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Robust Current Control of Doubly Fed Wind Turbine Generator under Unbalanced Grid Voltage Conditions

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Abstract— **This paper presents the design of a H ∞ current controller for doubly fed induction generators (DFIGs) in order to maintain stable operation under unbalanced voltage conditions. The H ∞ current controller has a multi-input and multi-output (MIMO) structure and is designed using the loop shaping method. Case studies have been carried out in order to verify the efficacy of the proposed H ∞ current controller for DFIGs. The case study results show that the proposed H ∞ current controller can realize different control objectives, i.e. stable stator current, stable stator active power and stable stator reactive power. It is also shown that the H ∞ current controller is less sensitive to the parameter perturbation.**

Index Terms-- **DFIG, H ∞ current controller, MIMO, unbalanced voltage conditions**

I. INTRODUCTION

Unbalanced voltage conditions in power systems are one of the frequent fault conditions during operations [1], [2]. Because the stator of doubly fed induction generators (DFIGs) is directly connected to the grid and the negative sequence impedance of DFIGs is usually small, the unbalanced voltage conditions will cause current unbalance, armature overheating, torque and power pulsation, etc. and will impact the secure and stable operation of DFIGs [2]-[4].

The control methods for DFIGs under unbalanced voltage conditions can be divided into two groups: (1) obtain the positive and negative sequence components of voltages and currents by positive and negative sequence separation, and implement closed loop current control using PI controllers in the positive and negative synchronous rotating frames [3]-[7]. Although the theory of such control methods is simple, the control system is complex and consists of a number of PI controllers. (2) replace PI controllers with more advanced controllers in order to realize better AC current pulsation following characteristics for rotor currents. Among the advanced controllers, the proportional resonant (PR) control or proportional integral resonant (PIR) controller is the most

commonly used one [8], [9]. However, the performance of the PR controller depends on the resonant point parameters and the parameters should be adjusted according to the machine speed change, therefore, the applications of such methods are limited.

In practice, the operating conditions of wind turbine generators (WTGs) is very complex and the existing methods have not considered the impact of machine parameter change and disturbance uncertainties on the performance of the complex control system. Since the H∞ control has successful applications when there are uncertainties of model parameters and disturbances, the robust control method is used to develop a control scheme for DFIGs under unbalanced voltages in order to handle the AC pulsation disturbances. The proposed robust current controller for DFIGs is developed by using the loop shaping method to efficiently suppress the AC pulsation under unbalanced voltage condition. The case study results show that the proposed robust current controller has better robustness and reliability compared to the PIR controller.

II. MATHEMATICAL MODEL OF DFIGS

In the synchronous rotating reference frame, with the rotor side voltage and current converted to the stator side, the equivalent circuit of DFIGs is shown in Figure 1.
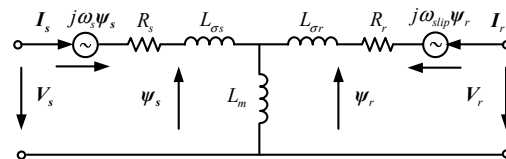

Figure 1 Equivalent circuit model of DFIG

The mathematical model of DFIGs is represented by (1) and (2). Since there is no neutral connection for the DFIG grid connection and hence no zero sequence loop, any vector of DFIGs can be decomposed into positive sequence and negative sequence components.

$$\begin{cases} \boldsymbol{\psi}_s = l_s \boldsymbol{I}_s + l_m \boldsymbol{I}_r \\ \boldsymbol{\psi}_r = l_m \boldsymbol{I}_s + l_r \boldsymbol{I}_r \end{cases} \quad (1)$$

$$\begin{cases} \boldsymbol{V}_s = r_s \boldsymbol{I}_s + \dfrac{1}{\omega_B} \dfrac{d\boldsymbol{\psi}_s}{dt} + j\omega_s \boldsymbol{\psi}_s \\ \boldsymbol{V}_r = r_r \boldsymbol{I}_r + \dfrac{1}{\omega_B} \dfrac{d\boldsymbol{\psi}_r}{dt} + j\omega_{slip} \boldsymbol{\psi}_r \end{cases} \quad (2)$$

$$\omega_{slip} = \omega_s - \omega_r \quad (3)$$

According to the symmetric component method, any vector can be decomposed into positive and negative components and projected to the positive and negative sequence synchronous rotating coordinate reference which is shown in Figure 2.
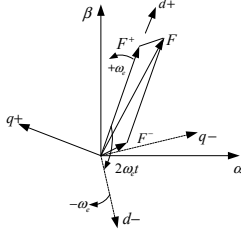

Figure 2 projections of vector F on positive and negative sequence synchronous rotating coordinate reference frames

Because the wind turbine generators (WTGs) and the grid connection circuits are usually three phase without neutral, there is no zero sequence loop. The DFIG model can be decomposed into positive and negative sequence components. In the decomposed model, the superscripts '+' and '-' denote the positive sequence and negative sequence rotating reference frame, and the subscripts '+' and '-' denotes the positive and negative sequence components. According to [13], the control commands of negative sequence current can be divided intro three categories:

