SIMULATION OF FLICKER MITIGATION VARIABLE SPEED WIND TURBINES WITH DFIG

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Abstract- Due to the variations wind speed variation, wind shear and tower shadow effects, grid connected wind generating systems are the sources of power which may produce flicker during continuous operation. This paper presents a model of an high-level variable-speed wind turbine with a 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 Simulation results show that damping the generator active power by IPC is an effective means for flicker mitigation of variable speed wind generation during continuous operation.

Keywords: Flicker, flicker mitigation, individual pitch control (IPC), variable speed wind turbine

1. 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 [1].

An open-loop pitch control is 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.

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°, the reactive power needed for flicker mitigation 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.

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.

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![Operating Principle of the Wind Turbine Doubly-Fed Induction Generator](image)

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°, the reactive power needed for flicker mitigation per unit of the wind turbine will be divided into two main parts, each performing one of the following tasks: 1) a simulation of the response of the lamp–eye–brain chain and 2) an on-line statistical analysis of the flicker signal and presentation of the results.

The level of flicker is quantified by the short-term flicker severity value. The calculation of flicker severity takes into account the response of the light emission from incandescent lights to voltage variations and also the response of the human eye and brain in perceiving variations in illumination. The function and design of the flicker meter are specified in the Standard IEC Publication 868 [5]. The block diagram shown in Fig. 1 describes the flicker meter architecture. Although the block diagram consists of five blocks, the flicker meter can be divided into two main parts, each performing one of the following tasks: 1) a simulation of the response of the lamp–eye–brain chain and 2) an on-line statistical analysis of the flicker signal and presentation of the results. Blocks 2, 3, and 4 perform the first task while the second task is accomplished by blocks 5. “Block 1” performs the first step in the flicker meter. This block scales the input voltage to a reference level. “Block 2” squares the input voltage in order to simulate the behavior of a lamp. “Block 3” is composed of a cascade of two filters where the first filter eliminates the dc voltage and the second filter eliminates the mains frequency. The second filter simulates the frequency response of voltage fluctuations of a light bulb combined with the human visual system. “Block 4” is composed of a squaring multiplier and a first-order low-pass filter with a time constant of 300 ms. Together, these form a nonlinear function. The output from “Block 4” represents the instantaneous flicker level. “Block 5” is the final flicker meter block, which makes an on-line statistical analysis of the instantaneous flicker level. The statistical analysis can be divided into two parts. First, the cumulative probability function of the instantaneous flicker level is established, and second, the short-term flicker severity value is calculated using a multipoint method. The cumulative probability function of the instantaneous flicker level is established, and second, the short-term flicker severity value is calculated using a multipoint method.

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During the last few decades, the appetite for energy in the world has been increasing at a tremendous rate, especially wind power generation has experienced an uninterrupted and accelerating growth and the trend is likely to continue. In order to enable even greater role of wind energy in power production it is necessary to increase the size and unit power of wind turbines. With the increase of wind turbine capacity, rotor diameter, nacelle weight, tower height and the flexibility of wind turbine increase rapidly. Dynamic loads caused by the rotational sampling of turbulence, the tower shadow and the wind shear affect large scale wind turbine more and more importantly, which is an essential factor that must be considered. To cope with such great loads massive structure would be needed which would increase wind turbine's price and also pose a limit to its further growth. Instead of massive structure to withstand the worst potential loads it is much more convenient to use intelligent control methods by which loads reduction can be achieved. Therefore, control algorithms that can assure load and fatigue reduction become a necessity and also attractive. As we know, the adjustment of pitch angle plays an important role in the output power of the wind turbine and the blade loads and fatigue. But the traditional collective pitch control strategies move the three blades synchronously for three bladed wind turbines.

Nowadays, many of the commercial turbines use individual pitch actuators anyway, the braking systems can be considered independent since with careful design, obviating the need for a high capacity shaft brake. So the blade pitch angles of the wind turbine could be controlled individually, and this process is named individual pitch control with the added advantage that the failure probability of the system is significantly reduced even if one of the blade mechanisms fails. How to coordinate the three blades to make the output power stable and attenuate the wind turbine loads is a research focus. In this paper, individual pitch control is applied to doubly fed induction generator based wind power generation system to mitigate the blade loads and also the tilt and yaw moments on the fixed part of the wind turbine structure. Three different simulation packages, namely TurbSim, FAST, and Simulink are used to model the wind, mechanical and electrical aspects of the wind turbine and DFIG system in detail.

