO are expecting an increase of line congestion in rural areas due the important increase of wind generation [2].

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 [3] and [4]. 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 and transmission capacities are well known. Other congestion management methods are proposed in [5]-[7]. 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 [8]. This is due to the difficulties to predict exact congestion magnitude and time instant and the small number of dispatchable generators in the distribution network (33kV in the example considered). 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 than 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 approach requires a strict control of the output of these generation entities. This control is possible using variable speed generators and their power electronics interface coupled with advanced control strategies. A great variety of control strategies has been described in several works [9], [10]. The proposed method is implemented and validated using in EUROSTAG simulations.

In Section II, the considered test system is introduced. Then, the real-time supervisor is presented in Section III. Simulations results are provided in Section IV to demonstrate the feasibility of the proposed real-time congestion supervisor, and finally, conclusions will be drawn in section V.

## II. Modeling of the system under study

The proposed test system is shown in Fig. 1 and the corresponding data are given in Appendix I. It's based on the IEEE 14-bus test network with the introduction of wind farms (WF) in the 33kV network at nodes 12, 13, 14. Their nominal power is respectively 12, 12 and 50 MW. WF14 had the highest rated power, and in case of low load and high wind, the line connecting the bus 9 to bus 14 may be congested. On the same line, congestion can appear in case of 33kV line opening line. A decentralized generator (Gen10) is connected at node 10; its nominal power is 20 MW. Gen1 and Gen2 perform primary frequency control. The dynamic data for the generators exciters is given in [11].

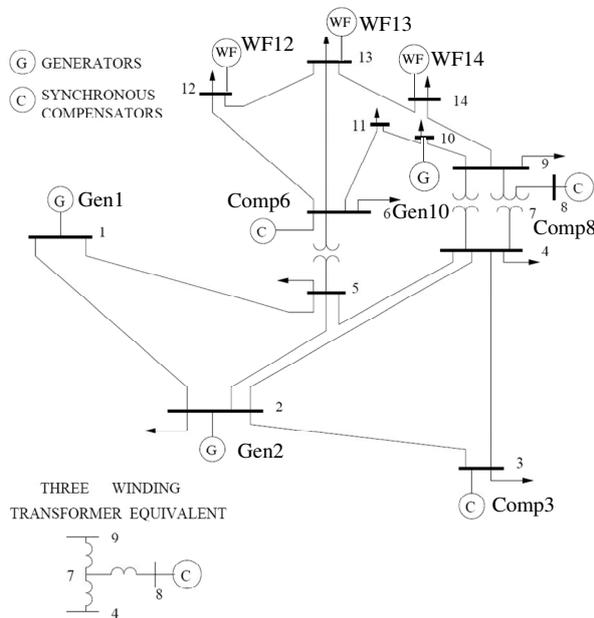


Fig. 1: IEEE 14-bus test system with different generators.

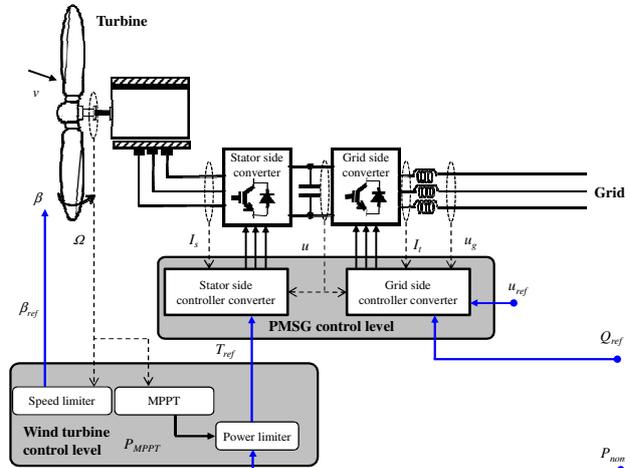


Fig. 2: Wind turbine model.

Each wind farm is represented by the equivalent Variable Speed Wind Turbine model (VSWT) of Fig. 2. The VSWT is based on a permanent magnet synchronous generator (PMSG). The inputs of the control system are the reactive power reference (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 **stator side converter controller** controls the torque of the PMSG using a stator current control loop;
- and the **grid side converter controller** 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 ( $\beta_{ref}$ ) 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 ( $\Omega$ ) 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 stator side converter controller of the PMSG control level. The torque reference is computed by equation (1):

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

The details of this wind generator control scheme are fully presented in [10].