1) To realize balanced rotor current in order to avoid unbalanced heating in the rotor windings.

$$\begin{cases} I_{rd-}^{-*} = 0 \\ I_{rq-}^{-*} = 0 \end{cases} \quad (4)$$

2) To realize stable stator active power output in ordert o ensure stable active power outout from wind power plants

$$\begin{cases} I_{rq-}^{-*} = \dfrac{V_{sq-}^-}{V_{sd+}^+} I_{rd+}^+ - \dfrac{V_{sd-}^-}{V_{sd+}^+} I_{rq+}^+ - \dfrac{2V_{sd-}^-}{\omega_s L_m} \\ I_{rd-}^{-*} = -\dfrac{2V_{sq-}^-}{\omega_s L_m} - \dfrac{V_{sd-}^-}{V_{sd+}^+} I_{rd+}^+ - \dfrac{V_{sq-}^-}{V_{sd+}^+} I_{rq+}^+ \end{cases} \quad (5)$$

3) To realize stable stator reactive power output

$$\begin{cases} I_{rd-}^{-*} = \dfrac{V_{sd-}^-}{V_{sd+}^+} I_{rd+}^+ + \dfrac{V_{sq-}^-}{V_{sd+}^+} I_{rq+}^+ \\ I_{rq-}^{-*} = \dfrac{V_{sq-}^-}{V_{sd+}^+} I_{rd+}^+ - \dfrac{V_{sd-}^-}{V_{sd+}^+} I_{rq+}^+ \end{cases} \quad (6)$$

III. DESIGN OF H∞ CURRENT CONTROLLER FOR DFIGS

A. Design of H∞ Controller using the Loop Shaping Method

The objective of the H∞ controller is to efficiently track the positive and negative sequence components of the machine rotor current and maintain the stability of the control system under certain types of disturbances.

According to the H∞ control formulation, (1) and (2) can be rewritten as (7) – (11).

$$G: \begin{cases} \dot{\boldsymbol{x}} = A\boldsymbol{x} + B_1 \boldsymbol{d} + B_2 \boldsymbol{u} \\ \boldsymbol{y} = C\boldsymbol{x} \end{cases} \quad (7)$$

$$\boldsymbol{x} = \begin{bmatrix} I_{sd} & I_{sq} & I_{rd} & I_{rq} \end{bmatrix}^T \quad (8)$$

$$\boldsymbol{d} = \begin{bmatrix} V_{sd} & V_{sq} \end{bmatrix}^T \quad (9)$$

$$\boldsymbol{u} = \begin{bmatrix} V_{rd} & V_{rq} \end{bmatrix}^T \quad (10)$$

$$\boldsymbol{y} = \begin{bmatrix} I_{rd} & I_{rq} \end{bmatrix}^T \quad (11)$$

where x is the state variable, d is the disturbance, u is the control variable, y is the measured value of the feedback.

Based on the above DFIG mathematical model, a multi-input and multi-output (MIMO) H∞ current controller has been designed using the loop shaping method and the diagram of the controller is shown in Figure 3. In Figure 3, G is the linearized model of the DFIG, Wp and Wu are error and control weight functions. P is the generalized control object, z_1 and z_2 are generalized outputs, K is the controller to be solved. All the signals in the figure are vectors and the transfer functions are matrices.
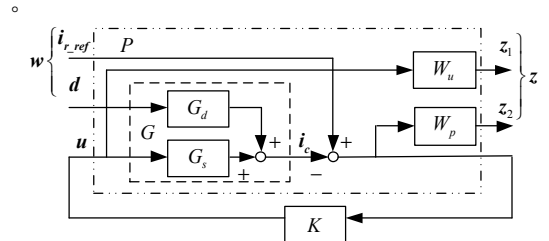

Figure 3. Diagram of DFIG H∞ current controller

B. Parameter designfor the H∞ controller

For the hybrid H∞ loop shaping issue, the design of the controller can be converted to find a stable controller K such that the closed loop transfer function of the generalized control object, P, can meet the requirement that the H∞ norm is minimized, i.e. by defining a proper peak value margin γ to ensure,

$$\left\| \begin{matrix} W_u S_i K & -W_u S_i K G_d \\ W_p S_o & -W_p S_o G_d \end{matrix} \right\|_\infty < \gamma \qquad (12)$$

where $S_i=(I+KG_s)^{-1}$ and $S_o=(I+G_sK)^{-1}$ are input and output sensitivity functions.

(12) shows that the performance of the system mainly depends on the shapge of $\|1/W_p\|_\infty$ and $\|1/W_u\|_\infty$. Because the order of the H∞ controller is the sum of the order of the control object and the weight function, in order to reduce the difficulty of using the H∞ controller, it is important to select a weight function which can meet the control requirements and is with a low order.

