Improved Frequency Control from Wind Power Plants Considering Wind Speed Variation

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Abstract— A fast frequency controller (FFC) for wind power plants (WPPs), which produces a temporary overloading power reference based on frequency deviation and rate of change of frequency, is proposed in this paper. Contrary to standard controllers proposed in the literature, the gains of the FFC are optimized for different wind speeds ensuring an improved frequency control from WPPs over the whole wind speed range. Two options for temporary frequency control implementations from WPPs are analyzed and compared. Moreover, the impact of mechanical, electrical and control limitations at different wind speeds and its effect on frequency control is discussed in the paper. Results show that by optimizing the gains, an improved frequency control can be obtained compared to standard controllers which apply a fixed gain over whole the wind speed range.

Index Terms—Frequency Control, Inertial Response, Temporary Overloading, Wind Power Plants

I. INTRODUCTION

Frequency in a power system indicates the balance between generation and load. It is important to keep the frequency within a tight margin, otherwise generation or load shedding might be initiated to ensure system stability. Following an under frequency event, caused by a loss of generation or increased load demand, the initial frequency dynamics are dominated by the inertial response of the spinning generation units. Synchronous generators (SGs) naturally contribute with kinetic energy (KE) to reduce the frequency decline, following an under frequency event. However, the effective natural inertia of the system decreases with the expected increased penetration of wind power in power system replacing the SGs. The reason is that modern wind turbines (WTs) connected to the system through power electronics do not inherently contribute with inertia to the system. This may lead to an increased rate of change of frequency (ROCOF) following a frequency event triggering system protection devices. However, inertia is essential to limit the ROCOF and thus to ensure time for slower generation control (primary followed by secondary reserves) to stabilize the system frequency. Due to the large WPPs penetration into the system over the last few years, transmission system operators (TSOs) are expecting WPPs to participate more and more in power system frequency control [1], [2]. However, there is no grid code specifying for how long the WPPs should contribute with additional power after under frequency events. Over the years, researchers have therefore proposed different frequency control methods for WPPs to support the system by injecting additional power into the system during an under frequency event [3]-[7].

One of these methods provides fast frequency control in order to emulate inertia from WPPs and thus to limit the ROCOF in case of frequency events. Different control concepts enabling the inertial response to produce additional power from WPPs have been proposed in the literature [8]-[14]. A method emulating the inertia based on ROCOF, referred as derivative control, is explained in [9], [10]. Due to the sensitivity of the derivative control towards noise, a low-pass filter is added to eliminate noise from the measurement. The other method, referred as proportional control, provides an additional active power reference proportional to the frequency deviation from nominal value [11], [12]. In [13]-[15], once the frequency event is detected, a fixed duration overloading method of the WT above its initial actual power output is implemented. Wind turbines capability to provide temporary overproduction depending on the initial pre-overproduction conditions, i.e. wind speed conditions, limits of the mechanical/electrical components and control strategy has been investigated in [16], by running case studies with different constant power overloading over fixed durations. In this light, it has been shown that at low wind speeds there might be a risk of stopping the WT during long overproduction periods.

Contrary to the above methods, where WPPs are assumed participating in temporary frequency control without reducing their power output during normal operation, in [17], a method to operate the WPPs at a deloaded power level under normal conditions is explained. This method is useful whenever extended frequency support from WPPs is necessary. Although this would potentially provide a more flexible,
longer-term frequency support, it involves loss in energy yield.

Two different frequency control options for WTs assuming constant power overloading over fixed duration have been proposed and tested in [15]. In both options, an overloading power reference of fixed magnitude and duration is generated once the under frequency event is detected. In Option 1, this overloading power reference is added to the fixed pre-overloading power output value, while in Option 2, it is added to the actual power output of the WT. This may result in higher power output from WT during overloading period for Option 1 compared to Option 2, particularly for below rated wind speeds. The reason is that in Option 2, the actual power output value of WT decreases during overloading period due to the power unbalance between WT aerodynamic power and the electrical power output. However, Option 1 leads to larger reduction in WT electrical power output after the overloading period and therefore results in a longer recovery period compared to Option 2, which could be more stressing for the primary frequency control of the power system. However in [15], no solid conclusions on which option to choose is done as the study is limited to one particular wind speed and does not consider the effect of overloading on the dynamics of the WT.