### 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) [12], [13] and its interpretation in the context of this study can be summarized through equation (2):

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

where  $P_{redispatched}$  is the re-dispatched power and  $\Delta P_{line}$  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.

**Table I: Order of efficiency for line (9-14).**

Order of efficiency	Re-dispatching		PTDF
	Increase of generation at bus	Decrease of generation at bus	
1	10	14	-67.4%
2	2	14	-60.6%
3	1	14	-60.4%
4	10	13	-31.2%
5	2	13	-24.5%
6	1	13	-24.2%
7	10	12	-26.5%
8	2	12	-19.7%
9	1	12	-19.5%
10	10	1	-7%
11	10	2	-6.8%
12	2	1	-0.2%

Thus the PTDFs magnitude will be used to order by efficiency the re-dispatching which relieves congestion. For a congestion of the line (9-14) between node 14 and node 9, Table I represents all the possible re-dispatching in the network considered in Fig. 1. 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 (9-14), the re-dispatch requires the smallest amount of active power equation (2).

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, one node will decrease its production while another will decrease its production. If no action is taken on the node which must increase its production, then primary reserve will automatically used to compensate the lack of production. The first method will be named “supervisor with re-dispatching” and the second will be named “supervisor with primary frequency control”. These two methods will be compared in Section IV.

The real-time supervisor for congestion management contains two parts; a controller located at a central location and a controller located at the generation site and requires communication with both TSO and the production units (Fig. 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 I 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.

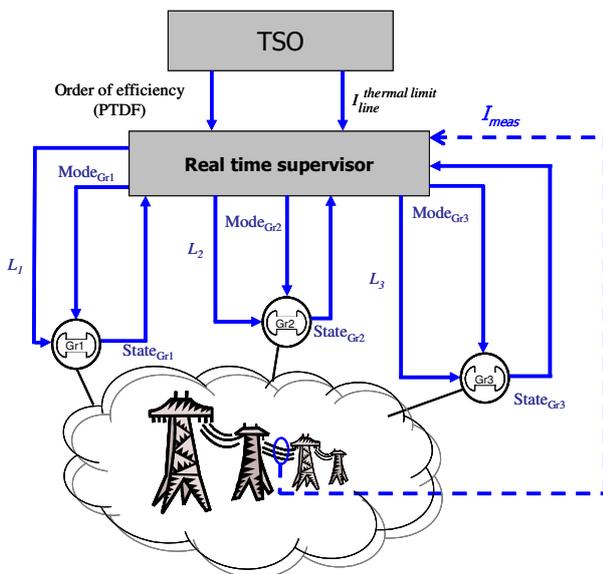


Fig. 3: Communication within the real time supervisor.

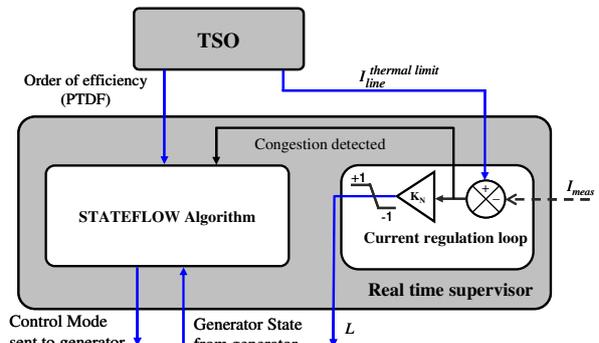


Fig. 4: Structure of the central real-time supervisor.

The **centralized supervisor** is shown in Fig. 4 and contains two controllers:

- 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.

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.

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

$$\Delta I_{\max} = I_{\max} - I_{\text{Line}}^{\text{Thermal limit}} = 15\% \quad (4)$$

where  $\Delta I_{\max}$  is the maximum overload allowed for the congested line (equation (4)) and  $PTDF_{\min}$  is the minimum PDTF that guarantees the stay below the maximum current  $I_{\max}$ . The full details are presented in [14].

- 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 [14], [16].

In the case of **supervisor with re-dispatching**, Fig. 5 shows the STATEFLOW algorithm for line (9-14) considering the information of Table I and the Gen 6 increase. If there is no congestion, then every generator operates in *Mode 1* (All the WF are to  $P_{\text{nom}}$  and Gen10 is to  $P_{\text{planned}}$ ). When line (9-14) is overloaded, the WF14 and Gen10 switch to *Mode 2* and control the following signal  $L$ . When the WF14 reaches its lower limit, the WF2 and Gen10 switch to *Mode 2* and WF14 operates at  $P_{\text{min}}$  (*Mode 4*). When the WF2 is back to its higher limit, the machine returns to its previous state.

