FLICKER MITIGATION BY INDIVIDUAL PITCH CONTROL OF FUZZY LOGIC VARIABLE SPEED WIND TURBINES WITH DFIG

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Abstract-Due to the wind speed variation, wind shear and tower shadow effects, grid connected wind turbines are the sources of power fluctuations which may produce flicker during continuous operation. This paper presents a model of an MW-level variable speed wind turbine with a doubly fed induction generator to investigate the flicker emission and mitigation issues. An individual pitch control (IPC) strategy is proposed to reduce the flicker emission at different wind speed conditions. The IPC scheme is proposed and the individual pitch controller is designed according to the generator active power and the azimuth angle of the wind turbine. The simulations are performed on the NREL (National Renewable Energy Laboratory) 1.5-MW upwind reference wind turbine model. Simulation results show that damping the generator active power by IPC with fuzzy logic controller is an effective means for flicker mitigation of variable speed wind turbines during continuous operation.

I.INTRODUCTION

During the last few decades, with the growing concerns about energy shortage and environmental pollution, great efforts have been taken around the world to implement renewable energy projects, especially wind power projects. With the increase of wind power penetration into the grid, the power quality becomes an important issue. One important aspect of power quality is flicker since it could become a limiting factor for integrating wind turbines into weak grids, and even into relatively strong grids if the wind power penetration levels are high. Flicker is defined as “an impression of unsteadiness of visual sensation induced by a light stimulus, whose luminance or spectral distribution fluctuates with time”. Flicker is induced by voltage fluctuations, which are caused by load flow changes in the grid. Grid-connected variable speed wind turbines are fluctuating power sources during continuous operation. The power fluctuations caused by wind speed variation, wind shear, tower shadow, yaw errors, etc., lead to the voltage fluctuations in the network, which may produce flicker. Apart from the wind power source conditions, the power system characteristics also have impact on flicker emission of grid-connected wind turbines, such as short-circuit capacity and grid impedance angle. The flicker emission with different types of wind turbines is quite different. Though variable-speed wind turbines have better performance with regard to the flicker emission than fixed-speed wind turbines, with the large increase of wind power penetration level, the flicker study on variable speed wind turbines becomes necessary and imperative. A number of solutions have been presented to mitigate the flicker emission of grid-connected wind turbines. The most commonly adopted technique is the reactive power compensation. However, the flicker mitigation technique shows its limits in some distribution networks where the grid impedance angle is low. When the wind speed is high and the grid impedance angle is $10^\circ$, the reactive power needed for flicker mitigation is 3.26 per unit. It is difficult for a grid-side converter (GSC) to generate this amount of reactive power, especially for the doubly fed induction generator (DFIG) system, of which the converter capacity is only around 0.3 per unit. The STATCOM which receives much attention is also adopted to reduce flicker emission. However, it is unlikely to be financially viable for distributed generation applications. Active power control by varying the dc-link voltage of the back-to-back converter is presented to attenuate the flicker emission. However, a big dc-link capacitor is required, and the lifetime of the capacitor will be shortened to store of the fluctuation power in the dc link. An open-loop pitch control is used in and to investigate the flicker emission in high wind speeds, however, the pitch actuation system (PAS) is not taken into account. Because the pitch rate and the time delay of the PAS make great contributions to the results of the flicker emission of variable-speed wind turbines, it is necessary to take these factors into consideration. In recent years, IPC which is a promising way for loads reduction has been proposed, from which it is notable that the IPC for structural load reduction has little impact on the electrical power. However in this paper, an IPC scheme is proposed for flicker mitigation.
of grid-connected wind turbines. The power oscillations are attenuated by individual pitch angle adjustment according to the generator active power feedback and the wind turbine azimuth angle in such a way that the voltage fluctuations are smoothed prominently, leading to the flicker mitigation.

The influence of the flicker emission on the structural load is also investigated. The FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code which is capable of simulating three-bladed wind turbines is used in the simulation.