In this paper, a FFC, which generates temporary overloading power reference to the WT based on the ROCOF and droop method is proposed. The WT operating conditions and the wind speed are considered in this paper to define the magnitude of the overloading power reference, and hence, the gains of the FFC. The procedure to calculate the optimal gains of the FFC at different wind speeds in the test power system is also discussed. The optimal gains of the FFC are calculated to yield maximum energy exchange from WT at different wind speeds, considering the operating constraints of the wind turbine. This results in an improved support from WT at higher wind speeds or can prevent the turbine to reach an unstable operating point when wind speed is expected to drop. Similar to [15], two options to generate the power reference for frequency control from WPPs are considered. In Option 1, the fixed pre-overloading power output, while in Option 2, the actual power output of the WT are considered to generate power reference during under frequency events. The performance of these two options is analyzed and in addition to [15] optimal gains of the FFC are estimated for both the options based on WT dynamics at different wind speeds. This analysis provide guidelines on how to choose the most suitable option for temporary overloading of the WT during under frequency events considering WT dynamics and wind speed variations.

The paper is organized as follows. Section II describes the modeling of the test power system and WT’s fast frequency controller. The methodology to calculate the optimal frequency controller gains is explained in section III. The simulation results along with the discussion of the two options for overloading the WT is presented in section IV. The concluding remarks along with the scope for future work are given in section V.

II. Model Description

A. Test Power System

A simple test system, shown in Fig.1, comprises of a lumped synchronous generator representing the power system, a WPP and a load, is considered for this study. This test system representation is an aggregated model of the test model of the transmission grid proposed in [18]. The ratings of the test system are given in Table I.

![Figure 1. Model of the test system](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous Generator Rating (MVA)</td>
<td>5000</td>
</tr>
<tr>
<td>WPP Rating (MW)</td>
<td>1000</td>
</tr>
<tr>
<td>Load (MW)</td>
<td>4000</td>
</tr>
</tbody>
</table>

Standard block diagrams and parameters for the turbine, governor and excitation system with AVR of the SG have been used [18],[19]. The parameters of the turbine and governing system are listed in Table II.

![Table I. Test system parameters](table)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Regulating Energy (pu)</td>
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</tr>
<tr>
<td>Governor Time Constant (s)</td>
<td>0.1</td>
</tr>
<tr>
<td>Turbine Time Constant (s)</td>
<td>1</td>
</tr>
<tr>
<td>Inertia Constant (s)</td>
<td>8</td>
</tr>
</tbody>
</table>

B. WPP and WT Model

A WPP of 1000 MW is considered in this work. The WPP model is an aggregated wind turbine model based on the aggregation method given in [20]. The IEC Type IV wind turbine model has been used in this study. It is based on the generic approach proposed by the IEC Committee in Part 1 of IEC 61400-27 [21] for the short term power system stability studies. Additionally, the model includes the aerodynamic behavior of the rotor and wind speed variability, as this is of high relevance for the study as explained in [22]. The WT model also contains a FFC, as shown in Fig. 2, which generates the temporary overloading power reference to the WT.

C. Fast Frequency Controller from WT

The block diagram of the FFC from the WT is shown in Fig. 2. It consists of an ‘Inertia and Droop’ Controllers, a ‘Gain Look Up Table’, an ‘Option Selection’ block which decides between the two options for frequency control, an ‘Optimal Operation’ block and ‘Power Reference Selection’ block, whose functions are explained below.

1) Inertia and Droop Controllers

This controller sends a temporary overloading power reference (ΔP), which is a combination of ΔP₁ and ΔP₂, to
the WT during under frequency events. $\Delta P_1$ is proportional to the frequency deviation from steady state value ($\Delta f$), whereas $\Delta P_2$ is proportional to the ROCOF ($\Delta f / \Delta T$). These controllers are inactive within certain frequency deviation and rate of change (dead band), with values depending on grid code requirements. The magnitude of overloading ($\Delta P$) can be varied by changing the power references $\Delta P_1$ and $\Delta P_2$ through tuning of the gains $K_D$ and $K_r$ respectively. A low pass filter is used to remove the high frequency noise in order to protect the WPP from short spikes in its power references.

