Robust Power Oscillation Damping by DFIG Wind Turbine using Mixed $H_2/H_\infty$ Control

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Abstract —The robust power oscillation damper (POD) design for doubly fed inducting generator (DFIG) based on a mixed $H_2/H_\infty$ control method is proposed in this paper. A practical 2nd-order lead/lag compensator with local input signal is chosen as the POD structure. The POD is additionally installed with the voltage control loop of DFIG so that the modulation of reactive power output can be performed to damp out power oscillations. To acquire both damping performance and robustness, the optimization of POD parameters is formulated based on a mixed $H_2/H_\infty$ control. The backtracking search algorithm is automatically employed to solve the optimization problem. Simulation study indicates that the damping effect and robustness of the proposed robust POD are higher than those of the conventional POD against various system faults, heavy power flow levels, and wind patterns.

Keywords — Power Oscillation Damping, Doubly Fed Induction Generator Wind Turbine, Mixed $H_2/H_\infty$ Control, Backtracking Search Optimization Algorithm.

I. INTRODUCTION

The interconnection among power systems not merely enhances the system reliability, but also augments the system economics. However, the longitudinal structure of system interconnection may suffer from the power oscillation with poor damping [1]. In the scenario of heavy power flow and severe faults, the undamped power oscillation may invoke the loss of system synchronism and the wide area blackouts. To handle the power oscillation, the power system stabilizer (PSS) has been successfully used. Nevertheless, the control of PSS may cause an adverse impact on the quality of voltage control of automatic voltage regulator (AVR) [2].

Currently, the integration of wind power generation into power systems highly increases. With the large participation of wind generators, the contribution of wind generators for stabilization of power oscillation is significantly anticipated. For instance, in the new Spanish grid code for wind power, the power oscillation damping function is included [3]. To realize this function, the doubly fed induction generator (DFIG) wind turbine has been paid attentions since the active and reactive power outputs of DFIG can be controlled. By equipping the power oscillation damper (POD), the power output can be modulated to eliminate the power oscillation [4]. Generally, the POD structure is the same as the PSS, which is the second-order lead/lag compensator. To achieve the satisfactory stabilizing effect of POD, an optimal tuning technique of POD parameters is required.

In the past researches, the parameters tuning methods based on bacterial foraging [5], differential evolution [6] and particle swarm optimization [7] have been proposed. The PODs in these works may fail to handle the power oscillation in the face of system uncertainties such as various power flow levels, severe short circuits, and network structures etc. The new POD tuning technique which considers both damping performance and robustness, is essentially required.

In this paper, the robust control design of POD using a mixed $H_2/H_\infty$ control method is presented. The optimization of POD parameters is carried out so that both damping performance and robust stability margin against system uncertainties are acquired. The backtracking search algorithm is applied to solve the optimization problem. Simulation study confirms the superior damping effect of the proposed robust POD over the conventional POD.

II. STUDY SYSTEM AND MODELING

A. Study System

Fig. 1 illustrates the DFIG wind generator and synchronous generator which are connected to the infinite bus. The synchronous generator (G) is presented by the six-order Park’s model. The DFIG wind turbine which is connected at bus 4, is used to supply electric power to the main grid. The electromechanical oscillation with poor damping causes the stability problem in this system.

B. DFIG and POD Modeling

Fig. 2 delineates the structure of DFIG wind turbine and control system [8], where $v_a$, $v_b$, $v_c$ are voltages of phases $a$, $b$, $c$, respectively, $i_{dr}$, $i_{dq}$, $i_{pr}$ are reference currents of phases $a$, $b$, $c$, respectively, $v_{dr}$ and $v_{dq}$ are direct ($d$) and quadrature ($q$) axis voltages of the rotor side converter, respectively, $i_{dr}$ and $i_{dq}$ are reference $d$ and $q$ axis currents of the rotor side converter, respectively, $i_{dr}$ and $i_{dq}$ are $d$ and $q$ axis currents of the rotor side converter.
As mentioned in [4], the control by rotor side converter provides better damping effect than that by grid side converter. In this study, the POD is additionally equipped with the controller of rotor side converter. By vector control technique in the rotor side converter, the independent control of active and reactive power outputs can be acquired. The converter is modeled by an ideal current source. As depicted in Figs. 3 (a) and 3 (b), $i_{qr}$ and $i_{dr}$ are used for rotor speed control and voltage control, respectively. The active and reactive power outputs of DFIG can be expressed in terms of $i_{qr}$, and $i_{dr}$ as:

$$P = \frac{x_1}{x_1 + x_u} v_{qr}$$

$$Q = -\frac{x_u v_{dr}}{x_1 + x_u} - \frac{v^2}{x_u}$$

where $P$ and $Q$ are active and reactive power outputs, respectively, $\omega_m$ is a rotor speed of DFIG, $p$ is the power speed characteristic which roughly optimizes the wind energy capture, $x_1$ is a stator self-reactance, $x_u$ is a magnetizing reactance, $T_r$ is the time constant of power control, $v$ is a magnitude of DFIG terminal voltage, $v_0$ is the initial reference voltage, $v_{ref}$ is the actual reference voltage, $v_{sl}$ is input signal of POD, $v_{ref}^{POD}$ is an additional signal of POD, $K_s$ is the voltage controller gain, and $i_{dr}$, $i_{qr}$, $i_{dr}^{max}$, $i_{qr}^{max}$ are $d$ and $q$ axis minimum and maximum rotor currents, respectively. Here, reactive power output which can be controlled by $i_{dr}$, is used to damp out the power oscillation by the stabilizing signal $v_{POD}$ from POD.

The POD structure which is a 2nd-order lead-lag compensator, is delineated in Fig.4. The POD consists of a stabilizer gain $K_{stab}$, a washout filter with time constant $T_1$, and two phase compensator blocks with time constants $T_2$, $T_3$, and $T_4$. The washout signal guarantees that the POD output is zero in steady state. An anti-windup limiter is equipped at the output of POD so that the output signal $v_{POD}^{ref}$ is between the minimum value ($v_{min}^{POD}$) and the maximum value ($v_{max}^{POD}$). To produce the satisfactory damping and the phase lead compensator, $K_{stab}$ and $T_1$, $T_2$, $T_3$ and $T_4$ are optimally tuned. Here, the proposed design is used to optimize five parameters of POD.
Both objectives mentioned above can be obtained [9]. Besides, by placing the dominant oscillation modes in the stability region with the specified damping ratio \( \zeta_{\text{spec}} \) and specified real part \( \sigma_{\text{spec}} \) as shown in Fig. 6, the desired stability region can be guaranteed.

Accordingly, the optimization problem can be formulated by

\[
\begin{align*}
\text{Minimize} & \quad \alpha \| T_{z_{\text{z}}} \|_\infty^2 + \beta \| T_{z_2w_2} \|_2^2 \\
\text{Subject to} & \quad \zeta \geq \zeta_{\text{spec}} \\
& \quad \sigma \leq \sigma_{\text{spec}} \\
& \quad \zeta_{\text{spec}} = 10\% , \sigma_{\text{spec}} = -0.5 , \alpha = 0.1 , \beta = 1 \\
& \quad 0.01 \leq K_{\text{stab}} \leq 5 \\
& \quad 0.01 \leq T_1, T_2, T_3, T_4 \leq 20
\end{align*}
\]

B. Backtracking Search Algorithm

The backtracking search algorithm (BSA) is a new evolutionary algorithm for solving real-valued numerical optimization problems. The BSA’s unique mechanism for generating a trial individual enables it to solve numerical optimization problems successfully and rapidly. The BSA uses three basic genetic operators such as selection, mutation and crossover to generate trial individuals [10]. BSA has a random mutation strategy that uses only one direction individual for each target individual, in contrast with many genetic algorithms. Fig. 7 shows the flow chart of BSA which can be described step by step as follows:

- **Step 1**: this is the initial step that generates the initial and old population, and it is described by formula bellow:

\[
P_{\text{initial}} = \text{rnd}(\text{up} - \text{low}) + \text{low} \\
P_{\text{old}} = \text{rnd}(\text{up} - \text{low}) + \text{low}
\]

where \( P_{\text{initial}} \) and \( P_{\text{old}} \) are the initial and old population respectively. \( \text{Up} \) and \( \text{low} \) are the limit range of dimensions of population, and \( \text{rnd} \) is the uniformly distributed pseudorandom numbers.

- **Step 2**: The objective function of initial population (Obj-fun \( P_{\text{initial}} \)) is calculated.

- **Step 3**: The new populations which are called as trail population, are generated by using mixed method between mutation and crossover described by

\[
P_{\text{trail}} = P + (\text{map}.F)(P_{\text{old}} - P)
\]

where \( P_{\text{trail}} \) is the trail population, and \( P \) is population that obtains from selection randomly between old and initial population. map is a binary integer-valued matrix calculated for crossover term [10]. \( F = 3 \times \text{rnd} \)
is the get-scale-factor, and rndn is the normally distributed pseudorandom numbers.

- Step 4: the objective function of trial population (Obj-fun (P\text{trial})) is calculated.
- Step 5: this is the selection step. The objective function between initial and trial population are compared.
- Step 6: this is negative comment step “No”. The fitness population (fitness P) is equal to the initial population (P\text{initial}), and then it continues to step 8.
- Step 7: this is the positive comment step “Yes”. The fitness population (fitness P) is equal to the trial population (P\text{trial}), and then it will continue to step 8.
- Step 8: Check the maximum iteration. If “Yes”, the process of minimization will stop and continue to step “End”, if No, it will continue to step 9.
- Step 9: In this step, the fitness population will update to old population, and the process of minimization will do again.

