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ANALYSIS OF INERTIAL RESPONSE AND PRIMARY POWER-FREQUENCY CONTROL PROVISION BY DOUBLY FED INDUCTION GENERATOR WIND TURBINES IN A SMALL POWER SYSTEM

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Abstract – The increase of wind power output displaces conventional generation challenging therefore power system secure operation. Actually wind turbines are not asked to provide all the ancillary services that conventional generators are obliged to.

The paper is aimed at studying the frequency stability of a small power system, with different level of wind penetration, analyzing the possible contribution to system security by the provision of inertial response and primary power frequency control by wind turbines.

Keywords: Wind turbine, DFIG, ancillary services, inertial response, primary power-frequency regulation

1 INTRODUCTION

Wind energy production is growing worldwide at a significant rate due to environmental concerns and to economical lowering of installation capital cost [1].

However, due to the low utilization factor of the turbines, in order to achieve a double digit energy share, a large amount of installed power is required, compared to traditional power plants. Therefore several Countries, like Ireland, are already facing periods in which the demand is mainly satisfied by wind farms with a share that may reach 50% [2]. In the specific the Irish Transmission System Operator is planning the network development at 2020 in order to allocate at least 6 GW of wind, both inland and offshore, with a forecasted load, including interconnections, of about 8 GW [3].

Power system frequency stability relies on the balance between the active power output of generators and the active power consumed by loads. The loss of a crucial system element can threat the security of the system. By the provision of ancillary services, the remaining generating units attempt to restore the system safe operation. Within time the wind farms have been asked to provide ancillary services such as voltage regulation [4]. Hence the voltage reactive power control capability has been inserted worldwide in the national grid codes [5]. However the frequency regulation is becoming a quite critical issue too. This service cannot be provided for "free" because of the need of having active power reserve, able to respond to frequency drops: the wind turbines should be asked to work constantly at a de-loaded operation level [6].

A first contribution to frequency stability can be related to the inertial response, in fact DFIG (Doubly Fed Induction Generator) turbines, because the electric generator is partially connected through the electronic converter, provide a smaller amount of inertial response compared to a conventional unit of the same size. An attempt of emulate this kind of response can be realized by adding, in the maximum power tracking control loop, a signal processed by a properly set filter that increases the reference power as the frequency decreases [7].

The purpose of this paper is therefore to analyze the control solutions that can be implemented in the turbine control system in order to achieve a non wasting energy inertial response. Moreover the changes that can be done in the pitch control system, to have the wind turbine being able to provide primary power frequency regulation, are analyzed. The simulations are performed in the DIgSILENT PowerFactory environment.

2 MODELS & SCENARIOS

2.1 Network model

The power system modeled, shown in Figure 1, is a representative network that can be useful for providing a first analysis of small power systems as the Irish one.

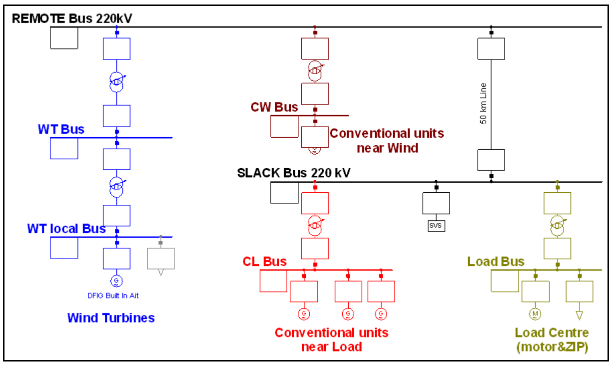

Figure 1: Test Network.

The system is thus a quasi mono bus system: the load centre is directly connected to the slack bus along with 3 conventional generators with nominal power 100 MW (120 MVA), named CL (see Table 1). These units are always on and each one is set to produce 60% of its nominal power. The load is assumed constant and equal to 600 MW and is divided into 60% of asynchronous machines and 40% of static loads as recommended in [8]. The wind farm is composed by 100 machines, 6 MW each, connected through a line to the slack bus, along with other conventional generators (named CW and shaded in the picture). The system is studied with different level of wind penetration (percentage of wind power referred to the load). The increase of wind power displaces the conventional units near the wind (CW) which thus are progressively shut down due to the fact that they have a technical minimum power: the overall system inertia and the primary power frequency capability is hence progressively reduced.