2) Optimal Operation Block

This block generates a power reference proportional to generator speed ($\omega_{gen}$). In normal operating conditions, it generates maximum power reference as $\omega_{gen}$ is at its optimal value. During overloading it generates a reduced power reference as $\omega_{gen}$ decreases with overloading, particularly at below rated wind speeds.

3) Power Reference Selection Block

The ‘Power reference selection’ block selects between optimal power reference ($P_{opt}$) during normal operation and frequency initiated power reference ($P_f$) during a frequency event. The $P_f$ is the sum of base power reference ($P_{base}$), which depends on the selected frequency control Option, and overloading power reference ($\Delta P$) generated by the frequency controller.

4) Frequency Control Option Selection

There are two options to select the base power reference ($P_{base}$) for frequency control. In Option 1, $P_{base}$ is equal to the WT output before the frequency event, freezing the output of the optimal operation block. In Option 2, $P_{base}$ is equal to the actual output of the optimal operation block, which decreases with overloading during frequency support at below rated wind speeds. Option 1 does not consider the reduction in actual WT electrical power output during the overload (due to reduction in $\omega_{gen}$ at below rated wind speeds) while Option 2 does. This results in a higher frequency initiated power reference ($P_f$) to the WT for Option 1 compared to Option 2 assuming constant and equal $\Delta P$ in both options. However, in this paper it is shown that $\Delta P$ can be varied by optimally changing the gains ($K_D$ and $K_r$) of the FFC with the average wind speed. It is also shown that $\Delta P$ is different for the two Options. The principle of these two options can be better understood by the graphs given in Fig. 3 showing the $P_f$, $P_{opt}$, and rotor speed ($\omega$) of the WT for the same under frequency event at below rated wind speed.

Above the rated wind speeds, the additional energy from the WT can be released by changing the blade pitch angle during the overloading period, hence, $\omega$ and $P_{opt}$ do not alter much. Hence, the study is more focused on the behavior of WT at below rated wind speeds. In Option 1, the effect of rotor speed on the WT aerodynamic power (hence the actual WT electrical power output) during the overloading period ($T_{OL}$) is ignored leading to an increased power support from the WT compared to Option 2 for the same operating conditions and gains of the FFC. However, this causes reduction of rotor speed and hence the actual power output of WT which leads to an increased recovery period ($T_{rec}$) after the overloading period with Option 1 compared to Option 2. It is hard to define which option is better. It mainly depends on the required performance, i.e. faster and higher initial power surge ($\Delta P$) or shorter recovery period ($T_{rec}$) of the WTs speed, hence smaller power drop ($\Delta P_{AOL}$). The answer to this may come from the characteristics of the specific power
system, e.g. for small, isolated power systems the emphasis will probably be on fast and high initial power surge.

5) Gain Look up Table

The gains of the FFC at different wind speeds are calculated by taking certain WT operational constraints and power system constraints into account. More details about these constraints are given in the next section. These gains are then stored in the Gain Look Up Table. Based on the estimated average wind speed, the FFC gains are dynamically updated to improve the frequency control from WPPs.

The capability of WTs for providing temporary overproduction strongly depends on the initial pre-overproduction conditions, i.e. wind speed conditions, limits of the mechanical/electrical components and control strategies. At wind speeds just below the rated, an imposed overproduction can stress the mechanical shaft drastically and causes a significant reduction in WT output power after overloading [16]. Similarly, at low wind speeds, the WT takes longer to recover to normal operation. However, at high wind speeds, the WT recovers quickly after overloading without causing reduction in power output. In general, the gains of the frequency controller are constant for all of the WT’s operating points and usually set to protect the WT operation at low wind speeds. However, adapting optimally the FFC gains based on the average wind speed influences the temporary overloading and the dynamics of the WT. In the next section, the calculation of optimal FFC gains for both options depending on the average wind speed is presented.

