Comparison of the Dynamic Response of Wind Turbine Primary Frequency Controllers

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***Abstract*— This paper presents a comparison of a variety of control strategies for the primary frequency control of wind power plants. These strategies include inertial as well as pitch angle regulators. The inertial control is sensitive to both the frequency variation through a standard droop control, and the rate of change of frequency. Since these controllers tend to counteract the operation of the Maximum Power Point Tracking (MPPT), the paper also investigates the effect of blocking the MPPT whenever the inertial control is enabled. The pitch angle control allows for a power reserve and prevents the rotor speed from exceeding the nominal value. A modified version of the WSCC 9-bus, 3-machine system with a 30% of wind penetration and a type 3 wind turbine model is considered in the case study. The behavior of these controllers are first analyzed separately. Then a compound controller, which merges together all strategies above, is proposed and discussed.**

I. Introduction

In recent years, the rapid growth of the penetration of wind power has led grid operators to face new challenges related to the control and the stability of power systems. Unlike conventional power plants based on synchronous generators, in fact, wind turbines are equipped with limited or null primary regulation capability. In particular, frequency regulation is often not available as wind turbines are operated to produce the maximum power according to wind speed conditions through the MPPT control. Moreover, the penetration of wind power plants reduces the overall inertia of the system as they are often based on non-synchronous machines and connected to the grid though power electronics devices. This situation is clearly prone to increase frequency and voltage variations following large disturbances and the risk of the occurrence of unstable conditions [1]. To cope with this emerging issue, new rules have been introduced in several grid codes aimed at defining primary and secondary frequency regulation for wind turbines [2]. This has led to several studies on the topic. However, there is currently a lack of a systematic comparison of the dynamic effect of the several solutions that have been proposed for the frequency control capability provided by wind power plants. This paper attempts to fill this gap.

Several proposals of frequency control strategies for Wind Energy Conversion System (WECS) can be found in the literature. In most cases, such controllers measure either the frequency deviation or the Rate of Change of Frequency (ROCOF) and then accordingly modify the output of the MPPT device. The devices based on the frequency deviation are basically droop controllers commonly used on synchronous machines. The main difference is that they do not measure the speed of the rotor of the machine but the frequency of the grid at the point of connection of the wind power plant. Due to the limited inertia of wind turbines, such controllers can only provide a transient effect, whereas the long term regulation is obtained through conventional synchronous machines [3]. The proposal of an additional power signal based on the ROCOF or the frequency deviation to simulate the inertial response of synchronous machines has been extensively explored [2], [4]–[7].

A variety of other solutions have been recently proposed. In [8], a predefined look-up table is implemented based on a “power shaping function” that takes the converter controls during frequency transients. This scheme appears to be more predictable than the controllers based on the measure of the frequency deviation. Reference [9] proposes a blended droop and ROCOF controller where the maximum value achieved by the ROCOF during a contingency is hold. This approach allows releasing more kinetic energy from the wind turbine.

When implementing a frequency regulator for WECS, one of the main issues is the counter reaction of the MPPT. Following a contingency, in fact, the frequency regulator leads the rotor speed to slow down, while the MPPT reaction is to recover the previous optimal speed. For this reason, in [8], the MPPT is blocked and its output is hold to its latest value whenever the frequency controller is enabled. To prevent the MPPT to be blocked all time, the frequency controller is equipped with a dead-band on the frequency error.

Finally, another way to provide frequency regulation through wind turbines is by means of the pitch angle control. This is mostly utilized to keep the rotor speed bounded to its nominal value in case of high wind speeds [2], [10]. Introducing an offset angle and accepting a decrease of the wind power production, the pitch control can function similarly to the rotating reserve of synchronous machines [11].

The main contributions of the paper are as follows.

- A comparison of most common primary frequency controllers that have been proposed in the literature for variable speed wind turbines. These are the droop control sensitive to the frequency variation, the control sensitive to the ROCOF; and the control based on the pitch angle position of the blades of the turbine. The comparison is aimed at determining strengths and weaknesses of each controller considered individually.
- A discussion on the effect of blocking the MPPT control

on the dynamic response of type 3 wind turbines when the frequency control is enabled.
- An analysis of the dynamic performance of a compound frequency control that blends together all the aforementioned control strategies.

II. Frequency Controllers for Wind Turbines

This section provides a detailed description of the mathematical formulation and practical implementation of the control strategies considered in the paper. Due to space limitations, only the control schemes of frequency controllers and their coupling with the MPPT device are discussed here. In the remainder of the section, it is also assumed that a reliable frequency measurement is available at system buses. The interested reader can find a thorough discussion on this topic in [12].

