A Robust Control Approach for Primary Frequency Regulation through Variable Speed Wind Turbines

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Keywords: frequency control, \( \text{H}_\infty \) control, linear matrix inequalities, wind power generation, variable speed wind turbines

The increasing penetration of wind power generation in power systems will require, in the near future, a more active role of wind turbines (WTs) in frequency regulation process during grid disturbances. The inertia emulation by wind turbines for primary control or Inertial Control (IC) is one of the classical approaches. Here, the utilization of a Proportional-Differential (PD) controller to emulate the behavior of synchronous machine inertial response is proposed. Due to the injection of a different amount of power than the optimal one, the WTs operate for few seconds out of their optimal speed and a slower Proportional-Integral (PI) regulator gives a second reference to the WT in order to recover the optimal speed operation. Another successful approach is the Modified Inertial Control (MIC) where a loop including a speed droop characteristic and a reset filter replaces the PD loop of the IC approach, making the generator to change its kinetic energy faster and in more efficient way.

The present paper proposes a robust control strategy for robust performance. This is realized by an \( \text{H}_\infty \) Linear Matrix Inequality (\( \text{H}_\infty \) LMI) controller that replaces completely the existing control loops in the classical approaches. The \( \text{H}_\infty \) LMI controller optimizes the trade-off between frequency deviation smoothing and WT speed deviation after the disturbance improving the closed-loop performance.

In order to demonstrate the effectiveness of the proposed scheme, several simulations were performed in a multi-machine test system using Matlab/Simulink.

In Fig. 1, the \( \text{H}_\infty \) LMI controller has a considerable better behavior compared to the base cases, after a load step disturbance. In case of the Modified Inertial Control without coordination (MIC-NC), a good overall profile is achieved although a considerable difference can be noticed in the first negative pick (compared to the proposed scheme). In case of the Modified Inertial Control with coordination (MIC-WC), the first negative pick is slightly improved, although the smoothing takes much more time to reach a steady state condition.

In order to demonstrate the robust performance of the proposed control scheme, first, a variation of the system inertia constant \( H \) and second, a variation of the WT inertia constant \( H_t \), both in the range of \([-10\%, +10\%]\) were considered.

In Fig. 2 the \( \text{H}_\infty \) LMI controller robustly improves the system performance in comparison of the MIC-WC. Furthermore, in the presence of WT inertia constant \( H_t \) variation, the \( \text{H}_\infty \) LMI controller has a much better performance compared to the IC controller case, as shown in Fig. 3.

Results show a considerable improvement in frequency deviation smoothing, compared with the two traditional approaches. A desirable robust performance was also obtained with the proposed scheme after variations in the system parameters.
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This paper presents a robust control approach to enhance the participation of Variable Speed Wind Turbines (VSWTs) in the primary frequency regulation during network disturbances. The proposed control system utilizes an $H_\infty$ Linear Matrix Inequality (H∞ LMI) based scheme to improve the closed-loop performance. In order to demonstrate the effectiveness of the proposed control scheme, it is compared with two classical control systems: the Inertial Control (IC) and the Modified Inertial Control (MIC). Several simulations on a multi-machine test system were performed in Matlab/Simulink environment. The H∞ LMI controller optimizes the trade-off between frequency deviation smoothing and wind turbine (WT) speed deviation after the disturbance. Results show a considerable improvement in frequency deviation smoothing, optimal speed recovery and power injection, during a sudden variation in the system load, compared with the two traditional approaches. A desirable robust performance was also obtained with the proposed scheme after variations in the system parameters.

Keywords: frequency control, $H_\infty$ control, linear matrix inequalities, wind power generation, variable speed wind turbines

1. Introduction

The rapidly increasing penetration of wind power generation in power systems, as seen in European countries and USA, will require, in the near future, a more active role of wind turbines (WTs) in transient stability and frequency regulation process during grid disturbances (11–17). Although few years ago, the fixed type WTs had a considerable part of the market in Europe the variable speed wind turbine (VSWT) is nowadays the dominant type in the market (12).

