A New Method to Mitigate Voltage Fluctuation of a Fixed Speed Wind Farm Using DFIG Wind Turbine

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Abstract

One of the important power quality aspects is flicker. Wind turbines are a source of power fluctuations which may cause flicker disturbances. There are numerous of factors that affect flicker emission of grid-connected wind turbines during continuous operation, such as wind characteristics (e.g. mean wind speed, turbulence intensity) and grid conditions (e.g. short circuit capacity, grid impedance angle, load type). The type of wind turbine also has influence on flicker emission. In this paper, the flicker emission of wind turbines equipped with squirrel-cage induction generators is investigated. Also show that in a wind farm by the replacement of some fixed speed wind turbines with DFIG wind turbines can reduce the flicker emission. This wind farm model has been implemented and simulated by using MATLAB/ Simulink. Simulation results show that the combination of fixed speed and variable speed wind turbines in output voltage of fixed speed wind farms is an effective means for flicker mitigation during continuous operation.

1. Introduction

Because of energy shortage and environment pollution, the renewable energy, especially wind energy, has attracted more attentions all over the world. As the wind power penetration into the grid is increasing quickly, the influence of wind turbines on the power quality is becoming an important issue. One of the important power quality aspects is flicker. Flicker causes irritation to the consumer at the receiving end and results in a serious limitation for weak networks where the flicker effect can emerge [1]. IEC 61400-21 describes procedures for determining the power quality characteristics of wind turbines [2]. According to IEC standard IEC 61000-4-15, a flickermeter model is built to calculate the short-term flicker severity *P*st.

There are numerous of factors that affect flicker emission of grid-connected wind turbines during continuous operation, such as wind characteristics (e.g. mean wind speed, turbulence intensity) and grid conditions (e.g. short circuit capacity, grid impedance angle, load type). The type of wind turbine also has influence on flicker emission [3].

Wind turbines can operate either with a fixed speed or a variable speed. The fixed-speed wind turbine has the advantage of being simple, robust and reliable and well-proven. And the cost of its electrical parts is low. Its disadvantages are an uncontrollable reactive power consumption, mechanical stress and limited power quality control. Owing to its fixed-speed operation, all fluctuations in the wind speed are further transmitted as fluctuations in the mechanical torque and then as fluctuations in the electrical power on the grid. In the case of weak grids, the power fluctuations can also lead to large voltage fluctuations.

During the past few years the variable-speed wind turbine has become the dominant type among the installed wind turbines. It is typically equipped with an induction or synchronous generator and connected to the grid through a power converter. The advantages of variable-speed wind turbines are an increased energy capture, improved power quality and reduced mechanical stress on the wind turbine. The disadvantages are losses in power electronics, the use of more components and the increased cost of equipment because of the power electronics. One of the variable speed wind turbine is DFIG wind turbine. The DFIG wind turbine has the ability to control active and reactive output power. Thus, output power variations of DFIG wind turbine are more fewer than SCIG wind turbine. In this paper show that in a wind farm by the replacement of some fixed speed wind turbines with DFIG wind turbines can reduce the flicker emission. Also a simulation model of MW-level fixed speed and variable speed wind turbines developed in MATLAB/ Simulink is presented, and simulation results of the replacement of DFIG wind turbines are investigated.

In this paper an investigation of the flicker emission is presented, considering different types of WT (fixed and variable speed), operating under a variety of wind conditions (mean value and turbulence intensity) and network characteristics (short circuit capacity and grid impedance angle). First the network and WT modeling approach is outlined and the algorithm implemented for the calculation of the flicker index is presented. Subsequently the results of the investigation are presented and discussed, illustrating the effect of the wind and network parameters on the flicker levels resulting from the operation of fixed speed and combinative wind farm.

2. Modeling of Wind Turbines

2.1 Model of a Constant-speed Wind Turbine

In the early 1990s the standard installed wind turbines operated at fixed speed. That means that regardless of the wind speed, the wind turbine's rotor speed is fixed and determined by the frequency of the supply grid, the gear ratio and the generator design. It is characteristic of fixed-speed wind turbines that they are equipped with an induction generator (squirrel cage or wound rotor) that is directly connected to the grid, with a soft-starter and a capacitor bank for reducing reactive power compensation.

(Fig. 1) depicts the general structure of a model of a constant-speed wind turbine. This general structure consists of models of the most important subsystems of this wind turbine type, namely, the rotor, the drive train and the generator, combined with a wind speed model.