A. *Droop and* ROCOF *Controllers*

These controllers work similarly and are typically coupled to the MPPT device of the wind turbine. For this reason, they are described together.

The droop controller, as the name suggests, is comparable to the primary frequency controllers of synchronous machines, and is also called proportional controller. As shown in Fig. 1, the droop controller is composed of a washout-filter, with time constant T_w, followed by a negative droop gain. As discussed in [3], non-conventional generators cannot contribute permanently with extra real power production, thus the need for a washout-filter, which inhibits steady-state signals from the controller and help preventing the machine from stalling.

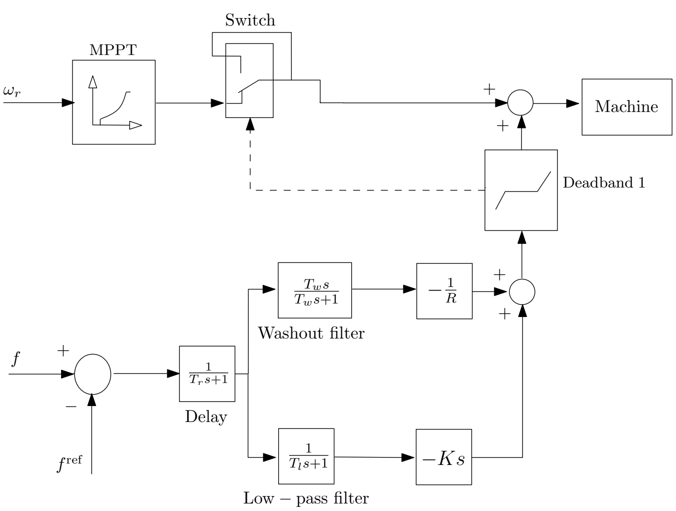

Fig. 1. Scheme of the droop and ROCOF controllers coupled to the MPPT controller.

Figure 1 also shows the ROCOF controller. This is composed of a low-pass filter, with time constant T_l, and the time derivative of frequency measurement, followed by a negative inertial factor (K). The low-pass filter is not only needed to reduce noise and numerical errors due to the derivative of a signal, but also to avoid stress of other parts of the WECS, caused by an abrupt signal from the inertial controller.

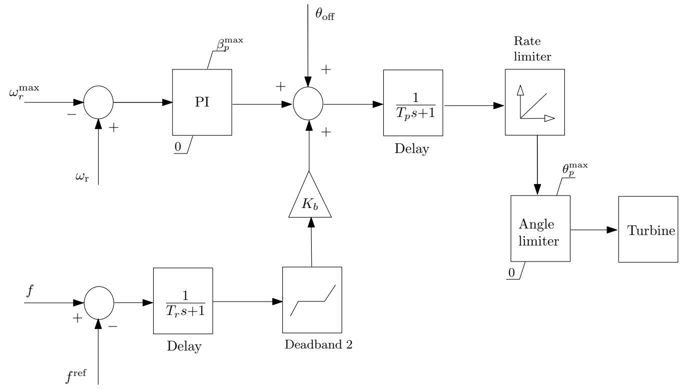

Fig. 2. Scheme of the pitch controller with inclusion of the frequency regulation capability.

The resulting frequency control signal is the sum of the output of the droop and inertial controllers, which is then added to the active power reference obtained from MPPT. Each regulating signal is expected to play a different role for different time scales following a contingency. The ROCOF control is more relevant in the first instants after the occurrence of a contingency due to its sensitivity to the rate of change of the frequency, while the frequency deviation is more effective to mitigate the frequency nadir. Hence one can expect that the effects of the two controllers are complementary.

Finally, Fig.1 shows the system to lock the output of the MPPT whenever the droop/ROCOF control is enabled. Hereinafter, this device is called MPPT *switch*. The behavior of the MPPT switch is strongly linked to the dead-band of the frequency controller. Whenever the frequency controller signal exceeds the dead-band, the MPPT output is hold to its current value, whereas, when the signal comes back to the dead-band region, the MPPT returns to its default operation.

B. *Pitch Angle Controller*

Figure 2 depicts the pitch angle controller scheme. A signal proportional to the frequency deviation is added to the output of the traditional PI controller, which only works when the rotor speed exceed the nominal value. Moreover, an offset signal is introduced to set the active power reserve and a deadband set the controller to be inactive in steady state conditions. The servo-mechanism which moves the blades is represented with a delay, a rate of change limiter and a hard limit. The latter bounds the output signal between zero and the maximum allowable angle deviation.