Recently, many attempts have been made to propose an effective control system to regulate the power injected by wind turbines for primary frequency regulation during grid disturbances. The inertial emulation by wind turbines for primary control, also known as Inertial Control (IC), is one of the classical and very successful approaches (18–22). Here, the utilization of a Proportional-Differential (PD) controller to emulate the behavior of synchronous machine inertial response, which is possible by making VSWTs to increase or decrease partially its kinetic energy (22), is proposed. In this scheme, a slower Proportional-Integral (PI) control loop is also added in order to recover the rotational optimal speed after few seconds. Promising results are obtained with this scheme; although a poor speed recovery and frequency deviation smoothing are achieved.

In Refs. (9) and (10), an interesting analysis for Doubly Fed Induction Generator (DFIG) wind turbines (WTs) can be found. Another interesting study can be also seen in Ref. (11), where the capability of WTs to deliver their kinetic energy to support a hydro dominant network is addressed. A useful approach applying intelligent technique can also be found in Ref. (12).

Another successful approach is addressed in Ref. (7); a generator speed droop characteristic is included together with a reset filter. A similar approach can be found in Ref. (13). In Ref. (7), the possibility of coordination between WTs and synchronous unit is demonstrated. The loop including the reset filter and the inverse of droop characteristic constant replaces the PD loop of IC approach, making the generator to change its kinetic energy faster and in more efficient way in order to inject more or less power to support the network during a disturbance. For the sake of simplicity, this approach that modifies the PD loop in the IC controller, is named hereafter Modified Inertial Control (MIC), and is compared in this paper with the proposed control scheme.

Despite the promising results, most of these proposed methods deal with classical control approach, combining PD controllers or reset filter with proportional gains, for frequency control, with slower PI controllers for optimal speed recovery.

The present paper proposes a robust control strategy for robust performance. This is realized by an $H_\infty$ Linear Matrix Inequality (H∞ LMI) controller that replaces completely the existing control loops in the classical approaches.

In order to demonstrate the effectiveness of the proposed scheme, several simulations were performed using a simplified VSWT model.
A single area multi-machine system has been considered as test case. A sudden increase in the system load was considered as disturbance. The frequency oscillations, the speed variation in the wind turbine, the power injected to the system by the wind turbines and the mechanical power of synchronous machines are analyzed. The proposed robust control performance is compared with the cases of Inertial Control, presented in Refs. (4) and (7), and the Modified Inertia Control (MIC), presented in Ref. (7). Results show a considerable improvement in frequency regulation, optimal speed recovery and power injection, compared with the mentioned classical control approaches. Finally, the robustness of the proposed scheme was compared with the above classical approaches in the presence of system parameter variations. As expected, a desirable robust performance is obtained with the proposed scheme.

2. Power System Modeling

2.1 Synchronous Generator The basic configuration of synchronous generator units, including governor, turbine and rotating masses is indicated in Fig. 1.

Where; \( P_L \) is the load, \( P_m \) is the synchronous generator mechanical power, \( P_{NC} \) is the power from nonconventional (NC) generation, \( P_g \) is the governor power set up, \( P_c \) is the secondary control signal, \( \Delta f \) is the frequency deviation, \( H \) is the system equivalent inertia constant and \( D \) is the system equivalent damping coefficient.

This configuration, adopted from Ref. (14), includes the essential turbine power and rate limiters, and governor dead band. Figure 2 shows the simplified model of the governor and turbine, including the above mentioned limiters. Here, \( T_g \) and \( T_t \) are the governor and turbine time constants, respectively, and \( R \) is the speed droop constant.

2.2 Variable Speed Wind Turbines Two types of variable speed wind turbines (VSWTs) are considered in this paper. The basic schemes of the DFIG and the Full Power Converter (FPC) wind turbines are shown in Figs. 3 and 4, respectively.