In the case of **supervisor with primary frequency control**, Fig. 6 shows the STATEFLOW algorithm for line (9-14) considering the information of Table I and primary frequency control (Gen1 and Gen2) compensates the loss of wind power production. When line (9-14) is overloaded, the WF14 controls following signal  $L$ . When the WF14 reaches its lower limit, the WF2 switches to *Mode 2* and WF14 operates at  $P_{\text{min}}$  (*Mode 4*). When the WF2 is back to its higher limit, the machine returns to its previous state.

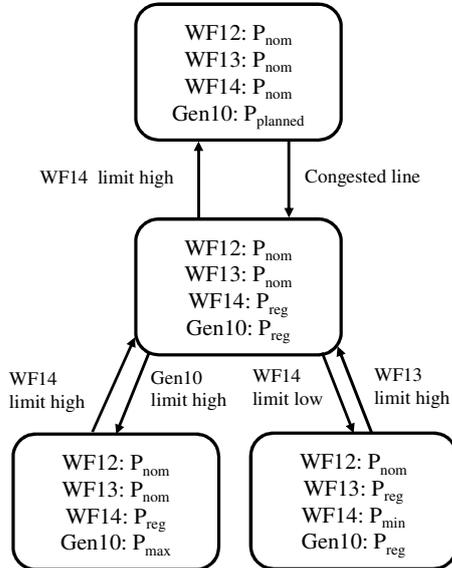


Fig. 5: STATEFLOW Algorithm for re-dispatching.

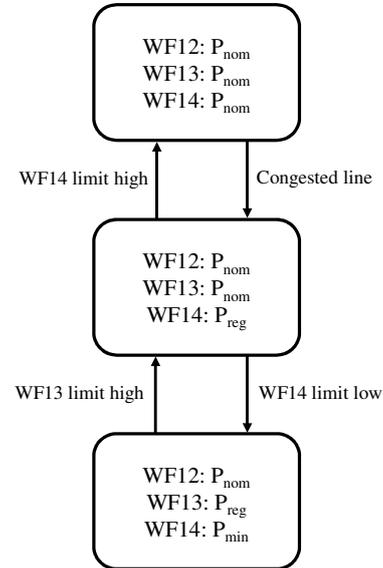


Fig. 6: STATEFLOW Algorithm for primary frequency control.

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 Fig. 7:

- The **power loop which** generates the active power reference ( $P_{\text{ref}}$ ) according to the level  $L$  sent to TSO and the measured active power ( $P_{\text{meas}}$ ).  $K_G$  is chosen to adjust the maximum dynamic response of each generator to a common value of  $\pm 5\text{MW/s}$  for a  $L$  value of  $\pm 1$ .

- 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).

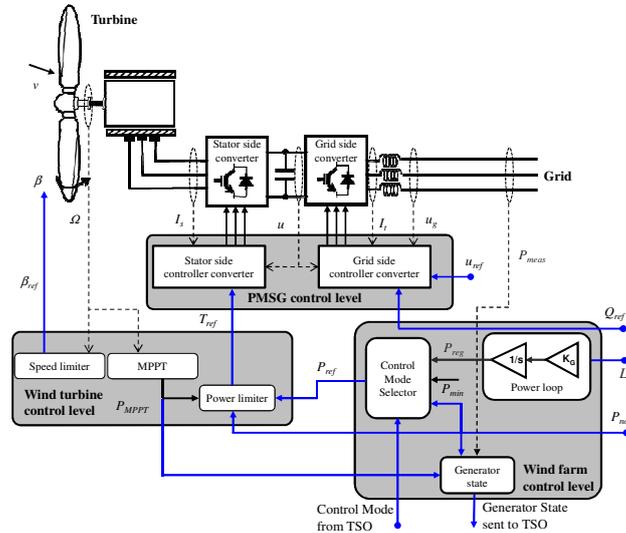


Fig. 7: Wind turbine model.

#### IV. Simulations and comparison

The test system shown in Fig. 1 was simulated using EUROSTAG. Fig. 8 shows the evolution of 33kV loads. The nominal power of load is given in appendix I.