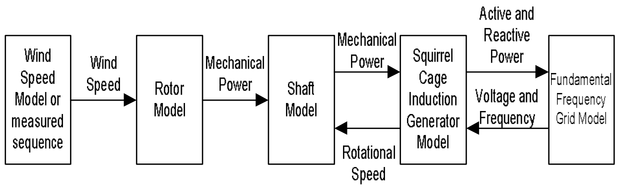

Figure 1 - General structure of constant-speed wind turbine model [4]

2.2 Model of a Wind Turbine with a Doubly fed Induction Generator

Variable-speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. The electrical system of a variable-speed wind turbine is more complicated than that of a fixed-speed wind turbine. (Fig. 2) depicts the general structure of a model of variable-speed wind turbines with doubly fed induction generator. It shows that a wind turbine with a doubly fed induction generator is much more complex than a constant-speed wind turbine. Compared with a constant-speed wind turbine, a variable-speed wind turbine has additional controllers, such as the rotor speed controller and the pitch angle controller. Additionally, if it is equipped with terminal voltage control, it also has a terminal voltage controller. The topology of the DFIG and SCIG wind turbines are illustrated in (Fig. 3,4)

2.3 Wind Modeling

Wind is an intermittent and variable source of energy. Wind speed varies with many factors and is random in magnitude and direction. For this study, the wind is simulated with four components, namely, base component, ramp component, gust component and noisy component [5] as:

$$v_w(t) = v_{base} + v_{ramp}(t) + v_{gust}(t) + v_{noise}(t) \tag{1}$$

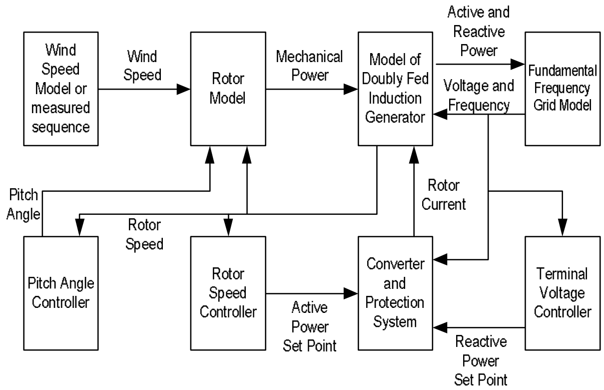

Figure 2 - General structure of a model of a variable speed wind turbine with doubly fed induction generator [4]

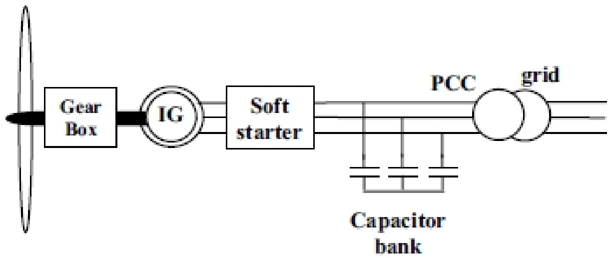

Figure 3 - Fixed-Speed wind turbine

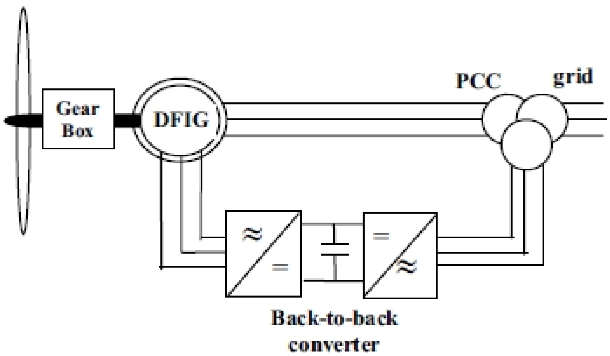

Figure 4 - Variable-speed wind turbine: based on doubly-fed induction

The power in the wind is proportional to the cube of the wind speed. However, only part of the wind power is extractable. Although a complete aerodynamic model of the wind turbine could simulate the interaction between the wind and the turbine blades in detail, the simple expression of (Eq. 2), which is quite often used to describe the mechanical power transmitted to the hub shaft, is sufficient for this study.

$$P_{wt} = \frac{1}{2}\rho A_{wt} v_w^3 C_p(\lambda, \beta) \tag{2}$$

Where ρ (kg/m) is the air density and A_{wt} (m^2) is the area swept out by the turbine blades. Cp, a dimensionless power coefficient, depends on the type and operating condition of the wind turbine. For a fixed-pitch turbine, Cp may be expressed as a function of λ, the ratio of blade tip speed to wind speed $\lambda = \omega_{rot} R / v_{eq}$, with R being the radius (m) of the wind turbine rotor and ω_{rot} (rad/s) being the angular speed. As for the mechanical model, emphasis is put on the parts of the dynamic structure of the wind turbine that contribute to the interaction with the grid. Therefore, only the drive train is considered, while the other parts of the wind turbine structure, e.g. tower and flap bending modes, are neglected. When modeling the drive train, it is a common practice to neglect the dynamics of the mechanical parts, as their responses are considerably slow in comparison to the fast electrical ones, especially for machines with great inertia. The rotational system may therefore be modeled by a single equation of motion:

$$J_{WG}\frac{dwrot}{dt} = T_W - T_G - D_{\omega rot} \tag{3}$$

Where J_{WG} is the wind turbine mechanical inertia plus generator mechanical inertia [kg.m^2], T_G generator electromagnetic torque [Nm], and D friction coefficient [Nm/rad]. MATLAB/ Simulink software library provides dedicated model of the wound rotor induction generator.