III. Case Study

This section provides a comprehensive comparison of the dynamic performance of the controllers described in the previous section. Controllers are considered both individually and combined together. This section focuses exclusively on the dynamic response of the frequency controllers. No economical appraisal is provided. We assume, however, that proper grid codes and policies regulate the provision of ancillary services, either rewarding wind power plants that provide the frequency control capability or imposing that such a control is a prerequisite for the connection to the grid.

A. Network Set up and Parameters

All simulations are based on a modified version of the WSCC 9-bus 3-machine system. The total nominal active power installed is 300 MW. The power production at bus 2 is assumed to be provided by two generators with capacity of 85 and 15 MW, respectively. Synchronous machines are represented by a 4th order d-q axis model, turbine governors with droop gain $R = 0.05$ and Automatic Voltage Regulators (AVRs). An Automatic Generation Control (AGC) acting on the turbine governors of the synchronous machines is also included.

The synchronous machine at bus 3 is replaced with a type 3 wind power plant that is an aggregated model of 50 variable-speed 2 MW Doubly Fed Induction Generator (DFIG) turbines, totaling a capacity of 100 MW. The model includes a 5th-order doubly-fed induction generator, a double-mass elastic shaft model with tower-shadow effect, a first-order AVR model, turbine governor and MPPT. Since only the primary frequency regulation time scale is of interest in this case study, the wind speed is assumed to be constant [13]. The parameters of the wind turbine and the DFIG are based on [14]. Relevant parameters are shown in Table I. The case study considers a single wind power plant to allow for a better comparison as topological aspects and dynamics couplings among power plants at different locations are excluded.

TABLE I
WIND TURBINE AND DFIG PARAMETERS

Parameter	Value	Unit
Rated power	2.0	MVA
Rated voltage	0.575	kV
Rated frequency	60	Hz
Stator winding resistance	0.0071	pu
Rotor winding resistance	0.005	pu
Stator leakage inductance	0.1714	pu
Rotor leakage inductance	0.1563	pu
Stator-rotor mutual inductance	2.9	pu
Angular moment of inertia	4	s
Blade length	35	m

The contingency is the outage of the 15 MW generator after 10 seconds from the beginning of the simulation. The loss of a synchronous machine is the most likely contingency that allows stressing the system and testing frequency controllers. For space constraints, only a single contingency is discussed here. We have, however, run several cases with different contingencies, including several generator outages and loss of loads at different locations, and found similar results as those presented in the remainder of this section.

Simulations are carried out with and without the MPPT switch device shown in Fig. 1. When the switch is not in use, inertial and droop controller gains are $K = 80$ and $R = 0.07$, respectively. When the MPPT switch is used, the gains are $K = 25$ and $R = 0.4$ (the value of R is high as lower values can lead the WECS to stall when the MPPT is blocked). Similarly, simulations have been solved with and without the pitch controller shown in Fig. 2. The gain of the pitch controller is set to $K_b = 500$. Other relevant parameters used in the simulations are shown in Table II. The gains and time constants of the frequency controllers have been obtained heuristically and found to be the best choice in terms of stability and dynamic performance of the controllers, e.g., lower possible frequency deviation and the shorter possible settling time for a given contingency.

TABLE II
TIME CONSTANTS AND DEAD-BAND BOUNDS

Parameter	Value	Unit	Parameter	Value	Unit
T_r	0.5	s	T_l	4.0	s
T_w	100	s	T_p	3.0	s
Dead-band 1	0.005	p.u.	Dead-band 2	0.005	p.u.

All results were obtained using Dome, a Python-based power system software tool [15]. The Dome version utilized in this case study is based on Python 3.4.0; ATLAS 3.10.1 for dense vector and matrix operations; CVXOPT 1.1.8 for sparse matrix operations; and KLU 1.3.2 for sparse matrix factorization. Dome includes same models as those provided with PSS/E for all basic devices considered in the simulations (wind turbines, synchronous machines, AVRs, etc.). Moreover, being its source code open, Dome allows easily implementing the custom frequency controllers considered in this paper.

B. Wind Turbine Droop and ROCOF Controls

Figure 3 shows the trajectory of the frequency of the Centre of Inertia (COI) considering no wind turbine frequency control as well as the droop and ROCOF control strategies discussed so far. The droop controller is the best regarding the frequency nadir, while the droop and ROCOF controls together increase the system inertia, with the advantage of a slower frequency drop and the drawback of an increased settling time.