The equation of motion, that rules this dynamic, is here recalled:

$$T_m - T_e = J \cdot \frac{d\omega_m}{dt} \quad (1)$$

where J is the combined inertia of generator and turbine, T_m and T_e the torques and ω_m the mechanical rotational speed. The above equation can be expressed in terms of per unit inertia time constant, H, defined as the ratio between the kinetic energy (in Ws) and the base power (in VA):

$$H = \frac{1}{2} \cdot \frac{J\omega^2_{m\_base}}{A_{base}} \quad (2)$$

It is assumed that both conventional and wind turbine units have the same inertia, H, which values 4 seconds [8], [9].

The wind generation model is based on the literature model described in [10], while the conventional units are equipped with IEEE standard models [11]:

- Governor: Steam turbine Gov. with fast valving
- AVR: IEEE Type 1 Excitation System
- PSS: IEEE Type PSS2A

Generation / Load	P (MW) - (number of units)	Inertia H (s) – droop
Wind Turbines (**WT**)	600 (100 x 6)	4 s
Conventional units near Load (**CL**)	300 (3 x 100)	4 s 5%
Conventional units near Wind (**CW**)	600 (6 x 100)	4 s 5%
Load (asynchronous machines)	360 (60 x 6)	0.5 s
Load (static load - ZIP)	240 (40 x 6)	-

Table 1: System data and equipment.

It is assumed that the wind production is constant in the timeframe considered for the analysis (i.e. 22 seconds). This hypothesis is quite realistic if the wind farm is the equivalent of a regional set of turbines. It has been observed, in fact, that the maximum rate of change of the wind production is about 15% of the nominal installed power in 15 minutes (i.e. about 0.5% in 30 seconds) [2].

2.2 Scenarios

Different scenarios are analyzed. The first one, see Table 2, provides an overview of the minimum frequency values (i.e. the nadir) due to the increase of wind power. The color used in the subset names are used for the diagrams too.

The dynamic is triggered by the loss of one of the unit belonging to the CL group, determining a 10% drop of the production (60 MW). The technical minimum of each conventional unit is 50% of nominal power, therefore if this value cannot be achieved during the dispatch, the unit is shut down. This analysis is useful to understand the importance in the inertial response provided by the conventional unit and to analyze the natural response of the DFIG turbine.

Subset	WT (MW - %)	CW (# - MW)	CL (# - MW)
No Wind	0 (0%)	6 x 70	3 x 60
30% Wind	180 (30%)	4 x 60	3 x 60
50% Wind	300 (50%)	2 x 60	3 x 60
70% Wind	420 (70%)	0	3 x 60

Table 2: Scenario 1 – System inertial analysis.

The second study carries on an analysis, with the configuration adopted in the last subset analyzed (i.e. 70% wind), concerning the possibility to have the wind turbines providing inertial response. There is in fact the possibility to modify the Maximum Power Tracking (MPT) reference power by means of a signal, sensible to the Rate of change of frequency (Rocof), in order to slow down the rotational speed of the turbine and thus to release a certain amount of energy. Different filter parameters are tested, as depicted in the subsets list of Table 3.

Subset	Filter Characteristics
70% Wind	None
70% Wind – Fast Filter	k = 3; T = 0.1
70% Wind – Slow Filter	k = 50; T = 10
70% Wind – Dual Filter	Both

Table 3: Scenario 2 – WT with inertial response.

The third scenario, see Table 4, provides an analysis of the capability of the turbines to grant primary power-frequency response by mean of the regulation of the blade pitch angle. This capability is then compared with the base case and with the best filter solutions of the previous scenario. The full capability, that is the combination of both inertial response and power frequency capability, is also analyzed.

Subset	Filter	Pitch offset
70% Wind	No	no
70% Wind – Dual Filter	Yes	no
70% Wind – Pitch	No	yes
70% Wind – Combined	Yes	yes

Table 4: Scenario 3 – WT with frequency control.