In Fig. 3, the active power \( P_e \) is controlled by modifying \( q \)-axis component of the rotor voltage \( V_{qr} \), by controlling the Rotor Side Converter (RSC). On the other hand, in Fig. 4, the active power \( P_e \) is controlled by modifying \( q \)-axis component of the stator voltage \( V_{qs} \), by controlling the Stator Side Converter (SSC). In these figures, GSC stands for the Grid Side Converter, \( P_w \) is the power absorbed from the wind, \( \omega \) is the WT rotational speed, \( V_{dr} \) and \( V_{ds} \) are the rotor and stator \( d \)-axis voltage signals, respectively.

A simplified VSWT model, adapted from Ref. (6), is considered, as shown in Fig. 5. Here, the active power is controlled by changing through the control signal \( \Delta v_q \) the \( q \)-component \( v_q \) of rotor voltage in case of DFIG type and stator voltage in case of FPC type. In this figure, \( H_t \) is the WT inertia constant, \( T_e \) and \( T_m \) are the WT electrical and mechanical torques, respectively; \( \Delta \omega \) is the WT rotational speed deviation, \( \omega_{opt} \) and \( \omega \) are the WT optimal and actual rotational speeds, respectively.

As mentioned in Ref. (6), for \( R_r \approx R_s \) and \( X_{lr} \approx X_{ls} \) both types of WTs have similar behavior and only one model can
be considered to analyze the proposed control scheme. Similar assumption was made in Ref. (7). Here, \( X_{lr} \) and \( X_{ls} \) stand for rotor and stator reactances, respectively; and \( R_r \) and \( R_s \) for rotor and stator resistances, respectively.

The aggregated power output of the wind farm will be hereafter indicated as \( P_{NC} \) in this work.

Table 1 shows the detailed expressions of the main parameters \( X_2, X_3 \) and \( T_1 \) utilized for the simplified model of Fig. 5. The numerical values of the parameters of the VSWTs, utilized for the calculation of Eqs. (1)–(3), are indicated in Table 3.

Here

\[
L_0 = \left[ L_{rr} + \frac{L_m^2}{L_{ss}} \right] \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 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\ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldOTS
between the frequency deviation smoothing and the rotational speed deviation, during grid disturbances.

4.1 Test Case In order to demonstrate the effectiveness of the proposed scheme a multi-machine test system is considered as case study. The configuration of the power network model, adapted from Ref. (14), is shown in Fig. 8.

In this diagram, the generation company Genco 1 is an aggregated model of two synchronous generators, each of them with a rated power of 400 MW. The generator company Genco 2 is an aggregated model of two synchronous generators, each of them with a rated capacity of 500 MW. The NC generation, consists of 200 units of 2 MW rated VSWTs. These machines are operating at the power indicated in Table 3. Here, Xm stands for magnetizing reactance, and the other terms were already defined in this paper (Section 2.2).

4.2 $H_\infty$ LMI Controller A linearized scheme of the test system, indicated in Fig. 9, is implemented in order to apply the proposed $H_\infty$ LMI control technique.

Table 3. Machine parameters and operating points

<table>
<thead>
<tr>
<th>Synchronous units</th>
<th>Genco 1 (MW)</th>
<th>Genco 2 (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operat. point</td>
<td>570</td>
<td>430</td>
</tr>
<tr>
<td>R (Hz/PU)</td>
<td>2.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Tc (s)</td>
<td>0.36</td>
<td>0.42</td>
</tr>
<tr>
<td>Te (s)</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>D (pu/Hz)</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td>2H (pu/s)</td>
<td>0.1667</td>
<td></td>
</tr>
<tr>
<td>Gov. dead band (%)</td>
<td>0.06</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VSWT</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operat. point</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Rot. speed (pu)</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td>Rr (pu)</td>
<td>0.00552</td>
<td></td>
</tr>
<tr>
<td>Rs (pu)</td>
<td>0.00491</td>
<td></td>
</tr>
<tr>
<td>Xr (pu)</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Xs (pu)</td>
<td>0.69273</td>
<td></td>
</tr>
<tr>
<td>Xm (pu)</td>
<td>3.96545</td>
<td></td>
</tr>
<tr>
<td>Ht (s)</td>
<td>4.5</td>
<td></td>
</tr>
</tbody>
</table>

The basic configuration of the close-loop system utilized for the design of $H_\infty$ LMI controller is indicated in Fig. 10. Here, the disturbance inputs “w”, the controlled outputs “z”, the measured signals “y”, and the control input “u”, are indicated. The weights $\eta_i$ utilized for the tuning of close-loop performance are also indicated. The three weights are selected as 1.5, 2.1 and 1, respectively. The measurement system is included in the $H_\infty$ LMI controller block.