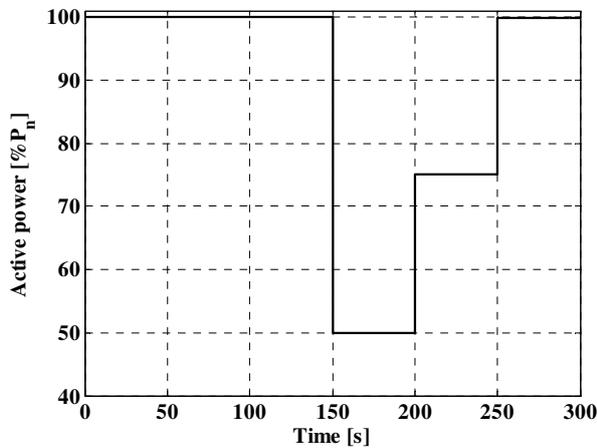


Fig. 8: Evolution of the 33kV load in percentage of nominal power.

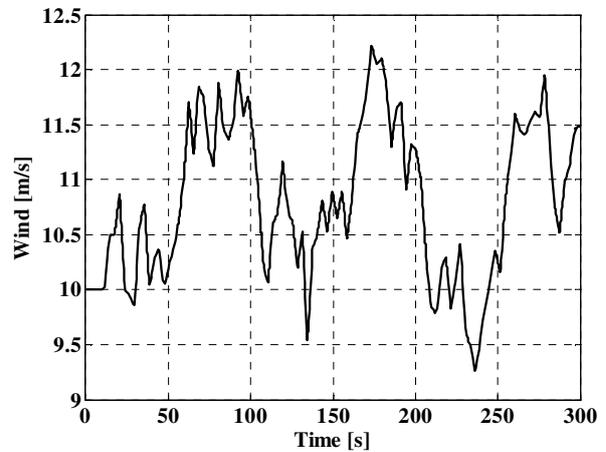


Fig. 9: Wind speed.

Fig. 9 shows the wind speed for all wind farms, the power for planned Gen10 will be 0MW. In the proposed scenario, two congestion of line (9-14) happens when line (6-13) is opened between  $t=60s$  to  $t=100s$  and when both low load and high winds are present between  $t=150s$  to  $t=200s$ .

This scenario will allow the demonstration of the efficiency on the proposed method and the comparison of supervision with the re-dispatching and supervision with the primary setting frequency.

The current in the congested line without congestion management (dotted line), with supervisor with primary frequency control (dash-dotted line) and with supervisor with re-distaching (full line) is shown in Fig. 10. In Fig. 11, the power of the WF14 ( $P_{WF14}$ ) is shown, the dotted line represents the maximum power that can be obtained from the wind by the WF (MPPT).

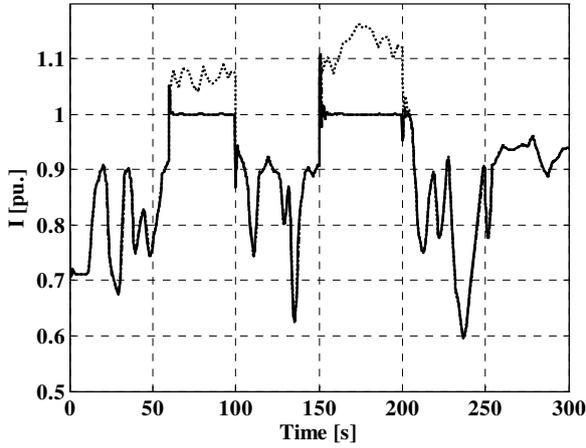


Fig. 10: Evolution of the line current.

1 p.u. represents the thermal current limit.

Dotted line: Without congestion management.

Dash-dotted line: supervisor with primary frequency control.

Full line: supervisor with re-dispatching.

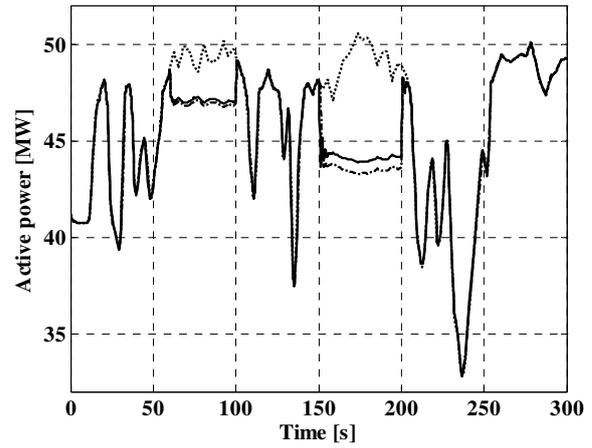


Fig. 11: Power of the WF2.