2.3 Wind Turbine model for frequency control

As foretold the wind turbine model used is the one widely described in the literature [10], and it is characterized by the presence of:

- Aerodynamic
- Pitch Control

- Two masses shaft
- Maximum Power Tracking (MPT)
- PWM converter controls and protection schemes

For the purposes of the study, the blocks of the MPT and of the Pitch Control are analyzed and modified as illustrated subsequently.

The MPT block diagram, shown in Figure 2, is originally composed by: the control characteristic, which sets the reference active power that the generator has to produce in function of the rotational speed, and a time delay (T_d = 0.2 s). The new block inserted includes the filter characterized by this transfer function:

$$\frac{k \cdot s}{s \cdot T + 1} \tag{3}$$

The ratio k/T determines the intensity with which the braking action on the shaft is realized, while the delay is related to the time constant, T. Thus this function sets a signal sensible to the Rocof in order to modify the power reference signal. This allows the wind turbine to provide an inertial response. The parameters influence the speed and the intensity of the response as will be highlighted further on in the simulations related to the second scenario.

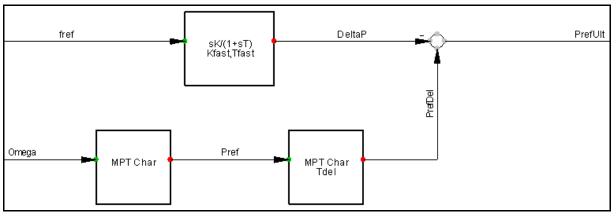

Figure 2: MPT block diagram.

For what concerns the pitch control system, the new control block diagram, shown in Figure 3, is modified by the insertion of an offset signal in the reference angle (generated by the blocks located in the upper part of the picture). This offset signal is created by the two blocks named:

- Droop pitch characteristic
- Pitch offset reference

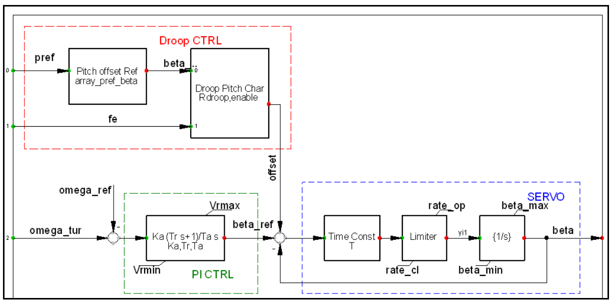

Figure 3: Pitch Control block diagram.

In the first block an equivalent of the classical droop characteristic, normally realized in the conventional generators governors, is implemented. It is recalled that the droop is the measure of how much the machine is sensible to the frequency changes and it is the value that quantify its contribution to the primary power frequency regulation. Figure 4 reports the droop characteristics implemented, these characteristics set the angle values in function of the system frequency. The different characteristics depend on the reference angle generated by the block previously described.

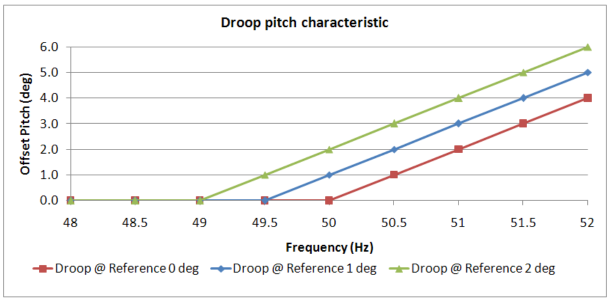

Figure 4: Droop pitch characteristic.

The curve in normal condition (zero degree reference angles) is the red one. As it can be seen the offset angle generated is zero in case of 50 Hz system frequency. If the turbine is asked to work in de-rated conditions, in order to provide an active power reserve, then the reference angle will be set to 1 or more degrees. In this way when the system frequency is equal to 50 Hz the offset angle will be, for example, 1 degree, allowing the turbine to spare some energy that will be released, by taking to zero pitch the blades and thus increasing the power coefficient, when the frequency drops. The time constant of the servo-mechanism is important in order to understand the effectiveness of this action. In the study its value is 0.5 seconds and the maximum rate of change of the blade angle is set to ±5 deg/s.

The pitch reference angle can be made function of the reference active power (see Figure 5), in order to reduce the turbine production just when the penetration of wind is really high. In fact, if the turbines are producing low power, it is quite reasonable to expect a low share in the global system consumption. Therefore there is no need to waste energy to provide an ancillary service that other units are already providing.