The droop and ROCOF controllers together do not perform as expected: the MPPT is instantaneous and coupled to the rotor speed, which is rapidly reduced because of the ROCOF signal fast response. This leads to an early speed recovery and, therefore, a lower frequency nadir and a frequency overshoot, compared to the droop only controller.

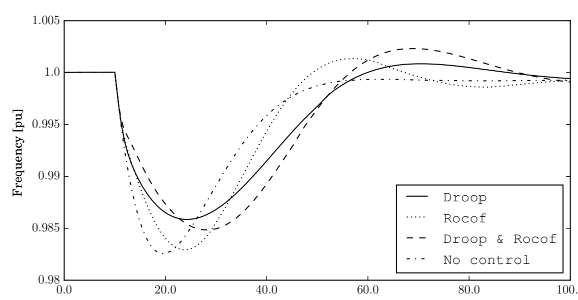

Fig. 3. Frequency of the COI of the WSCC system considering the effect of the different wind turbine frequency controllers.

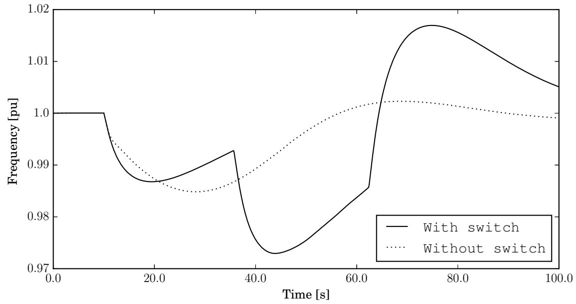

Fig. 4. Frequency of the COI of the WSCC system considering the effect of the MPPT switch coupled with the droop & ROCOF controls.

C. *Effect of the* MPPT *switch on Droop and* ROCOF *Controllers*

Figure 4 shows the performance of the droop and ROCOF controllers coupled together with and without the MPPT switch. For $t < 30$ s, the controller with the switch shows a good behavior as it reduces faster the frequency drop and increases the frequency nadir. However, once the frequency controller output signal falls back within the dead-band, the MPPT switch turns off, and the frequency drops again due to the discontinuity of the active power produced by the WECS. This phenomenon triggers a non-smooth oscillatory behavior due to the interaction of the MPPT switch, dead-band and frequency controller as shown in Figure 4. Similar results can be obtained coupling the MPPT switch with the droop and ROCOF controllers, taken individually.

An alternative approach to the MPPT switch would be to make the MPPT slower. For example, in [3] the MPPT is composed by a PI controller. Such a delay has to be tuned in order to be fast enough to follow wind speed variations and slow enough to avoid conflicts with the frequency controller.

D. *Pitch Angle Control*

Figures 5 and 6 show that the pitch control improves the performance of both the inertial and droop controllers. The pitch angle control stops at about $t = 40$ s due to the pitch angle offset restoration. This fact leads to a reduction of the rate of change of the frequency of the COI and, consequently, to a slower recovery of the synchronous speed.

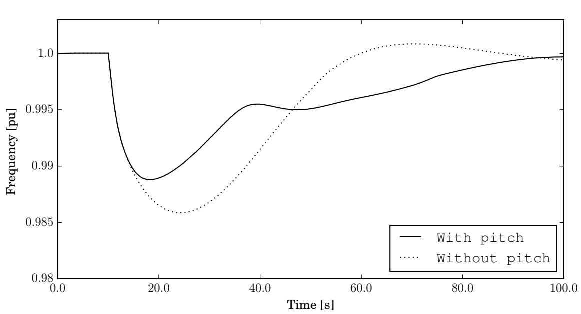

Fig. 5. Frequency of the COI of the WSCC system considering the effect of the pitch angle and droop controls.

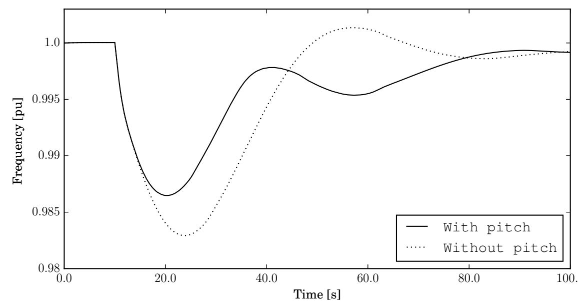

Fig. 6. Frequency of the COI of the WSCC system considering the effect of the pitch angle and ROCOF controls.

Figure 7 shows that the pitch angle controller improves also the behavior of the combined droop and ROCOF controllers, reduces the frequency nadir and prevents the frequency overshoot. The pitch angle control releases the power available by varying the angular position of the blades; prevents the rotor speed to slowdown severely; and, in turn, avoids the stalling of the turbine. The pitch angle control also reduces the time required by the rotor speed to recover the WECS output power to the value set by the MPPT device.