After the weight function is selected, the optimal or sub-optimal solution of the controller can be obtained by solving the Algebraic Riccati equations (the iterative calculation is required to obtain the solution). Because the per unit model is used, W_u is set to 1. In order to realize the control objective, a complex function weight function is defined,

$$W_p = \frac{s/M + \omega_1}{s + \omega_1 A} + \frac{k\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \qquad (13)$$

Where the first part is for the basic control performance, the second part is to determine the control performance at the specified resonant frequency. ω_1 (100Hz) is the low cross-over frequency, due to the second part of the weight function, the bandwidth of the controller is larger than the cross-over frequency. It is good to constraint the rotor mode by increasing the bandwidth of the current controller, however, it will reduce the damping ratio of the stator mode. When the bandwidth of the current loop is approaching the resonance frequency, the system sensitivity will drastically increase at the stator mode frequency and the system capability against disturbances decrease. Therefore, it is better to set the current control bandwidth between the cross-over frequency and the resonance (synchronous??) frequency and limit the gain of T below 10dB. In this paper, ω_n=100Hz, ξ=0.02, k=3.

C. Robust stability analysis

When there are uncertainties of system parameters, the robust stability of a system can be quantified by calculating the structural singular value μ,

$$\mu = \frac{1}{\min\{\bar{\delta}(\Delta) : \det(I - M\Delta) = 0\}} \qquad (4)$$

When μ is less than 1, the system is stable under all parameter perturbation. The smaller μ is, the better the system robustness is. According to the control bandwidth requirement explained in the previous section, a H∞ controller (K_Hinf) and a PIR controller have been designed and the singular value of the two controllers have been calculated which is shown in Figure. It is shown that the H∞ controller is less sensitive to the parameter perturbation than the PIR controller.
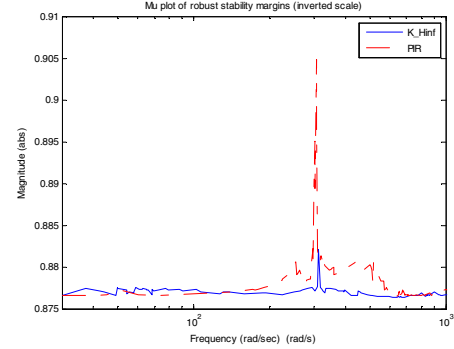

Figrue 4. Plot of structural (??) singular value μ

IV. CASE STUDIES

In order to verify the efficacy of the proposed H∞ controller, case studies have been carried out using MATLAB.

TABLE I. SIMULATION PROCESS DESCRIPTION

t(s)	5-5.2	5.2-5.3	5.3-5.4
Control objectives	Balanced Rotor current	Balanced Stator active power	Balanced Stator reactive power

TABLE II. DFIG PARAMETERS

Stator Resistance	0.00706*(1±2%) pu	Rotor Resistance	0.005*(1±2%) pu
Stator Inductance	3.6710*(1±2%) pu	Rotor Inductance	3.656*(1±2%) pu
Mutual inductance	3.5*(1±2%) pu	Rotor speed	1.2 pu

The case study results are shon in Figure 5. The subpots are stator three phase voltage, stator dq axis currents, rotor dq axis currents, and stator active and reactive power from the top to the bottom. During the time period of t=5~5.2 s, the stator dq axis current waveforms do not have AC pulsation and are balanced, during the time period of t=5.2~5.3 s, by injecting certain stator negative current, the stator active power is stable, during the time period of t=5.3~5.4 s, the reactive power is stable. The case study results show that the H∞ controller can efficiently control the positive and negative components of the rotor current and realize the control objectives.
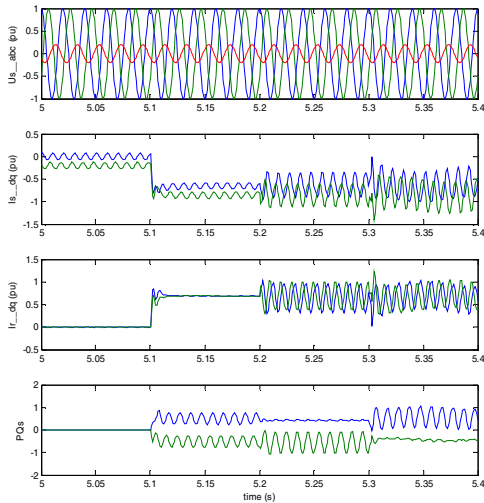
Figrue 5. Time domain simulation results

V. CONCLUSION

Under unbalanced voltage conditions, the rotor voltages and currents of DFIGs have negative sequence component. In order to keep stable operation of generators, it is essential to properly control the negative sequence component to realize different control objectives. An H∞ current controller for DFIGs is proposed in this paper and the efficacy of the proposed H∞ current controller has been verified by simulations.

The simulation results show that the proposed H∞ current controller has the following advantages.

1) The control system of DFIGs is simplified by replacing the conventional PI controller of the current control loop with the proposed H∞ current controller.

2) In the synchronous rotating frame, the proposed H∞ current controller can realized multi-objective control and has better performance.

3) The comparison of the structure singular values shows that the proposed H∞ current controller has better robustness than the conventional PI controller and is less sensitive to the external disturbances or internal machine parameters.

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