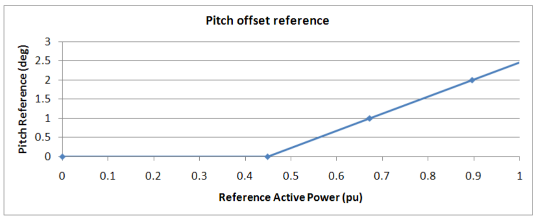

Figure 5: Beta offset reference angle.

Instead, when the wind is blowing strong and the wind power share is considerable (i.e. in the case studied is 70%) it is quite reasonable to shed some wind production to provide an active power reserve. The characteristic designed in Figure 5 establishes that until the turbine active power does not reach 45%, the reference pitch angle is zero that means that the turbine is not asked to work in de-rated conditions. After this point the increase of the reference angle is linear with the active power.

However it would be necessary to translate this reference angle into the correspondent power value. The correct evaluation of the amount of reserve provided depends on the working point of the turbine. This requires the knowledge of the aerodynamic power coefficient, c_p, which depends on the actual pitch angle and on the Tip Speed Ratio (TSR, i.e. the ratio between the peripheral blade speed and the wind speed). At 70% of nominal power (4.2 MW), TSR is, in steady state condition (i.e. with a wind equal to 11 m/s and a rotational speed equal to 1.09 pu), about 7. Thus, as it can be appreciated in the aerodynamic characteristic reported in Figure 6, 1 deg offset means a cp reduction of 0.01 thus a power reserve of 0.15 MW. This means that the wind turbine could produce 4.35 MW but it is forced to produce 4.2 MW (-3.5%).

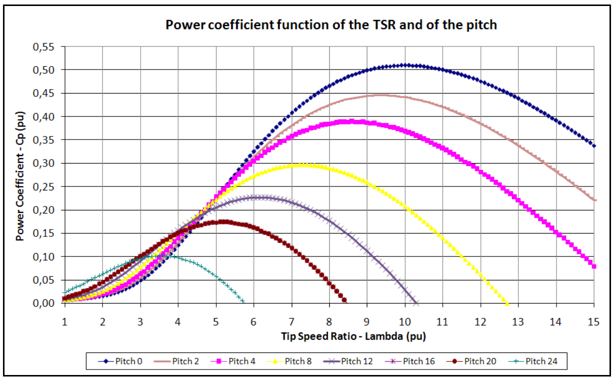

Figure 6: Aerodynamic characteristic.

It has to be noted that the non-linear dependence between the power coefficient and the TSR implies that there will not be a linear relation between the reference pitch angle and the amount of active power reserve. In fact, the more the wind is strong the more the TSR is reduced and the more the blades must be pitched. However it is beyond the scope of this work to analyze such relationship and thus the analysis is performed in just one operating point (i.e. 70% nominal power).

3 RESULTS

3.1 Scenario 1: System Inertial Analysis

This first analysis reports a survey of the system behavior in case of increase of wind penetration, without any ancillary service provision by the wind farm. The curve colors are the one used in the summary tables to list the different subset: in this scenario (Table 2) the black curve is used for the 0%, the red one for the 30%, the blue one for the 50% and the brown one for the 70% wind penetration. The 10% conventional generation tripping is triggered after 1 second of simulation.

Figure 7 shows the frequency curves and it is divided in two parts with different time scale (respectively 1 and 16 seconds) to better focus the frequency slope, the nadir and the steady state value. It is straightforward to observe how all these parameters decrease with the increase of wind power. The first two (slope and nadir) due to the lack of frequency response by the wind farm, the third (steady state frequency) due the reduction of primary power reserve from the set of generating plants.