Dotted line: Without congestion management.

Dash-dotted line: supervisor with primary frequency control.

Full line: supervisor with re-dispatching.

In the case of **congestion management with re-dispatching**, 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  $t=60s$  to  $t=100s$  and from  $t=150s$  to  $t=210s$ , this couple is WF14-Gen10 (Table I); the WF14 decreases its production (Fig. 11) while the conventional generator Gen10 increases its production (Fig. 12). Fig. 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 Fig. 10 shows that this method uses the minimum necessary re-dispatching. In Fig. 13, the frequency is shown and in Fig. 14, the action of groups of primary frequency control (Gen1+Gen2) is shown. The comparison of full line and dotted line on the Fig. 13 and Fig. 14 shows that the approach with re-dispatching avoids the use of primary reserve for congestion management.

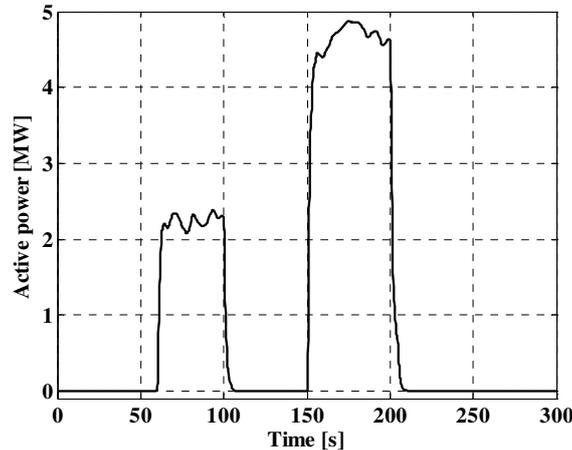


Fig. 12: Power of Gen10.

In the case of **congestion management with primary frequency control**, the STATEFLOW controller selects the available generator whose decrease of production will avoid the line overload with a minimum re-dispatching effort; from  $t=60s$  to  $t=100s$  and from  $t=150s$  to  $t=210s$ , this generator is WF14 (Table I); the WF14 decreases its production (Fig. 11) while the primary frequency control (Gen1 and Gen2) balances the decrease of the WF14. Fig. 10 shows the same results with primary frequency control with re-dispatching. In Fig. 13 and in Fig. 14, the action of primary frequency control is shown. By comparing the dash-dotted line and dotted line, we see that the frequency is lower and that the generators produce more during periods of congestion.

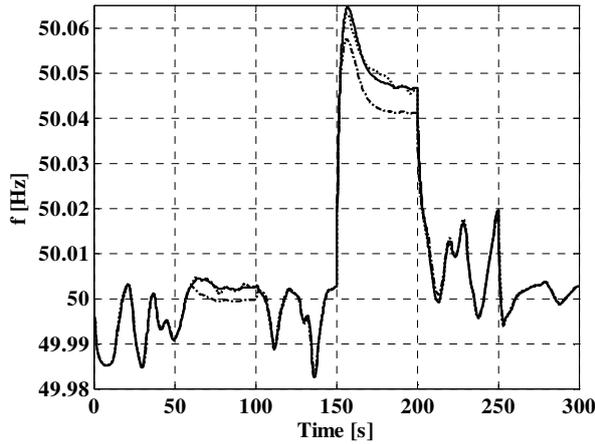


Fig. 13: Frequency.

Dotted line: Without congestion management.

Dash-dotted line: supervisor with primary frequency control.

Full line: supervisor with re-dispatching.

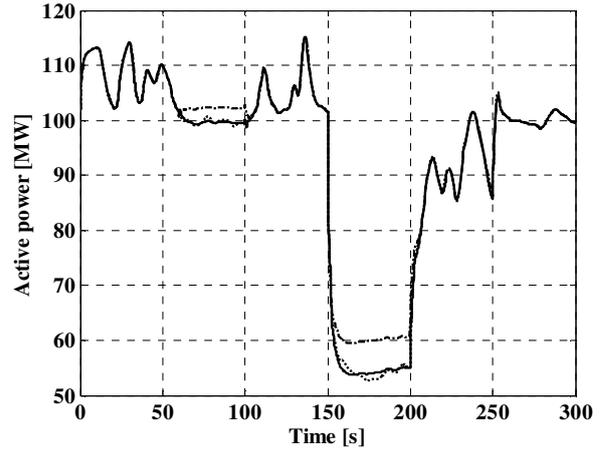


Fig. 14: Sum of Gen1 power and Gen2 power.

