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Flicker Mitigation for Variable Speed Wind Generating System

B. Rajanikanth[1], B. Srinu[2]

[1]PG Scholar, Anurag Engineering College

[2]Assistant Professor, Anurag Engineering College

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 fiicker during continuous operation. This paper presents a model of an high-level variable-speed wind turbine with a generator to investigate the fiicker 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.***

1. Introduction

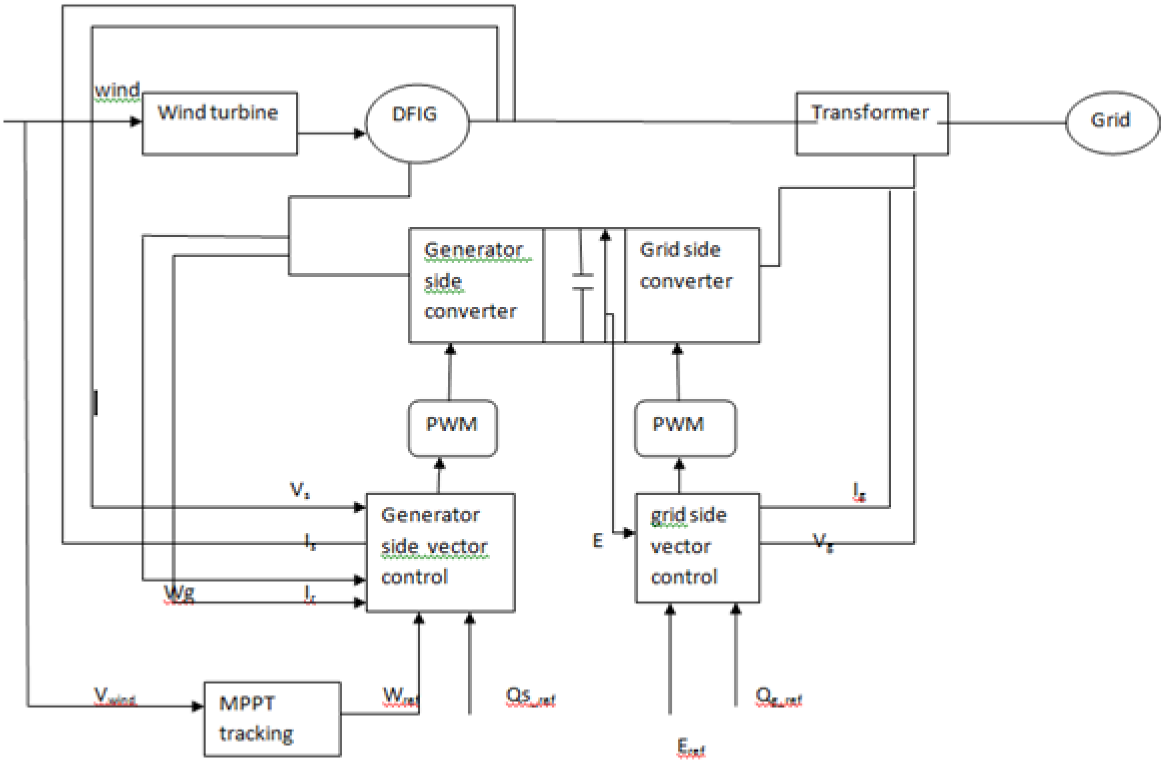
During the last few decades, with the growing concerns about energy shortage and environmental pollution, great efforts have been taken around the world to implement renew- able energy projects, especially wind power projects. With the increase of wind power penetration into the grid, the power qual- ity becomes an important issue. One important aspect of power quality is flicker since it could become a limiting factor for in- tegrating 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



2. Wind Turbine Modelling

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 signif- icantly 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. 1

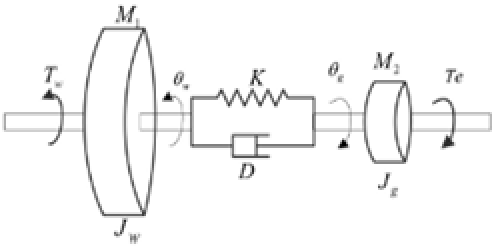


Figure 1: Two-mass model of the drivetrain.

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.

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

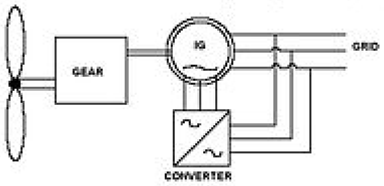
$$J_g \frac{d^2\theta_g}{dt^2} = D\left(\frac{d\theta_w}{dt} - \frac{d\theta_g}{dt}\right) + K(\theta_w - \theta_g) - T_e$$

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

3. 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).



PRINCIPLE OF DFIG CONNECTED TO A WIND TURBINE

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:
$J_{d\omega rdt}=T_m-T_{em}$.
In steady-state at fixed speed for a lossless generator $T_m = T_{em}$ and $P_m = P_s + P_r$.
It follows that:
$P_r=P_m-P_s=T_m\omega_r-T_{em}\omega_s=-T_{m\omega s-\omega r\omega s}\omega_s=-sT_m\omega_s=-sP_s$
,
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

4.1 Control of Back-to-Back Converter

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 vs and Is are the stator voltage and current, ir is the rotor current, vg 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 ω_{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].

4.2 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.

4.3 Individual Pitch Control for Flicker Mitigation:

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.