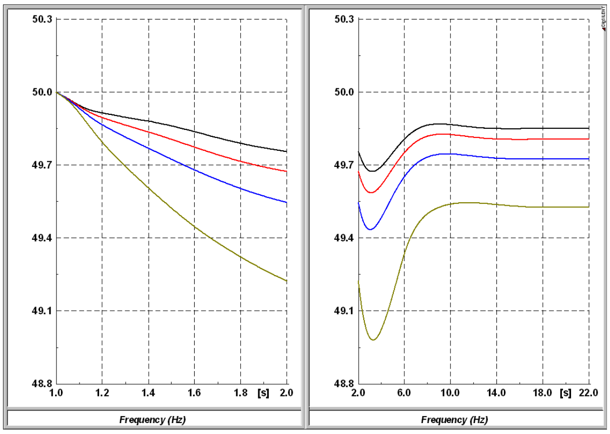

Figure 7: System frequency for System Inertial Analysis.

Figure 8 shows a comparison between the produced active power by the conventional plant (CL) and the one by WT. Both diagrams report the normalized active power to allow a better comparison of the amount of inertial response. It can be seen how the natural response of the DFIG is quite small (few percentage points) compared to the one provided by the conventional plant (from 10 to 30%).

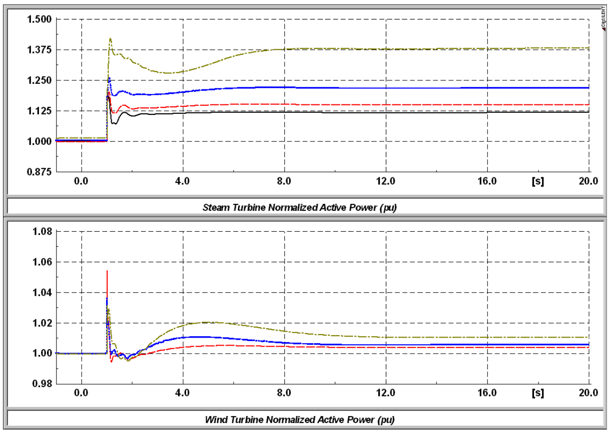

Figure 8: Steam turbine active power (normalized to 120 MW); Wind turbine active power (normalized to 180 – 300 – 420 MW).

3.2 Scenario 2: WT with Inertial Response

The second scenario envisages the possibility to have the wind turbines providing inertial response. The analysis is performed in the generation configuration called 70% Wind subset. In this case the curve colors are the same used in the Table 3: black curve for the subset without any inertial response, red one for the subset with fast response, blue curve for the one with slow response and brown one for the case that analyzes the combination of both signals.

The frequency curves, similarly to the previous case, are depicted in Figure 9. The red curve highlights how the overriding of the MPT reference by means of the signal, sensible to the fast change in the frequency, forces the WT to counteract the drop of the frequency. The nadir value, however, is slightly delayed and reduced. The subset scenario that provides the results of the slow overriding signal can be appreciated with the blue curve. In this case the inertial response of the turbine is delayed, and thus the frequency slope is not reduced but the nadir is improved. The analysis is completed with the case in which both these signals are added to the MPT reference power and the results are described by the brown curve. It can be seen that benefits of both the previous subsets are obtained. This dual filter subset is reported to highlight the fact that just by using this simple control methodology it is possible to grant some kind of improvements in the WT frequency behavior.

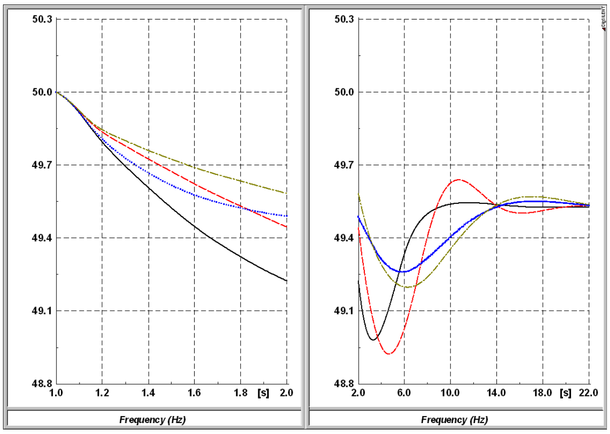

Figure 9: System frequency for WT with Inertial Resp.

It is interesting to analyze the active power produced by the steam and the wind units. In all the cases the overall energy released by the wind turbines is always the same. By the analysis of the second diagram of Figure 10, it can be seen that the power curve is different in shape, due to the kind of response (i.e. fast or slow) that the WT is providing, but similar in the area under the curve (i.e. the energy). In all the cases at the end of the simulation the turbine power is always the same and slightly higher than at the beginning, the reason of this can be searched in the slight increase of the aerodynamic power coefficient. Benefits can also be appreciated concerning the increase of the active power provided by the conventional units. The lower is the reduction of frequency, in term of intensity and rate of change, and the lower is the active power ramp.