Loads upon the wind turbine structure arise from several factors. The main cause of the wind turbine structural loading is the fact that only a portion of the wind power can be transformed into the driving torque of the wind turbine rotor while large amount of it is transformed into the rotor thrust that will increase prominently with the increase of the wind speed and the wind turbine dimension. The sources of the structural loadings are also due to stochastic process and to periodic processes. The stochastic process is referred to as turbulence that determines wind speed at different times and heights. These periodic processes are due largely to two effects termed wind shear and tower shadow. Wind shear is used to describe the variation of wind speed with height while tower shadow describes the reduction of wind speed due to the tower structure. For a three bladed wind turbine, since the three blades are at different positions and under turbulent and periodic wind field, they are subjected to periodic blade loadings with oscillating magnitude which are very undesirable since they cause oscillatory stress on the structure which are responsible for a significant contribution to fatigue loads. In order to calculate loadings on the elements of the fixed part of the structure, it is first necessary to transform the loads defined in terms of rotating axis system into the hub loads expressed in terms of a fixed axis system, since the blade root bending moments are the source of the loads on the fixed part of the structure.

Slodividual pitch control is applied to DFIG based wind power system in this paper. It demonstrates a relatively straightforward approach of individual pitch control algorithm capable of attenuating the dominant fatigue loads on the blade(1p) and on the fixed components (3p), resulting in significant fatigue load reductions on the whole wind turbine. The individual pitch control process is tested with FAST and Simulink, demonstrating the effectiveness of the proposed control strategy. Developments of control strategies to tackle problems such as tower vibration and drive train oscillation, and loads reduction under grid fault conditions are subjects of ongoing and future work.

Previous work has demonstrated that significant reductions in fatigue loading on a wind turbine can be achieved by using individual pitch control, in which the pitch of each blade is adjusted individually, in response to measured loads. The asymmetrical out-of-plane rotor load is measured and an additional pitch action (dominated by the rotational frequency of the rotor) is calculated for each blade in order to minimize this load. This results in the near-elimination of the dominant once-per-revolution (‘1P’) peak in the out-of-plane load spectrum seen by the rotating components, and fatigue loads can be reduced by 20%–40%. The load reduction is also transferred to the nacelle and tower, but here it is the low-frequency loads which are removed, resulting in a load reduction of a few per cent at best, since the fatigue on the fixed components is dominated by the peak at the blade passing frequency (‘3P’ for a three-bladed turbine), which is largely unaffected by the individual pitch control action. This article demonstrates a relatively straightforward addition to the individual pitch control algorithm which is capable of reducing the dominant load peak on the fixed components, resulting in significant fatigue load reductions on the whole structure.

### III. RELATED WORK

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. An open-loop pitch control is 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.

**FLICKER**

Since the inception of electric lighting, the dimming and flickering of lights has been a reality for most consumers. In general, the main cause of these effects is switching operations of industrial processes and electrical appliances connected to the supply system. As shown in Figure 1, the current drawn by an appliance causes a voltage drop across the impedance of the electricity supply network, which results in a lower voltage supplied to the lighting system. Electrical equipment can often have complex program cycles which cause the current drawn from the supply to fluctuate. For example, a washing machine will switch on and off current to heat the water; there will be a surge of current as the motor starts to turn and varying current as the motor speed is controlled. The fluctuating current flows through the network impedance and induces a voltage drop which changes at the same rate as the current.

Flicker may be produced, for example, if a steel mill uses large electric motors or arc furnaces on a distribution network, or frequent starting of an elevator motor in an office building, or if a rural residence has a large water pump starting regularly on a long feeder system. The likelihood of flicker increase as the size of the changing load becomes larger with respect to the prospective short circuit current available at the point of common connection.

The relationship between amplitude of load changes and $P_{st}$ is linear, i.e. halving the switched load results in half the $P_{st}$. The relationship between number of load changes per time ($n/T_{P}$) and $P_{st}$ is non-linear. A halving of load changes reduces $P_{st}$ by only about 20%. In order to have half the $P_{st}$, the number of load changes must be reduced by a factor of 9.

**IV. PROPOSED WORK**

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. An open-loop pitch control is used 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.

Normally, pitch control is used to limit the aerodynamic power captured from the wind. In low wind speeds, the wind turbine should simply try to produce as much power as possible, so there is no need to pitch the blades. For wind speeds above the rated value, the pitch control scheme is responsible for limiting the output power. The PI controller used for adjusting the pitch angles works well in normal operation, however, the performance of the pitch control system will degrade when a rapid change in wind speed from low to high wind speed is applied to the turbine rotor. It takes a long time for a positive power error contribution to cancel the effects of the negative pitch angle contribution.
that has been built up from integration of these negative power errors. The integrator antiwindup scheme is implemented as shown in Fig. 4, in which the anti windup term with gain $K_{aw}$ is fed back to the integrator only. This prevents the integrated power error from accumulating when the rotor is operating in low wind speeds. The value for $K_{aw}$ may be turbine dependent. When the pitch angle is not saturated, this antiwindup feedback term is zero.