III. CALCULATION OF OPTIMAL GAINS FOR THE FAST FREQUENCY CONTROLLER

The optimal frequency controller gains are estimated based on the assumption that WT is maximum overloaded during the frequency event. To calculate the capability of WPPs for temporary overloading, it is therefore important to test it under a critical power system frequency event which leads to maximum overloading of the WPP. The gains $K_D$ and $K_I$ of the WT’s FFC determine the amount of temporary overloading power reference ($\Delta P$) to the WT. The following steps are followed to estimate the optimal gains of the FFC.

A. Critical Frequency Event of the Test System

The largest infeed loss in a power system is an example of significant imbalance and is one of the (N-1) contingency criteria in transmission system planning. Therefore, a generation loss of 600 MW is considered as reference incident in the test power system (shown in Fig. 1) to create an under frequency event, shown Fig. 4.

It is also considered that only synchronous machines are participating in frequency control. The frequency control from WPPs is disabled. This results in a critical frequency event as the overall power system inertia reduces because the WPP deliver maximum available power during normal conditions and do not participate in frequency control.

B. Calculation of optimal frequency controller gains

The objective of calculating optimal frequency controller gains is to determine the maximum possible temporary overloading of the WT during under frequency events. This necessitates the calculation of the maximum possible energy yield from the WT during under frequency events. The maximum energy yield test on the WT is more accurate if it is tested in open loop conditions, i.e. manipulating the WT power set point for temporary overloading, independently of the power system response and impact [16]. Therefore, the calculated critical frequency from section III A is fed as input to the FFC (which generates the temporary overload power reference) of the WT connected to the test system, as shown in Fig. 2. In order to simulate the impact of this under frequency event on the overloading of the WT, the test power system is replaced with a WPP feeding to a voltage source as shown in Fig. 5. This is called overloading test of the WT. The overloading of the WT can be varied by changing the gains of the fast frequency controller, $K_D$ and $K_I$. The optimal gains are the ones leading to maximum energy yield from the WT without violating certain operating constraints of the WT and power system as explained below. The energy extracted from the WT depends upon the magnitude and duration of temporary overloading. Therefore, the study is aimed at estimating the gains of the FFC of the WT participating in temporary frequency control during the first few seconds after the under frequency event. Based on the dynamics after the under frequency event, shown in Fig. 4, the duration of the WT overload is considered as 5.5s, after which the oscillations in the frequency are reduced.

Figure 5. Test power system for calculation of FFC gains

The WT and power system operational constraints considered during the calculation of the optimal gains are:

- Minimum rotational speed: $\omega_{min} = 0.5 \ pu$
- Maximum power overload: $P_{OLMax} = (\frac{P_f}{P_N}) = 110\%$ where $P_N$ is nominal active power output of WT
- Maximum power drop after overloading period: $\Delta P_{OLMax} = 10\%$
- Maximum recovery time: $T_{recMax} = 60 \ s$

![Figure 4. Critical frequency of the test system shown in Fig.1 for the generation loss of 600 MW](image-url)
The limit $\omega_{\text{min}}$ protects the WT from stalling caused by the overload. The $P_{\text{OLMax}}$ is limited by the overall rating of the WT. Also, it limits the drive train torque value during the overload. The $\Delta P_{\text{OLMax}}$ is the limitation set by the associated power system to avoid second frequency dip after the release of WT overload. The $T_{\text{recMax}}$ ensures that the WT recovers fast enough to resume normal operation or even to participate in frequency control, if required, for any next event. These operational constraints ensure safe dynamical operation of WT during the overloading period and also at the recovery period after the overload. The optimal frequency controller gains are calculated for different wind speeds for both Option 1 and 2 meeting the above mentioned WT constraints. It is assumed that both the gains $K_D$ and $K_I$ are equal in each test case to simplify the analysis as the main objective is to calculate the maximum possible energy yield from the WT during under frequency event.