Particular attention must be paid to the behavior of the wind turbines internal variables, as the mechanical torque and the rotational speed. The first one, reported in the upper diagram of Figure 11, is important in order to evaluate the stress on the shaft. The second one to allow an evaluation of the maximum slow down intensity that can be requested to the turbine.

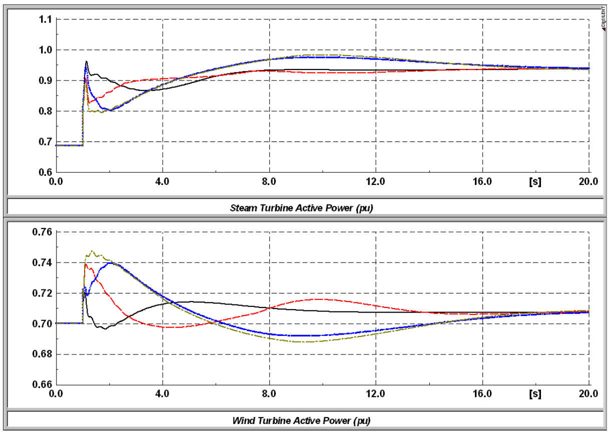

Figure 10: CL active power; WT active power.

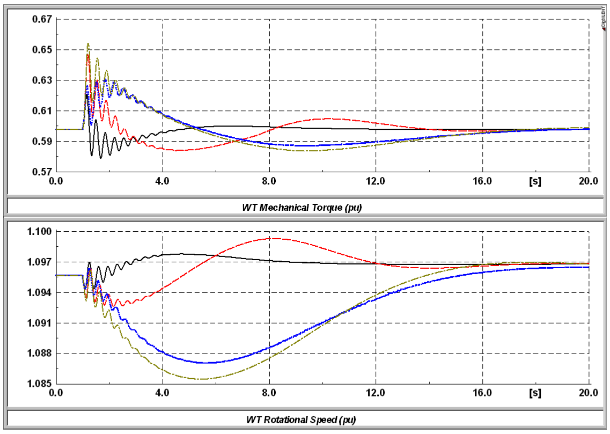

Figure 11: WT mechanical torque; WT rotational speed.

If too much kinetic energy is requested, the excessive reduction in the turbine rotational speed could lead to a reduction in the power coefficient. Figure 12 can help to better understand that. In the last two subset scenarios, where much more energy is drawn from the shaft, the power coefficient is reduced by 0.004 pu (i.e. 1%), that implies a reduction in the rotor efficiency.

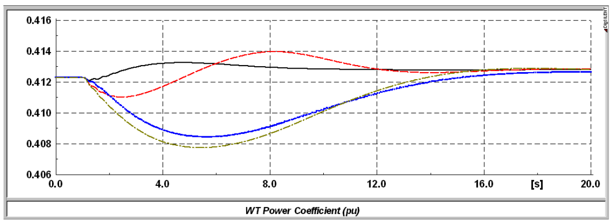

Figure 12: WT Power coefficient.

3.3 Scenario 3: WT with Frequency Control

This last scenario provides an analysis of the capability of the turbines to provide primary power-frequency response. In these subsets it is assumed that the wind speed is slightly superior than in the other cases. That because the comparisons are done at the same power level and this is needed in order to have the wind turbine to spare some energy. This capability (blue curve) is then compared with the base case (black curve) and with the dual filter solutions (red curve) of the previous scenario. The full capability, the combination of both inertial response and power frequency capability, is also analyzed (brown curve).

The frequency curves are reported in Figure 13. By the simple provision of primary power regulation, the wind turbines do not help the system to reduce the frequency rate of change, as evidenced by the blue curve. The improvements are obtained in the steady state frequency though, as part of the WT power reserve is released. If the simple inertial response (i.e. the dual filter solution, reported in the red curve) and the primary power regulation (blue curve) are combined (brown curve) the improvements are remarkable. Both the Rocof and the nadir are reduced.