In this paper the wound rotor induction generator model with detailed description of the stator and rotor direct and quadrature axis currents (or flux linkages) and the rotor speed is applied. For a detailed PWM voltage source converter model, the power electronic components should be switched on and off at a high frequency [several kilohertz (kHz) or higher], which requires a very small simulation time step to well represent the PWM waveforms. The simulation speed is thus fairly slow. Therefore, the detailed PWM voltage source converter model is unsuitable for flicker calculation that requires a long simulation time. Since the study interest is not concentrated on the switches of the PWM converter, an average model without switches is used so that the simulation can be carried out with a larger time step resulting in a simulation speed improvement [6].

Modeling the DFIG involves modeling the wound rotor induction machine, the rotor-side converter, the grid-side converter, and dc capacitor between them, along with an aerodynamic model of the wind turbine. The rotor-side controller controls the rotor current of the induction machine. Selecting the synchronously rotating reference frame attached to the stator flux vector enables decoupled control of the electrical torque and rotor excitation current. Consequently, the stator active and reactive powers can be controlled separately. In this paper, the vector-controlled model of the rotor-side controller will be modified for effective flicker mitigation.

3. Studied System

The case simulated in this study is shown in (Fig. 5). It represents a wind farm consists of three 2 MW wind turbines connected to a 20 kV distribution system exporting power to a 132 kV grid through a 30 km 20 kV feeder. In this paper simulations were carried out for two scenarios of operating wind farm:

- Scenario 1: a wind farm with three SCIG wind turbines
- Scenario 2: a wind farm with two SCIG wind turbines and a DFIG wind turbine

(Table 1) provides the parameters of the generators in detail.

Table 1 - GENERATOR PARAMETERS

Parameters	value
SCIG speed	1571 rpm
DFIG speed	1000-1500 rpm
Rated voltage	0.69 kV
Base angular frequency	314.16 rad/s
Stator/rotor turns ratio	0.4333
Angular moment of inertia	1.9914 p. u.
Stator resistance	0.0175 p. u.
Rotor resistance	0.019 p. u.
Stator leakage inductance	0.2571 p. u.
Rotor leakage inductance	0.295 p. u.
Mutual inductance	6.921 p. u.

4. Flicker Emission

In this section flicker emission of each of the above scenarios has been investigated during continuous operation. The level of flicker is quantified by the short-term flicker severity Pst, which is normally measured over a ten-minute period. The short-term flicker severity of bus 690V, the PCC, is calculated on the basis of the voltage variation. A base case with parameters given in (Table 2) is first considered, where the turbulence intensity, short circuit capacity ratio, grid impedance angle are defined as [7]:

$$In = \frac{\Delta v}{v} \quad (4)$$

$$SCR = \frac{S_k}{S_n} \quad (5)$$

$$\psi_k = \arctan(\frac{X}{R}) \quad (6)$$

where Δv is the wind speed standard deviation, v is the mean wind speed, S_k is the short circuit apparent power of the grid where the wind turbines are connected, S_n is the rated apparent power of the wind turbines, R and X are the resistance and reactance of the grid line.

Table 2 - BASE CASE FOR SIMULATION

Parameter	Value
Mean wins speed (v)	9 m/s
Turbulence intensity (In)	0.1
Short circuit capacity ratio (SCR)	20
Grid impedance angle (ψ_k)	50 deg

Flicker emission of grid connected wind turbines depends on many factors, such as wind parameters, grid condition, etc. On the basis of the base case, the dependence of flicker emission on the following factors is studied:

- mean wind speed ;
- turbulence intensity ;
- short circuit capacity ratio ;
- grid impedance angle .

In the following cases, the concerned factors are to be changed while the other parameters are kept constant as that in the base case.

5. Results

For the both fixed speed and combinative wind farms, the variation of short-term flicker severity with mean wind speed, turbulence intensity, short circuit capacity ratio and grid impedance angle at the point of common coupling (PCC) are illustrated in (Figs. 5-8). Simulation results shown that, by the replacement of a fixed speed wind turbines with DFIG wind turbine can reduce the flicker emission. In this way, the DFIG wind turbine with its grid-side convertor behaves similarly to a STATCOM at the wind farm terminal. The difference is that the grid-side converter is already there without any additional cost in the case of a doubly fed induction generator.