Dotted line: Without congestion management.

Dash-dotted line: supervisor with primary frequency control.

Full line: supervisor with re-dispatching.

Table II shows the loss of WF14 at time  $t=80s$  and  $t=170s$ . At both times, the loss of wind generation on the WF14 is higher for the congestion management with primary frequency control in comparison to congestion management with re-dispatching. This is due to the higher PTDF value for Gen10-WF14. This shows that the use of a specific generator with a high PTDF reduces production losses during the congestion.

Furthermore, in case of congestion due to the line opening ( $t=80s$ ), PTDF values are modified. This could lead to a modification of the order of efficiency in Table I. However for high values of PTDF, the modification will not change the PTDF sign. Therefore, the selection of the re-dispatching nodes may not be optimal but the quantity to re-dispatch to avoid the congestion will be optimal for this node couple. It is therefore not necessary to recompute the PTDF in case of line opening.

**Table II: Difference between the decreases of the WF14 with re-dispatching and the decreases of the WF14 with primary frequency control.**

The decreases of the WF14	At $t=80s$ , 2.23MVA overload on line (9-14) due to line (6-13) opening		At $t=170s$ , 5.65MVA overload on line (9-14) due to load decrease	
	PTDF value [%]	Re-dispatched quantity in simulation	PTDF value [%]	Re-dispatched quantity in simulation
primary frequency control	Gen1-WF14: 71.1 Gen2-WF14 : 71.2	3.31MW	Gen1-WF14: 60.4 Gen2-WF14 : 60.6	7.51MW
re-dispatching	Gen10-WF14: 76.2	3.13MW	Gen10-WF14: 67.4	6.86MW

## V. Conclusion

This paper presents a method for real-time congestion management of power grids. Through dynamic network simulation, it is shown that this method avoids the congestion of the lines while reducing the production constraints to the minimum. This is possible thanks to the real-time regulation of current in the line. In presence of weakly predictable production and load forecasting, the real time congestion management can guarantee the network security despite power variations and loss of lines. 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 cost of congestion management in using real-time management and will present an automatic construction of the STATEFLOW algorithm.

## Appendix I. Modified IEEE 14-bus System Data.

**Table III: Line data.**

From Bus	To Bus	Resistance [p.u.]	Reactance [p.u.]	Line charging [p.u.]	Tap ratio	Line rating [MVA]
1	2	0.01938	0.05917	0.0528	1	292.41
1	5	0.05403	0.22304	0.0492	1	292.41
2	3	0.04699	0.19797	0.0438	1	292.41
2	4	0.05811	0.17632	0.0374	1	292.41
2	5	0.05695	0.17388	0.034	1	292.41
3	4	0.06701	0.17103	0.0346	1	292.41
4	5	0.01335	0.04211	0.0128	1	292.41
4	7	0	0.20912	0	0.978	42.25
4	9	0	0.55618	0	0.969	16
5	6	0	0.25202	0	0.932	42.25
6	11	0.09498	0.1989	0	1	25
6	12	0.12291	0.25581	0	1	25
6	13	0.06615	0.13027	0	1	25
7	8	0	0.17615	0	1	25
7	9	0	0.11001	0	1	42.25
9	10	0.03181	0.08450	0	1	25
9	14	0.12711	0.27038	0	1	25
10	11	0.08205	0.19207	0	1	25
12	13	0.22092	0.19988	0	1	25
13	14	0.17093	0.34802	0	1	25

**Table IV: Bus data.**

Bus No.	Bus Type	P Load [p.u.]	Q Load [p.u.]	Voltage magnitude [p.u.]
1	PV	0	0	1.060
2	PV	0.217	0.127	1.045
3	PV	0.942	0.190	1.010
4	PQ	0.478	0	*
5	PQ	0.076	0.016	*
6	PV	0.112	0.075	1.070
7	PQ	0	0	*
8	PV	0	0	1.062
9	PQ	0.295	0.166	*
10	PQ	0.090	0.058	*
11	PQ	0.035	0.018	*
12	PQ	0.061	0.016	*
13	PQ	0.135	0.058	*
14	PQ	0.149	0.050	*

\* Voltage to be kept within the range 0.97-1.10

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