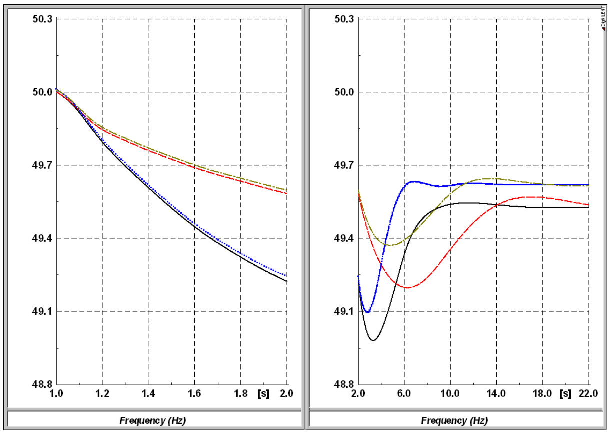

Figure 13: System frequency for WT Frequency Control.

Improvements can be appreciated also in the steam turbine response. In the first diagram of Figure 14, reporting the CL active power, it can be seen (brown curve) how the power value, in steady state condition, is reduced and moreover how much more gentle is the power increase. The wind power output, reported in the second diagram, is higher in the steady state for the subsets with provision of power reserve (blue and brown) compared to the value in the case with no services at all (black) and just inertial response (red).

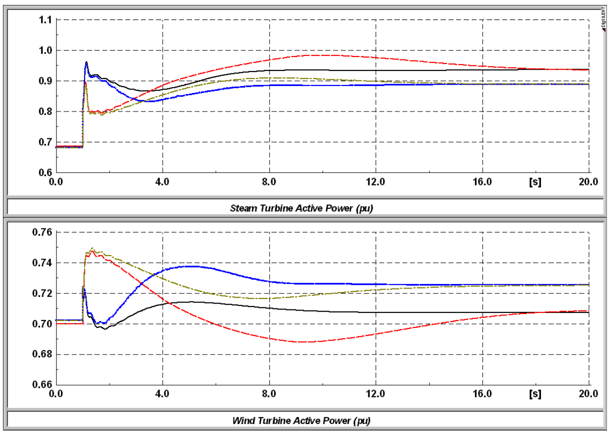

Figure 14: CL active power; WT active power.

The mechanical torque and the rotational speed are reported in Figure 15. The combined configuration (inertial response plus power frequency control) consumes less kinetic energy than the simple inertial response.

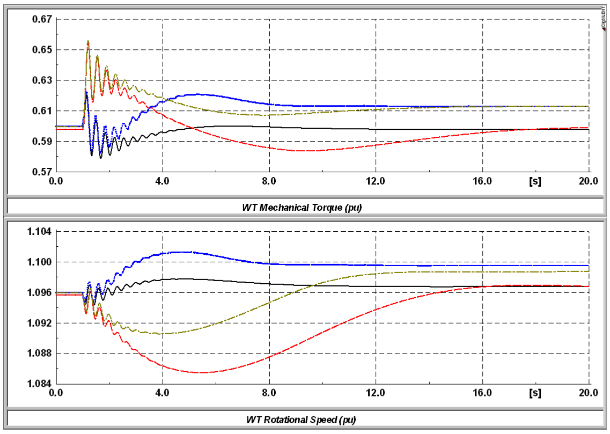

Figure 15: WT mechanical torque; WT rotational speed.

At last, it is interesting to have a look to the power coefficient and to the pitch angle (Figure 16). In the subsets where the power reserve is released (blue and brown curves) it is possible to appreciate that the power output ramp up is due to the increase of the power coefficient (from 0.39 to 0.40, that means +2.5%). It is also worth to note that not all the power reserve has been released, in fact the pitch angle steady state value is 0.3 deg. This is coherent with the droop characteristic shown in Figure 4: the power reserve is completely released only if the frequency is below 49.5 Hz.