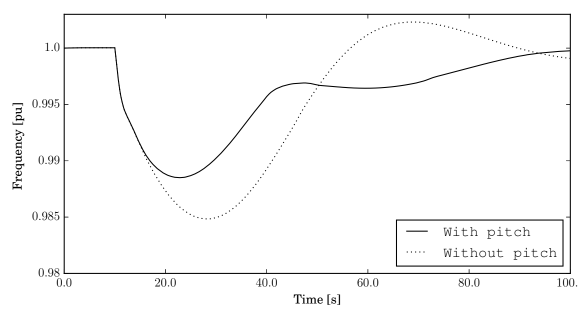

Fig. 7. Frequency of the COI of the WSCC system considering the effect of pitch angle, droop and ROCOF controls combined.

E. *Comparison with Conventional Primary Frequency Control*

For a 2 MW wind turbine, as those used in this case study, the kinetic energy stored in the rotor blades, which is about six times the one of the rotor of the machine, is not negligible compared to standard synchronous machines [16]. Moreover the power output ramp up and ramp down achievable through the inertial and droop controllers are faster than those of traditional thermal power plants. For these reasons, the primary frequency regulation provided by wind power plants can lead to smoother frequency variations compared to those obtained using exclusively traditional turbine governors. This behavior is illustrated in Fig. 8, which compares the transient behavior of the frequency of the COI for the considered modified WSCC system with inclusion of a controlled WECS and for the original WSCC 9-bus system with synchronous generators.

F. *Interaction of* AGC *and Wind Turbine Frequency Control*

The AGC allows restoring the frequency to the nominal value and the pitch angle to its initial offset value θ_{off} (see Fig. 2).

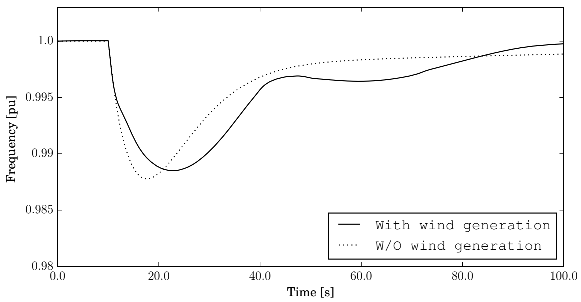

Fig. 8. Transient response of the frequency of the COI for the original WSCC system and the case with WECS including the compound controller.

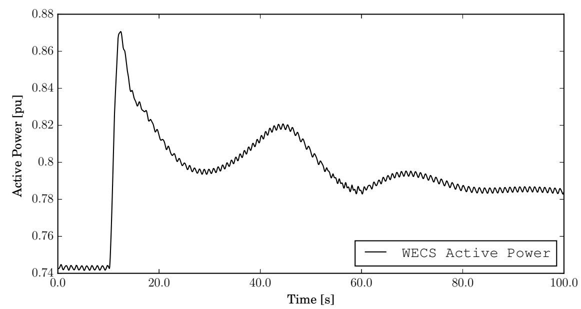

Fig. 9. Active power production of the WECS with inclusion of the compound controller.

Figure 9 shows the behavior of the active power produced by the WECS without AGC. In this case, the wind turbine contributes to recover the nominal frequency by increasing its power output both during the initial transient and in steady-state conditions. The ripple that characterizes the active power output is due to the shadow tower effect. The long-term oscillation, however, is a consequence of the proportional controller of the pitch control.

IV. Conclusions

This paper presents a thorough comparison of a variety of controllers that enable wind turbines to provide primary frequency regulation. These are a droop, a ROCOF and a pitch angle controllers. First their behavior is studied individually. Then a compound model that combines the three strategies above is proposed and tested. The effect of a device that blocks the MPPT when the frequency control is enabled is also analyzed.

Simulation results indicate that, overall, the compound model provides the best performance as it is able to benefit from the advantages of the three controllers while reducing their drawbacks. The droop and ROCOF parts of the compound controller, in fact, have a fast response during the initial phase of the transient thus reducing the frequency nadir, whereas the pitch angle controller provides a power reserve capability that can be exploited in the long term. The compound controller is also found to perform slightly better than primary frequency regulation provided by conventional power plants.

On the other hand, the effect of the MPPT switch, while beneficial in the first instants after the occurrence of the contingency, can lead to undesirable effects when the frequency is recovered. Future work will investigate strategies to improve the interaction between the MPPT and the frequency control of wind turbines.

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