$H_\infty$ optimal control is a frequency-domain optimization and synthesis theory, useful for the plants that face problems of variability and uncertainty. Systems that can tolerate plant variability and uncertainty are called robust. The $H_\infty$ optimizes the performance and robustness of control systems (15). The $H_\infty$ is particularly useful for conflicting design objectives, as in the case of the present paper, where frequency control and WT rotational speed variation conflicts each other.

In many cases the classical controller design techniques can lead to a perfectly satisfactory solution and more powerful tools are not necessary. Problems arise when the plant dynamics are complex and poorly modeled or when the performance specifications are conflicting, as in the case of the problem at hand in this paper.

In this work, an $H_\infty$ LMI approach is utilized. Three factors make LMI techniques appealing (16):

1. A variety of design specifications and constraints can be expressed as LMI.
2. Once formulated in terms of LMI, a problem can be solved exactly by efficient convex optimization algorithms.
3. While most problems with multiple constraints or objectives lack analytical solutions in terms of matrix equations, they often remain tractable in the LMI framework.

The main objective of an $H_\infty$ LMI control system is the design of a control law “u” based on the measured signals vector “y” such that the effects of the disturbances “w” on
the controlled outputs “z”, expressed by the infinity norm of its transfer function does not exceed a given value γ defined as the guaranteed robust performance (16)(17).

An optimal H∞ can be achieved by minimizing the guaranteed robust performance index γ. In this work, this is done using the Robust Control Toolbox of Matlab, which incorporates the LMI Control Toolbox (16). Using this tool, the controller K(s), indicated as “H∞ LMI” in Fig. 10, is obtained with the robust performance index γ*, where γ − γ* < ε, and ε is a very small positive number.

In order to get the controller K(s), the state space representation of the system G(s) is needed. This can be written as:

\[
\begin{align*}
\dot{x} &= Ax + B_1 u + B_2 y \\
y &= C_1 x + D_{11} u + D_{12} y \\
z &= C_2 x + D_{21} u + D_{22} y
\end{align*}
\]

where:  \( \dot{x} \) is the derivative of the state space vector:

\[
x = \begin{bmatrix}
\Delta f \\
\Delta p_{m1} \\
\Delta p_{m2} \\
\Delta p_{q1} \\
\Delta i_d \\
\Delta \omega \\
\Delta f'
\end{bmatrix}
\]

Each term of the state space vector was already defined in this work. The coefficients of Eq. (4) can be expressed as follows:

\[
A = \begin{bmatrix}
\frac{D}{2H} & \frac{1}{2H} & \frac{1}{2H} & 0 & 0 & \frac{X_1}{2H} & 1 & 0 \\
0 & -\frac{1}{T_1} & 0 & \frac{1}{T_1} & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{1}{T_2} & 0 & \frac{1}{T_2} & 0 & 0 & 0 \\
-\frac{1}{T_1} R_1 & 0 & 0 & -\frac{1}{T_1} & 0 & 0 & 0 & 0 \\
-\frac{1}{T_2} R_2 & 0 & 0 & 0 & -\frac{1}{T_2} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{1}{T_1} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{X_3}{2H} & 0 & 0 \\
-\frac{D}{2H} & \frac{1}{2H} & \frac{1}{2H} & 0 & 0 & \frac{X_3}{2H} & 1 & \frac{1}{T_e}
\end{bmatrix}
\]

\[
B_1 = \begin{bmatrix}
\frac{1}{2H} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
-\frac{1}{2H} & 0 & 0
\end{bmatrix}
\]

\[
B_2 = \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
x_2 \\
\frac{T_1}{T_1} \\
0 \\
0
\end{bmatrix}
\]

\[
C_1 = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & \eta_1 \\
0 & 0 & 0 & 0 & 0 & -\eta_2 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
C_2 = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & -1
\end{bmatrix}
\]

\[
D_{11} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
D_{12} = \begin{bmatrix}
0 & 0 & \eta_1 \\
0 & 0 & 0
\end{bmatrix}
\]

\[
D_{21} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
D_{22} = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