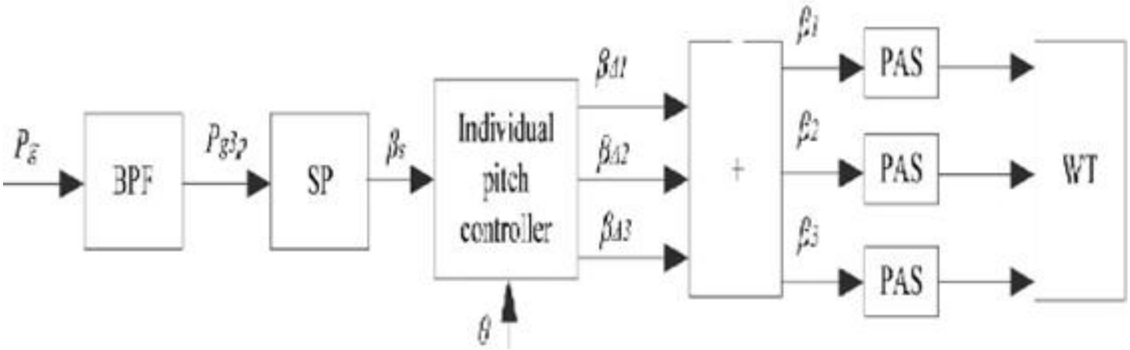


Figure 2: Proposed individual pitch control scheme.

4.4 Design of BPF

The transfer function of the BPF can be expressed as follows:
$F(s)=Ks/s2+(\omega c/Q)s + \omega c^2$
where ωc is the center frequency
K is the gain, and Q is the quality factor.
which corresponds to the 3p frequency can be calculated by the measurement of the generator speed

ω_c*ωg=3 ω_g/N,

where N is the gear ratio. The gain of the BPF at the center frequency is designed as 1 in order to let all the 3p frequencies pass the filter (F(s)=*KQ*/ωc= 1). Q which is responsible for the bandwidth of the BPF should be adjusted to let only the 3p component pass. In this case, Q is designed as
$Q = \omega_c$

Individual Pitch Controller Design The individual pitch controller will output the three pitch angle increments ß for each blade based on the pitch signal ßsΔ1,Δ2,Δ3 and the azimuth angle θ.

In this paper, the wind turbine is simulated by FAST, in which blade 3 is ahead of blade 2, which is ahead of blade 1, so that the order of blades passing through a given azimuth is 3–2–1-repeat. The individual pitch controller will output a pitch increment signal which will be added to the collective pitch angle for a specific blade, dependent on the blade azimuth angle.
The principle of the individual pitch controller is described in Table I. For example, if the azimuth angle belongs to the area of(0, 2p/3), then ßΔ2 equals ßs, and both ßΔ1and ß Δ3 equal 0. The three pitch increments will be, respectively, added with the collective pitch angle to give three total pitch angle demands. The three pitch angle signals will be sent to the PAS. The PAS can be represented using a first-order transfer function:

$F (s)= 1/T_{pas}s +1$

which is a turbine dependent time constant of the PAS. In this case T= 0.1.

The control scheme shown in Fig. 7 is used for mitigation pas of the 3p component of the generator active power, leading to the reduction of the flicker emission which is caused by the 3p effect. Similar method can also be used to reduce the 6p component of the generator active power. However, this 6p component mitigation needs a much faster pitch actuation rate.

5. Simulation Study

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.

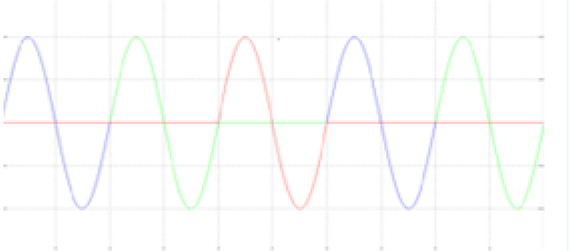


Figure 3: high wind speed individual pitch angles

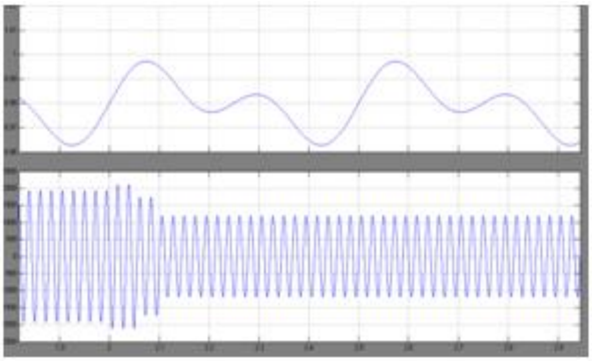


Figure 4: view of the generator active power and reactive power with IPC

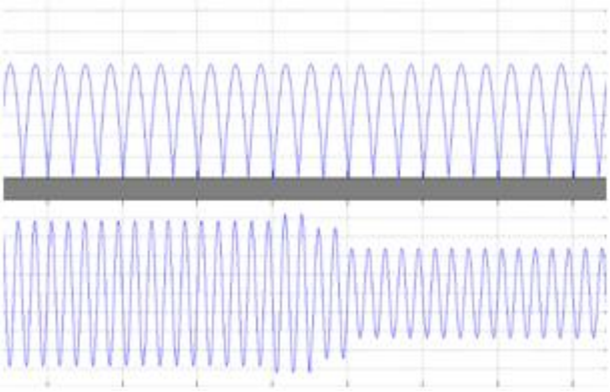


Figure 5: view of the generator active power and reactive power without IPC

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.

6. 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.

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Author Profile

B. Srinu is Assistant Professor in Anurag Engineering College

B. Rajanikanth is PG Scholar in Anurag Engineering College