II. INDIVIDUAL PITCH CONTROL

How can designers build wind turbines with longer lifetimes? Recent economic and technical developments such as the pressure to reduce the overall cost of electricity generated by wind turbines, the necessity to reduce O&M costs as well as increased emphasis on reliability and predictability of power production make it urgent to find a technical solution to that question. Load reduction is a key element of the solution. In addition, load reduction gains an increasing importance due to the trend towards larger wind turbines. Individual pitch control (IPC) plays a key role in compensating loads. So what is IPC? Any pitch control system allows control of the turbine speed and consequently the power output. It also acts as a brake, stopping the rotor by turning the blades. Moreover, pitch control, especially an IPC system, has a role in reducing fatigue loads on the turbine structures. Recently developed wind turbines are variable speed turbines capable of adapting to various wind conditions. This adaptation is realized via new generator concepts on the one hand, and a pitch control system on the other hand. Pitch control means the turning of rotor blades between 0° and 90°. When wind speeds are below rated power, typically below 12 m/s, the rotor blades are turned fully towards the wind which means that the pitch is positioned at 0°. At increasing wind speeds the pitch of the blades is controlled in order to limit the power output of the turbine to its nominal value. When wind speeds reach a predefined threshold, typically 28 m/s, the turbine stops power production by turning the blades to a 90° position. Collective pitch control adjusts the pitch of all rotor blades to the same angle at the same time. In contrast, IPC dynamically and individually adjusts the pitch of each rotor blade. Based on current individual loads this pitch adjustment is carried out in real-time. The main benefit of IPC is the reduction of fatigue loads on the rotor blades, the hub, and mainframe and tower structures. In order to compensate these loads, especially symmetric loads caused by inhomogeneous wind fields, the pitch of each rotor blade has to be adjusted independently from the other blades. A reduction of fatigue loads has two considerable advantages: It allows lighter designs and translates into longer lifetimes of wind turbines. What is meant by lighter designs? In cases where components are designed according to fatigue loads, a reduction of these loads allows savings in cost and material notably for the rotor blades and the tower structure, which are the most expensive elements of a wind turbine. Moreover, lighter rotor blades enable a more efficient turbine, especially in low wind conditions. Finally the load reduction through IPC gives designers the option to develop low wind turbines from existing designs, which means a reduction of time to market.
III. MODELING OF PROPOSED THEORY WIND TURBINE CONFIGURATION

The overall scheme of a DFIG-based wind turbine system is shown in Fig.1, which consists of a wind turbine, gearbox, DFIG, a back-to-back converter which is composed of a rotor side converter (RSC) and GSC, and a dc-link capacitor as energy storage placed between the two converters. In this paper, FAST is used to simulate the mechanical parts of wind turbine and the drive train. The pitch and converter controllers, DFIG, and power system are modeled by Simulink blocks.

A. FAST
The open source code FAST is developed at the National Renewable Energy Laboratory (NREL) and accessible and free to the public. FAST can be used to model both two and three bladed, horizontal-axis wind turbines. It uses Blade Element Momentum theory to calculate blade aerodynamic forces and uses an assumed approach to formulate the motion equations of the wind turbine. For three-bladed wind turbines, 24 degree of freedoms (DOFs) are used to describe the turbine dynamics. Their models include rigid parts and flexible parts. The rigid parts include earth, base plate, nacelle, generator, and hub. The flexible parts include blades, shaft, and tower. FAST runs significantly fast because of the use of the modal approach with fewer DOFs to describe the most important parts of turbine dynamics.

B. Mechanical Drive train
In order to take into account the effects of the generator and drive train on the wind turbine, two-mass model shown. Which is suitable for transient stability analysis is used. The drive train modeling is implemented in FAST, and all values are referred to the wind turbine side. The equations for modeling the drive train are given by

\[ J_w \frac{d^2 \theta_w}{dt^2} = T_w - D \left( \frac{d\theta_w}{dt} - \frac{d\theta_g}{dt} \right) - K(\theta_w - \theta_g) \]  

\[ J_g \frac{d^2 \theta_g}{dt^2} = D \left( \frac{d\theta_w}{dt} - \frac{d\theta_g}{dt} \right) + K(\theta_w - \theta_g) - T_e \]  

Where \( J_w \) and \( J_g \) are the moment of inertia of wind turbine and generator, respectively, \( T_w \), \( T_e \) are the wind turbine torque and generator electromagnetic torque, respectively, \( \theta_w \), \( \theta_g \) are the mechanical angle of wind turbine and generator, \( K \) is the drive train torsional spring, is the drive train torsional damper.