The state space model of the obtained robust H∞ LMI controller K(s) can be written as follows:

\[
\begin{align*}
x_k &= A_k x_k + B_k y \\
u &= C_k x_k + D_k y
\end{align*}
\]

where the numerical values of the coefficients, achieved by the command “hinfn” of Matlab, can be expressed as:

\[
A_k = \begin{bmatrix}
-30.6 & 67.3 & -8.2 & 5.5 & -20.0 & 15.2 & 41.0 \\
79.3 & -334.5 & 59.1 & -8.7 & 96.4 & -12.4 & -10.7 \\
66.6 & -248.8 & -400.8 & -52.3 & 365.7 & 358.8 & -218.0 \\
7.6 & -36.4 & -90.9 & -1398.9 & -23.7 & 150.7 & 3.6 \\
47.1 & -123.7 & 542.3 & -18.2 & -637.7 & -386.2 & -212.9 \\
41.8 & 98.1 & 619.9 & 229.7 & -561.7 & -606.9 & -186.8 \\
469.7 & -1488.7 & 165.3 & -24.8 & -87.0 & 28.2 & -1408.8
\end{bmatrix}
\]

\[
B_k = \begin{bmatrix}
15.2 & -7.6 \\
-50.2 & 12.1 \\
-42.5 & 7.4 \\
-3.3 & 1.2 \\
-35.7 & -1.3 \\
-13.4 & 13.1 \\
-301.3 & 51.8
\end{bmatrix}
\]

\[
C_k = \begin{bmatrix}
-0.0004 & -0.0466 & -0.0008 & 0.0006 & -0.0204 & 0.020 & -0.0618
\end{bmatrix}
\]

\[
D_k = \begin{bmatrix}
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}
\]

The order of the controller K(s) is normally equal to the size of the system G(s) (8th order in this work). However, one order was reduced using standard model reduction in Matlab, and a 7th order controller is presented here. The value of the robust performance index is equal to γ* = 4.0397.
5. Simulation Results

In this section the results of the simulations comparing the proposed control scheme ($H\infty$ LMI) with two classical cases are presented. The case without controller (WC) is also included. Two cases will be considered for the MIC: with and without coordination with two synchronous units of Genco 1. For the sake of simplicity, these two cases are named in this paper as (MIC-NC) and (MIC-WC), respectively.

A step increase of 0.05 pu in the load, in the system base of 1000 MW, is applied to the network indicated in Fig. 9 and the results are analyzed in the following sections. It is shown that the control action will be completed after 30 seconds following the fault. In order to show the differences among each controller a span of approximately 10 seconds for most of the cases was considered. In case of rotational speed a span of 30 seconds was considered.

5.1 Frequency Deviation

The frequency deviation curves following mentioned disturbance scenarios are indicated in Fig. 11.

The $H\infty$ LMI controller has a considerably better behavior compared to the base cases. It can be noticed that in case of the MIC-NC, a good overall profile is achieved although a considerable difference can be observed in the first negative pick (compared to the proposed scheme). In the case of the MIC-WC, the first negative pick is slightly improved, although the smoothing takes much more time to reach a steady state condition. The response of the IC, for the first pick smoothing, is also good but is much delayed compared to the other controllers. The better performance achieved here is due to the ability of the $H\infty$ LMI controller of optimizing the conflicting objectives between frequency smoothing and rotational speed variation.

5.2 Rotational Speed

In Fig. 12, the $H\infty$ LMI controller recovers the optimal speed faster than the other traditional controllers. Here, the IC has similar behavior.

The speed deviation is slightly bigger in case of $H\infty$ LMI controller as compared with the cases of MIC-NC and MIC-WC. This is due to more active power injection by the NC generators in order to reach an optimal performance for the frequency regulation. Despite the bigger speed deviation, the $H\infty$ LMI controller recovers the speed faster due to the optimized design approach.