IV. SIMULATION AND ANALYSIS OF RESULTS

The variation of the optimal gains of the FFC with the average wind speed for both Option 1 and Option 2 is shown in Fig. 6. It can be observed that the optimal gains vary with wind speed for both options. Which constraint is limiting the optimal FFC gains at different wind speeds is also shown in Fig. 6. The maximum power overload ($P_{\text{OLMax}}$) is the constraint for overloading (hence optimal FFC gains) at high wind speeds (above 1 pu). At high wind speeds, the aerodynamic power is altered by changing the pitch angle, thereby producing more electrical power output during the overload. At medium wind speeds (between 0.7 and 1 pu), the maximum power drop after overloading period ($\Delta P_{\text{OLMax}}$) is the major constraint limiting the overloading. Similarly, at lower medium wind speed range (0.5 pu to 0.7 pu) is the recovery period ($T_{\text{recMax}}$), and at lower wind speeds (less than 0.5 pu) is the minimum rotational speed ($\omega_{\text{min}}$) of the WT are limiting the optimal frequency controller gains. Therefore by dynamically adapting the gains of the FFC considering the average wind speed will result in an improved frequency support in case of increased wind speeds. Similarly, this prevents the turbine to reach an unstable operating point in the case that the average wind speed is evolving differently than expected, i.e. dropping. It can also be observed from Fig. 6 that the magnitude of these optimal gains is higher for Option 2 than for Option 1, especially at medium wind speed range. As mentioned above, Option 2 considers the variation of actual power output; hence, the recovery is faster leading to lower reduction in the power output after the overload encouraging higher FFC gains compared to Option 1. The difference between these two options can be understood in detail from the overloading test results of the WT at medium wind speed range (0.8 pu), shown in Fig. 7 and Fig. 8. The difference between the two options are more predominant at medium wind speed range, hence the results at 0.8 pu wind speed is discussed in detail.

In the next part, the dynamics of the WT for open loop overloading test are discussed in section A, the performance of the two options for frequency control in actual power system is discussed in section B. Finally, in section C, few recommendations are made for WPPs to participate in frequency control.

A. Dynamics of WT with Option 1 and Option 2 for WT open loop overloading test at 0.8 pu wind speed

The overloading test provides information on the WT’s limitations to support the grid during frequency dips. As shown in Fig. 7, in both options, the frequency input signal to the FFC, electrical power reference from optimal operation block ($P_{\text{opt}}$), WT electrical power output ($P_{\text{out}}$), WT rotor speed ($\omega$), and the aerodynamic power ($P_{\text{aero}}$), are presented.

In Option 1, as the overloading power reference from FFC ($\Delta P$) is added to the pre-overloading optimal power reference, $P_{\text{out}}$ is always higher than $P_{\text{aero}}$ during the whole overloading period (for 5.5 s). Hence, the rotor continues to
decelerate, which further decreases $P_{\text{aero}}$, until the release of overload. This leads to a higher power drop ($P_{\text{out}}$ falls from 0.6 pu to 0.5 pu) after release of overload. Therefore, maximum power drop after overload ($\Delta P_{AOL\text{Max}}$) is the limiting parameter for the gains ($K_D = K_I = 1.8$) of the FFC at medium wind speed range. For better understanding of the results $P_{\text{out}}$ and $P_{\text{aero}}$ are plotted together for both options in Fig. 8.

In case of Option 2, $\Delta P$ is added to the actual power output of the WT i.e. the output of optimal operation block ($P_{\text{opt}}$), which decreases when the rotor speed drops. Therefore $P_{\text{out}}$ increases faster during the initial phase of overloading i.e. up to 6.1 s due to the higher $\Delta P$ generated by higher estimated gains of the fast frequency controller. However, $P_{\text{out}}$ decreases below its pre fault value during the mid-phase of overload (from 7 s to 9 s) because of the faster reduction in $P_{\text{opt}}$. During this period $P_{\text{out}}$ is less than $P_{\text{aero}}$, which drives the rotor speed ($\omega$) towards its pre-overloading value and leads to faster WT recovery. It can also be observed, from Fig. 7, that the frequency signal is rising (during 6.5 s to 9 s) after the first dip; hence reduction in WT power output does not deteriorate the overall frequency of the power system. In the last phase of overloading (from 9 s to 10.5 s), $P_{\text{out}}$ becomes slightly higher than $P_{\text{aero}}$, due to fall in frequency, causing slight reduction in rotor speed until the release of overloading. For Option 2, $\Delta P_{AOL\text{Max}}$ is also the limiting parameter for the gains ($K_D = K_I = 11$) of the FFC, as $P_{\text{out}}$ falls from 0.6 pu to 0.5 pu.