IV METHODOLOGY

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.

In order to take into account the effects of the generator and drivetrain on the wind turbine, two-mass model shown in Fig. 2.

![Image](https://via.placeholder.com/150)

Figure 4: Two-mass model of the drivetrain.

which is suitable for transient stability analysis is used. The drivetrain modeling is implemented in FAST, and all values are referred to the wind turbine side.

$$J_d \frac{d\theta}{dt} = T_e - D \left( \frac{d\theta}{dt} - \frac{d\theta}{dt} \right) - K(\theta_e - \theta_i)$$

$$J_s \frac{d\theta_s}{dt} = D \left( \frac{d\theta}{dt} - \frac{d\theta}{dt} \right) + K(\theta_e - \theta_i)$$

Are the mechanical angle of wind turbine and generator, $K$ is the drive train torsion spring, $D$ is the drive train torsion damper.

DFIG Modelling

The doubly fed machine operation at unity stator power factor requires higher flux in the air-gap of the machine than when the machine is used as wound rotor induction machine. It is quite common that wound rotor machines not designed to doubly fed operation saturate heavily if doubly fed operation at rated stator voltage is attempted. Thus a special design for doubly fed operation is necessary.

A multiphase slip ring assembly is traditionally used to transfer power to the rotating winding set and to allow independent control of the rotor winding set. The slip ring assembly requires maintenance and compromises system reliability, cost and efficiency. Attempts to avoid the slip ring assembly are constantly being researched with limited success (see Brushless doubly fed induction electric machines).

The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis currentvector control or direct torque control (DTC). DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

The doubly fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30% operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible.

The mechanical power and the stator electric power output are computed as follows:

$$P_m = T_m \omega_r, P_s = T_{em} \omega_s.$$  

For a lossless generator the mechanical equation is:

$$J_d \frac{d\omega_r}{dt} = T_m - T_{em}.$$  

In steady-state at fixed speed for a lossless generator $T_m = T_{em}$ and $P_m = P_s + Pr$. It follows that:

$$Pr = P_m - Ps = T_{m} \omega_r - T_{em} \omega_s = sT_{em} \omega_s = sP_s,$$

where $s$ is defined as the slip of the generator: $s = (\omega_s - \omega_r)/\omega_s$.

4. Wind Turbine Control and Flicker Emission Analysis
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 in Fig. 1, where $v_s$ and $i_s$ are the stator voltage and current, $i_r$ is the rotor current, $v_g$ is the grid voltage, $E_{ref}$ 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 [1].

**Pitch Controller Modelling**

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 adaption 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.
The flicker emission produced by grid connected wind turbines during continuous operation is mainly caused by fluctuations in the generator active power. The flicker emission will be mitigated effectively if the higher harmonics of the generator power can be reduced. When the wind speed is above the rated wind speed, the pitch angle should be tuned by a traditional collective pitch controller (CPC) to keep the output power at its rated value in order not to overload the system, and normally the 3p effect is not taken into consideration. For attenuating the generator power oscillations, caused by the 3p effect, each of the three pitch angles can be added by a small pitch angle increment, which is dependent on the generator active power and wind turbine azimuth angle. When the wind speed is below the rated wind speed, usually the control objective of the wind turbine is to implement maximum power tracking by generator electrical torque control. Pitch control is not used in this area. However if the pitch angles can be adjusted around a small average value, the 3p effect can also be reduced. For this purpose, the output of the CPC should leave a small amount of residual for pitch movement. This means a small part of wind energy will be lost.

IV. RESULTS

The flicker mitigation using IPC is tested in many wind speed conditions. The variable speed wind turbine with DFIG and back-to-back converter are simulated with the proposed IPC method.

There are also drawbacks of the proposed IPC method, such as loss of a small amount of wind energy in low wind speed and high demand of the PAS. There is an alternative flicker mitigation method, which is the turbine rotor speed control taking advantage of the large rotor inertia. In this way, the wind power fluctuations can be stored in the wind turbine rotor, leading to the flicker mitigation. However, this paper is focused on the IPC method. The IPC method for flicker mitigation proposed in this paper may be equally applicable to other types of variable speed wind turbines, such as a permanent magnet synchronous generator or a doubly salient permanent magnet generator, etc.

IV. CONCLUSION

This paper describes a method of flicker mitigation by IPC of variable-speed wind turbines with high-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.

REFERENCE


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