5.3 Injected Power

The injected power for the base cases and the proposed control are compared in Fig. 13. The $H\infty$ LMI controller injects more power than the MIC-NC and MIC-WC cases but much less than the IC case. This is because the $H\infty$ LMI controller was designed to optimally smooth the frequency oscillation and restore the normal operating speed.

The power injection is important in order to reduce the mechanical stress in the gearbox during this transient operation. It should be a compromise between frequency regulation and injected power. In case of $H\infty$ LMI controller this can be adjusted easily by changing the values of the constant weights.
shown in Fig. 10.

5.4 Mechanical Power In Fig. 14 and Fig. 15 the required mechanical power by two aggregated synchronous machines are indicated.

In both cases, the H∞ LMI approach shows a smoothed shape compared with the classical control types. The curve shapes are the result of a more optimized power injection and synchronous unit participation in the control process. The difference is especially clear for the case of MIC-WC. Here the coordination signal gives a special role to the synchronous units of Genco 1 to control the frequency, compared to the synchronous units of Genco 2. The curves for MIC-WC and MIC-NC cases, shown in Fig. 14 and Fig. 15, show a clear difference in the mechanical power injection for two MIC cases.

6. Robust Performance Evaluation

In order to demonstrate the robust performance of the proposed control scheme two cases were considered: First, a variation of the system inertia constant H and second, a variation of the WT inertia constant Ht, both in the range of [−10%, +10%]. Here, a span of only 2.5 s was considered, in the first case, and 5 s, in the second case, in order to clarify the differences between the achieved robust performances.

6.1 Variation of System Inertia Constant H In Fig. 16 the performance of the proposed robust control and the two classical approaches are compared for the variation of the system inertia H. Considering that the MIC, for both cases, had similar behavior, only the case of MIC-WC is shown.

As can be seen, the H∞ LMI controller robustly improves the system performance in comparison of the MIC-WC. The variation of the IC performance is also very small, although different behavior for this case is found for other system parameter variation, as explained in Section 6.2. Comparing the first and second negative picks for −10%, 0%, and +10% variations in H, almost no variation is noticed in case of H∞ LMI controller. In case of MIC-WC, the variations in these picks are quite significant.

6.2 Variation of WT Inertia Constant Ht In the presence of WT inertia constant Ht variation, the H∞ LMI controller has a much better performance compared to the IC controller case, as shown in Fig. 17.

In this figure, only the IC performance is shown in order to emphasize the difference in robustness of both controllers. In the case of the MIC approach a good performance is also found for WT inertia variation.

Comparing the three first picks for −10%, 0%, and +10% variation of Ht, the wide range of variation in the IC curves is quite evident.

7. Conclusion

In this paper, a robust control approach based on an H∞ LMI control technique is presented to improve the participation of Variable Speed Wind Turbines (VSWTs) in the primary frequency regulation during grid disturbances. First, an overview of the current classical approaches and the proposed scheme are given and then a single area system is considered in order to perform a comparison with two classical approaches: Inertial control (IC) and Modified Inertial Control (MIC). The main contribution of this paper is that the proposed control approach replaces entirely the frequency regulation and the speed regulation loops (in the classical approaches) providing a single control loop with a robust performance behavior and optimized trade-off between frequency regulation and speed deviation, for a given network disturbance.

It is shown through simulations that the proposed scheme improves the frequency response after a sudden perturbation in the network. Moreover, the power injection and the speed deviation are also optimized in the presence of a network disturbance.

A comparison analysis showing the robustness of the proposed scheme is also realized, comparing its performance with that of the classical controllers in presence of system and WT inertia constant variations. Here, the proposed scheme showed a strong robustness compared to the classical approaches.

It is noteworthy that the proposed approach can be adapted, in further works, in order to be utilized also as a combined primary and secondary controller for a multi-area system and for turbulent wind speeds.

(Manuscript received March 23, 2010, revised July 3, 2010)

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