During medium wind speeds, a slight decrease in rotor speed leads to a higher reduction of active power output from WT. $\Delta P_{AOL\text{Max}}$ is the constraint for the temporary overloading and hence for the optimal gains of the frequency controller. In case of Option 2, it is possible to extract more energy from the WT during the first phase of frequency dip, thereby better utilizing the kinetic energy stored in the WT rotor to limit the ROCOF and frequency nadir, compared to Option 1. For Option 2, the recovery of the WT has started during the overload period itself as the overloading considers the actual WT power output. However, in case of Option 1, the recovery is possible only after finishing the overloading period. Hence, higher FFC gains, therefore better frequency control, are possible with Option 2 compared to Option 1 for the same value of $\Delta P_{AOL\text{Max}}$.

B. Testing of WPP to deliver frequency control in the test power system

The calculated fast frequency controller gains ($K_D, K_I$) and the conclusions drawn from the overloading test (Fig. 5) for both options are verified by applying these gains to the frequency controller of WPP connected to the test power system shown Fig.1. The same frequency event is created, as explained in section IIIA, by applying a generation loss of 600 MW. The test is performed for a wind speed of 0.8 pu so as to verify the conclusions drawn from the overloading test. The frequency of the test power system with and without the participation of WPP in frequency control is shown in Fig. 9. It can be observed that overloading with Option 2 leads to a better performance compared to Option 1 due to higher optimal FFC gains at medium wind speeds. The dynamics of the WT for both options are given in Fig. 10.

![Figure 9](image-url)  
Frequency of the power system considering contribution from WPPs (Option 1 and Option 2) at wind speed - 0.8 pu

![Figure 10](image-url)  
Dynamics of the WT for Option 1 and 2 for the case in Fig. 9.
applying these gains to a WPP connected to a test power system.

C. Recommendation for participation of WPPs in power system frequency control

If the main objective of the WPP is to participate in temporary frequency control i.e. mainly inertial support, then the energy yield from the WTs can be increased to limit the ROCOF and frequency nadir by adapting appropriate gains of the FFC depending on the wind speed range. Thereafter, the primary control should take over the responsibility to stabilize system frequency be followed by secondary control. In that case, Option 2 is preferred over Option 1 due to its merits on higher temporary overloading with better WT dynamics. If the WPP are expected to participate in frequency control for an extended time period (for example more than 10s), then it may not possible to rely on overloading the WT. Therefore, reloading/down regulating the WT with a certain percentage is required to ensure stable operation of the power system and WPP. This will, however, result in loss of revenue for the WPP owner. Setting up new markets accommodating remuneration for the WPPs participating in frequency control may compensate this loss.

Another important conclusion from the results is that the temporary overloading of the WT and hence the gains of the FFC vary with wind speed. These gains can be adapted in advance based on the very short term average wind speed forecast to improve the temporary overloading of the WT without compromising system stability. One optimal gain can be chosen for each wind speed range, thereby limiting the gains to three or four values for the possible operating range of the wind turbine. To compensate for the inherent forecast errors, the gains could be set conservatively corresponding to the lower part of the considered range, i.e. corresponding to 0.5 pu wind speed for the lower medium average wind speed range (0.5-0.7 pu), for example.

V. Conclusions

In this paper an improved fast frequency controller for WPP is presented. This controller generates an additional temporary overloading power reference to the WT based on the frequency deviation and rate of change of frequency. Two different control options have been proposed and the dynamics of the WT have been analyzed at different wind speeds. It has been observed that the performance can be improved in case the frequency initiated power reference is based on the actual power output (Option 2) instead of the constant pre-overloading power output of the WT (Option 1). Moreover, the gains of the fast frequency controller have been optimized over the whole wind speed range considering the limitations and dynamics of the WT. This way the response is improved while stability is still ensured. These gains can e.g. be adapted in advance based on the very short term average wind speed forecast to improve the frequency response of the WT over the whole wind speed range.

References