C. DFIG Model
The model of the DFIG is based on \( dq \) equivalent model shown. All electrical variables are referred to the stator. \( uds, uqs, udr, uqr, ids, iqs, idr, iqr \) and \( \psi ds, \psi qs, \psi dr, \psi qr \) are the voltages, currents, and flux linkages of the stator and rotor ind- and q-axes, \( rs \) and \( rr \) are the resistances of the stator and rotor windings, \( Ls, Lr, Lm \) are the
stator, rotor, and mutual inductances, \( L_{1s}, L_{1r} \) are the stator and rotor leakage inductances, \( w_1 \) is the speed of the reference frame, \( w_s \) is the slip angular electrical speed. The RSC of DFIG is controlled in a synchronously rotating d-q reference frame with the d-axis aligned along the stator flux position. The electrical torque \( T_e \), active power \( P_s \), and reactive power \( Q_s \) of DFIG can be expressed by

\[
T_e = \frac{3}{2} P \frac{L_m}{L_s} \psi_s i_{qr} \quad (3)
\]

\[
P_s = -\frac{3}{2} u_s \frac{L_m}{L_s} i_{qr} \quad (4)
\]

\[
Q_s = \frac{3}{2} \frac{\psi_s}{L_s} u_s - \frac{3}{2} u_s \frac{L_m}{L_s} i_{dr} \quad (5)
\]

Where \( P \) is the number of pole pairs, \( \psi_s \) is the stator flux, \( u_s \) is the magnitude of the stator phase voltage. From (4) and (5), due to the constant stator voltage, the active power and reactive power can be controlled via \( i_{qr} \) and \( i_{dr} \).

**WIND TURBINE CONTROL AND FLICKER**

a) EMISSION ANALYSIS

For a DFIG-based variable speed wind turbine, the control objective is different according to different wind speed. In low wind speed, the control goal is to keep the tip speed ratio optimum, so that the maximum power can be captured from the wind. In high wind speed, since the available power is beyond the wind turbine capacity, which could overload the system, the control objective is to keep the extracted power constant at its rated value.

Vector control techniques are the most commonly used methods for a back-to-back converter in a wind turbine system. Two vector control schemes are illustrated, respectively, for the RSC and GSC, as shown, where, \( v_s \), and \( i_s \) are the stator voltage and current, \( i_r \) is the rotor current, \( v_g \) is the grid voltage, \( i_g \) is the GSC currents, \( w_g \) is the generator speed, \( E \) is the dc-link voltage, \( P_s \) ref, and \( Q_s \) ref are the reference values of the stator active and reactive power, \( Q_r \) ref is the reference value of the reactive power flow between the grid and the GSC, \( E_{ref} \) is the reference value of the dc-link voltage, \( C \) is the dc-link capacitor. The vector control objective for RSC is to implement maximum power tracking from the wind by controlling the electrical torque of DFIG. The reference value of the generator speed \( \omega_{ref} \) is obtained via a lookup table to enable the optimal tip speed ratio. The objective of GSC is to keep
the dc-link voltage constant, while keeping sinusoidal grid currents. It may also be responsible for controlling the reactive power flow between the grid and the grid-side converter by adjusting $Q_g$ ref. usually, the values of reactive power of RSC and GSC are set to zero to ensure unity power factor operation and reduce the current of RSC and GSC.

IV. MATLAB/SIMULINK CIRCUITS

![Fig.4 Proposed individual pitch control scheme](image)

![Fig.5 Matlab/simulink circuit for high wind with IPC scheme](image)
Fig. 6 Matlab/simulink circuit for high wind without IPC scheme

Fig. 7 Matlab/simulink circuit for low wind with IPC scheme
Fig. 8 Matlab/simulink circuit for low wind without IPC scheme

Fig. 9 Matlab/simulink circuit for high wind with IPC scheme fuzzy logic controller
MATLAB/SIMULINK RESULTS

Fig. 10 Matlab/simulink circuit for low wind with IPC scheme fuzzy logic controller

Fig. 11 Matlab/simulink result for high wind with IPC scheme
Fig. 12 Matlab/simulink result for high wind without IPC scheme

Fig. 13 Matlab/simulink result for low wind with IPC scheme

Fig. 14 Matlab/simulink result for low wind without IPC scheme

Fig. 15 Matlab/simulink result for high wind with IPC scheme fuzzy controller
CONCLUSION

This paper describes a method of flicker mitigation by IPC of variable-speed wind turbines with MW-level DFIG. The modeling of the wind turbine system is carried out using FAST and Simulink. On the basis of the presented model, flicker emission is analyzed and investigated in different mean wind speeds. To reduce the flicker emission, a novel control scheme by IPC is proposed. The generator active power oscillation which leads to flicker emission is damped prominently by the IPC in both high and low wind speeds. It can be concluded from the simulation results that damping the generator active power oscillation by IPC is an effective means for flicker mitigation of variable speed wind turbines during continuous operation.

REFERENCES

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