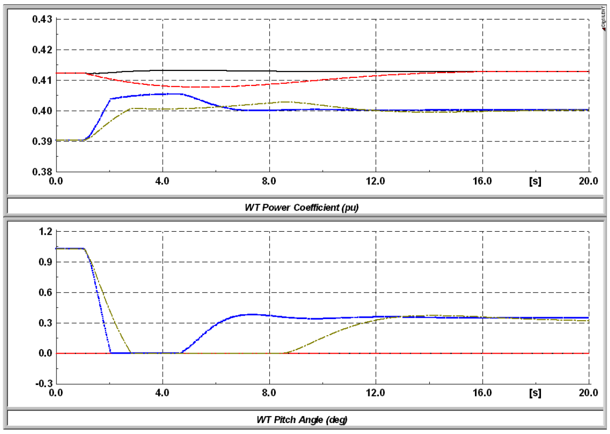

Figure 16: WT Power coefficient; WT Pitch angle.

3.4 Overall Results

Table 5 reports a synthetic overview on the minimum frequency (nadir), on the maximum rate of change of frequency (Rocof) and on the steady state frequency in the different scenarios analyzed. Two Rocof are calculated: the first one is the frequency drop in the first 0.1 seconds after the contingency while the second is the frequency drop between 0.1 and 0.2 seconds (both divided by 0.1 seconds). It is important to highlight when the Rocof values are calculated because the greatest reduction of frequency could not be experienced in the first instants of the contingency. At the end, it is reported the steady state frequency, that is the value reached at the 22nd second of the simulation.

Scenario	Subset	Nadir (Hz)	Rocof (Hz/s) @ 0.1s	Rocof (Hz/s) @ 0.2s	Steady State (Hz)
1: system inertial analysis	No Wind	49.76	-0.50	-0.40	49.85
	30% Wind	46.59	-0.60	-0.40	49.81
	50% Wind	49.44	-0.67	-0.63	49.73
	70% Wind	48.98	-0.85	-1.20	49.53
2: WT with inertial response	70% Wind	48.98	-0.85	-1.20	49.53
	70% Wind – Fast F.	48.92	-0.78	-0.85	49.53
	70% Wind – Slow F.	49.26	-0.83	-1.09	49.53
	70% Wind – Dual F.	49.20	-0.76	-0.78	49.54
3: WT with frequency control	70% Wind	48.98	-0.85	-1.20	49.53
	70% Wind – Dual F.	49.20	-0.76	-0.78	49.54
	70% Wind – Pitch	49.10	-0.75	-1.18	49.62
	70% Wind – Combo	49.37	-0.67	-0.77	49.62

Table 5: Overall Results.

It is possible to appreciate, in the first scenario, how the greatest Rocof values increase from about -0.5 Hz/s of the subset with no wind to -1.24 Hz/s of the 70% wind subset. The Steady State frequencies go down because of the progressive lack of regulating power.

The results of the second scenario highlight how it would be possible, without waste of wind energy, to improve the dynamic behaviour of the system frequency, by reducing the worst Rocof from -1.2 to 0.78 Hz/s and the Nadir from 48.98 to 49.2 Hz.

However the steady state frequency can be improved only if the WT are asked to work in de-rated condition thus being able to provide regulating power. The more the regulating power the higher is though the energy continuously wasted.

4 CONCLUSIONS

The aim of this paper has been to provide an analysis of the system frequency response with the increase of wind turbine contribution, starting from a 0% penetration getting to 70%. Due to the wind presence, the conventional units have been progressively shut down, thus reducing the system inertia and frequency response capability. This because even if the WT and the conventional generators both have the inertia equal to 4 seconds, the wind turbines, due to their electronic interface, provide a small amount of inertial response.

In the more challenging scenario (70% wind penetration), the effect of the wind turbine inertial response and power frequency regulation has been envisaged. The inertial response has been realized by mean of a filter whose signal modifies the MPT reference power. The frequency regulation has been studied by implementing a droop characteristic for the blade pitch angle whose effect is to slightly reduce the turbine power coefficient and thus to reduce the output in order to create a power reserve. Improvements have been obtained in terms of reduction of frequency nadir and Rocof compared to the 70% Wind case with no provision by the wind turbines.

Further studies will focus on characterizing the relationship between the pitch angle and the amount of active power reserve, considering the non linearity induced by the aerodynamic characteristics of the blade profiles. Moreover the influence on the frequency stability of the WT connection length and typology (i.e. cables) to the main load centre, will be envisaged.

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