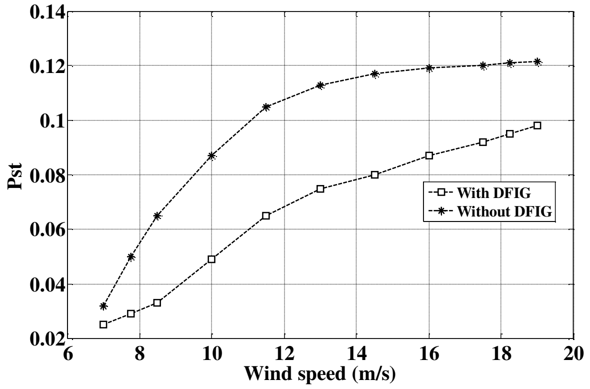

Figure 5 - Short-term flicker severity, Pst variation with mean wind speed for fixed speed and combinative wind farms.

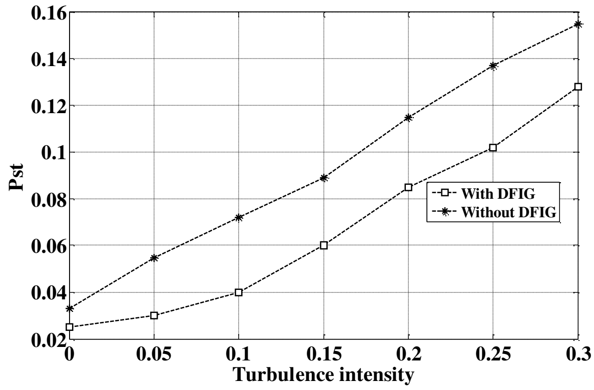

Figure 6 - Short-term flicker severity, Pst variation with turbulence intensity for fixed speed and combinative wind farms.

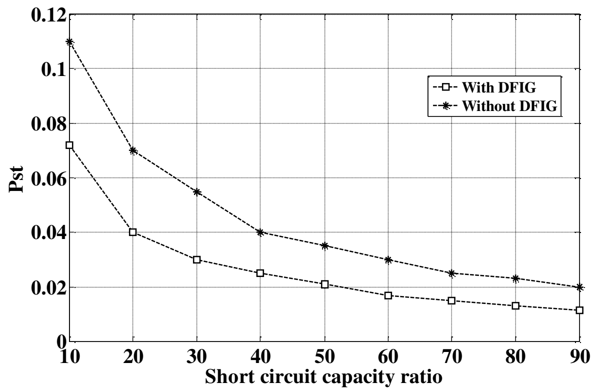

Figure 7 - Short-term flicker severity, Pst variation with short circuit capacity ratio for fixed speed and combinative wind farms.

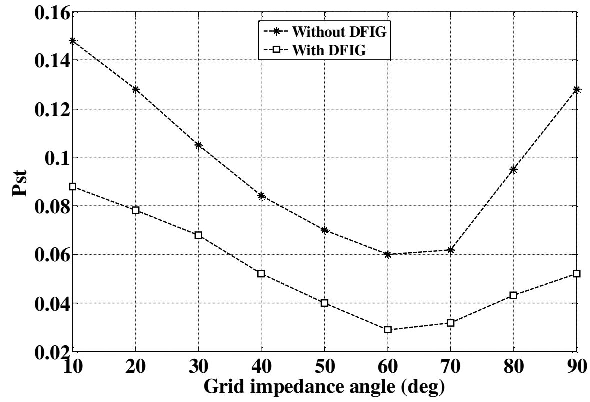

Figure 8 - Short-term flicker severity, Pst variation with grid impedance angle for fixed speed and combinative wind farms.

With grid-side convertor of DFIG wind turbine an alternative flicker mitigation is carried out to control measure- directly controlling the voltage at the PCC, which can also be realized by regulating the reactive power of the PWM voltage source converters. The aim of the voltage controller is to keep the voltage at a constant value such that the voltage fluctuations as well as flicker are reduced.

6. Conclusions

This paper describes a method of flicker mitigation by the replacement of some fixed speed wind turbines with DFIG wind turbines. On the basis of the developed wind turbine models, the flicker emission of fixed speed and variable speed wind farms during continuous operation based on wind characteristics (e.g. mean wind speed, turbulence intensity) and grid conditions (e.g. short circuit capacity, grid impedance angle, load type) is investigated. Flicker mitigation is realized by using the DFIG wind turbine in fixed speed wind farm which is significant in the flicker emission. It can be concluded from the simulation results that in comparison with fixed speed wind farm, the combinative wind farm has lower flicker emission.

7. References

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