IV. SIMULATION RESULTS

The POD design is developed by MATLAB, Simulink and PSAT tool box [8]. The BSA parameters are set as follows; population = 25, maximum iteration = 100. The POD is designed under case 1 as shown in TABLE I. After the optimization, Fig. 8 demonstrates the convergence curve of

objective function of the proposed control method. The optimized parameters of POD which is referred to as RPOD are provided in TABLE II.

The stabilizing effect of RPOD is compared with the conventional POD (CPOD), which is designed by the pole replacement method. To obtain the same damping ratio as RPOD, the optimization problem of CPOD is given as follows:

\[
\text{Minimize} \left( |z - z_{\text{spec}}| + |\sigma - \sigma_{\text{spec}}| \right) \tag{7}
\]

Subject to

\[
|z| \geq z_{\text{spec}}
\]
\[
|\sigma| \leq \sigma_{\text{spec}}
\]
\[
0.01 \leq K_{\text{stab}} \leq 5
\]
\[
0.01 \leq T_1, T_2, T_3, T_4 \leq 20
\]
\[
z_{\text{spec}} = 10\%, \sigma_{\text{spec}} = -0.5
\]
The optimized parameters of CPOD are provided in TABLE II. The eigenvalue analysis results in case 1 are shown in TABLE III. Without POD, the damping ratio of the oscillation mode is very poor. On the other hand, the damping ratio of the oscillation mode is improved as expected by both CPOD and RPOD.

Next, nonlinear simulations of case studies 1 to 4 in TABLE I are carried out. Figs. 10 (a)-(d) show the power flow from bus 2 to bus 3 of cases 1-4, respectively. In cases 1 and 2, the DFIG without POD cannot damp out the power oscillation. On the contrary, both CPOD and RPOD are able to suppress the power oscillation. In cases 3 and 4, the CPOD completely loses damping effect and fail to stabilize the oscillation. On the other hand, the RPOD is very robust against various uncertainties. It is able to get rid of the oscillation robustly.

Fig. 11 shows the comparison of $\|T_{m2}\|_\infty$ between CPOD and RPOD when $P_{m2}$ is varied from 3.2 to 5.45pu. Note that $\|T_{m2}\|_\infty$ implies the robustness of POD against system uncertainties. Obviously, when the power flow increases, $\|T_{m2}\|_\infty$ in case of CPOD largely changes. The CPOD is very sensitive to the heavy power flow from bus 2 to infinite bus. This signifies that the damping effect of CPOD is deteriorated at the high level power flow. On the other hand, the change in $\|T_{m2}\|_\infty$ in case of RPOD is lesser. The RPOD is not much sensitive to the variation of the power flow. This shows the high robustness of RPOD.

### Table II. Optimal Parameters of PODs

<table>
<thead>
<tr>
<th>POD</th>
<th>$K$</th>
<th>$T_w$</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_3$</th>
<th>$T_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPOD</td>
<td>2.0154</td>
<td>10</td>
<td>3.2892</td>
<td>0.5765</td>
<td>1.2550</td>
<td>16.8830</td>
</tr>
<tr>
<td>CPOD</td>
<td>3.3543</td>
<td>10</td>
<td>0.2146</td>
<td>9.4152</td>
<td>11.7140</td>
<td>1.3701</td>
</tr>
</tbody>
</table>

### Table III. Eigenvalue Analysis Results

<table>
<thead>
<tr>
<th>Control device</th>
<th>Eigenvalue</th>
<th>Damping ratio (%)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No POD</td>
<td>-0.232 ± j7.62</td>
<td>3.04%</td>
<td>1.21</td>
</tr>
<tr>
<td>RPOD</td>
<td>-1.070 ± j7.42</td>
<td>14.25%</td>
<td>1.18</td>
</tr>
<tr>
<td>CPOD</td>
<td>-0.847 ± j6.90</td>
<td>12.19%</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Fig. 9. Wind speed patterns of (a) case 1, (b) case 2, (c) case 3, (d) case 4.

Fig. 10. Power flow from bus 2 to bus 3 of (a) case 1, (b) case 2, (c) case 3, (d) case 4.
V. CONCLUSION

This paper presents a new POD parameters tuning technique based on a mixed $H_2/H_\infty$ method. Since the POD structure is the 2nd-order lead/lag compensator with local input signal, it is easy to realize in real power system. The optimization of POD is conducted so that the desired system damping and robustness can be guaranteed. The POD parameters are automatically tuned by backtracking search algorithm. Eigenvalue analysis results and nonlinear simulation clearly confirm the superior robustness and damping performance of the proposed POD over the conventional POD under various power flow levels and severe faults.

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