MODELING AND SIMULATION OF WIND FARMS WITH VARIABLE SPEED WIND TURBINES USING FULL-SCALE CONVERTERS FOR POWER SYSTEM DYNAMIC STUDIES

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ABSTRACT

In order to study the impact of a wind farm on the dynamics of the power system, a significant issue is to develop adequate equivalent models that allow characterizing the dynamics of all individual wind turbine generators (WTGs). In this sense, with the advance of power electronics, direct-driven permanent magnet synchronous generators (PMSGs) have drawn increased interest to wind turbine manufacturers due to its advantages over other variable-speed WTGs. In this way, this paper presents a comprehensive dynamic equivalent model of a wind farm with direct-driven PMSG wind turbines using full-scale converters and its control scheme. The proposed simplified modeling is developed using the state-space averaging technique and is implemented in the MATLAB/Simulink environment. The dynamic performance of the wind farm and its impact on the power system operation is evaluated using the phasor simulation method.

Keywords: Wind farm, variable speed wind turbine, permanent magnet synchronous generator (PMSG), power conditioning system, equivalent aggregated model, state-space averaging modeling, phasor simulation method, control techniques.

1. INTRODUCTION

Globally, wind power is experiencing a rapid development. Medium- to large-scale grid-connected wind turbine generators (WTGs) are becoming the most important and fastest growing power source in the world [1]. This trend is expected to be increased in the near future, sustained by the cost competitiveness of wind power technology, industry maturation, environmental concerns, the growth in energy demand, the rising cost of fossil fuel generation, and the availability of a good wind resource in many regions worldwide. These profits include the strong support provided by governments of different countries, as investment subsidies and incentives [2].

Under this scenario, the power electronic technology plays an important role in the integration of distributed (or dispersed) generation (DG) into the electrical grid since the DG system is subject to requirements related not only to the RES itself but also to its effects on the power system operation and stability [3]. The use of power electronic converters enables wind turbines to operate at variable speed, and thus permits to provide more effective power capture than the fixed-speed counterparts. In variable speed operation, a control system designed to extract maximum power from the wind turbine and to provide constant grid voltage and frequency is required. With the advance of power electronics technology, direct-driven permanent magnet synchronous generators (PMSG) have increasingly drawn more interests to wind turbine manufactures due to its advantages over other WTGs [4].

In recent years, numerous topologies of power conditioning systems (PCSs), varying in cost and complexity, have been developed for integrating PMSG wind turbine systems into the electric grid. In modern PMSG WTGs designs, the PCS is typically built using a full-scale power converter made up of a two-stage power conversion hardware topology that meets all the constraints of high quality electric power, flexibility and reliability imposed for applications of modern distributed energy resources [3], [5]. This PCS design is composed of a back-to-back converter that enables to...
control simultaneously and independently the active and reactive power flow exchange. Because of technology constraints, the size of individual WTGs is still limited to some MWs. Consequently, large-scale wind power developments are implemented using wind farms, aka wind parks. A wind farm is typically composed of a large number of individual WTGs connected by an internal electrical network and operating simultaneously. With the rapid increase of wind penetration in power systems, the dynamic influence of a wind farm on power system dynamics is becoming an important issue for integration and operation of wind farms. This situation brings new challenges to the operation and management of the power system, especially when the intermittent energy source constitutes a major part of the total system capacity because issues related to integration, stability effects, and voltage impacts become increasingly important. In order to study the impact of wind farms on the operation of the power system, an important issue is to develop appropriate wind farm models in order to represent the dynamics of many individual WTGs [6]. The dynamic behavior of wind farms is usually represented by a detailed model, in which the dynamics of each individual WTG and its PCS are fully represented. Because a large wind farm normally consists of a large number of WTGs, this detailed model presents a high order model and requires excessive simulation time. The detailed model is therefore not suitable for studying the impact of the entire wind farm on the dynamic behavior of a large-scale power system and simplified models are required. To reduce the simulation time, the complexity of the wind farm model can be reduced by equivalent models [7]. This paper focuses on the dynamic modeling and control issues of a wind farm with variable-speed direct-driven PMSG wind turbines for dynamic studies in DG systems. The proposed simplified wind farm modeling approach groups all WTGs that experience similar wind velocities into an equivalent aggregated WTG model. This simplified modeling is developed using the state-space averaging technique and is implemented using SimPowerSystems of MATLAB/Simulink using the phasor simulation method. In addition, a new three-level control scheme is designed, capable of simultaneously and independently exchanging both active and reactive powers with the electric system. The dynamic performance of the proposed wind farm and especially its impact on the power system operation is evaluated through computer simulation.

2. DYNAMIC MODEL OF INDIVIDUAL WIND TURBINE GENERATORS

This section presents the mathematical model for each component of the individual direct-in-line wind power systems, including the wind turbine, the mechanical shaft system, the generator and the power electronic interface with the electric utility grid, as shown in Fig. 1. The wind turbine generator used in this paper employs a direct-driven (without gearbox) PMSG directly coupled to the wind turbine and connected to the electric grid through the PCS. The stator windings of the PMSG are directly connected to the PCS composed of a full-scale power converter built using a back-to-back AC/DC/AC converter topology which includes a machine- and grid-side converter with an intermediate DC link.

2.1. Wind Turbine

The proposed model is based on the steady-state aerodynamic power characteristics of the wind turbine. The wind turbine analyzed is a classic three-bladed horizontal-axis (main shaft) wind turbine design with the corresponding pitch controller. The output mechanical power available from a variable speed wind turbine can be expressed as follows [8]:

\[
P_m = C_p(\lambda, \beta) \frac{\rho A v^3}{2},
\]

where:
- \(\rho\): air density
- \(A\): area swept by the rotor blades
- \(v\): wind speed
- \(C_p\): so-called power coefficient (or coefficient of performance) of the wind turbine

The power coefficient \(C_p\) is a nonlinear function of the blade pitch angle \(\beta\) and the tip-speed ratio \(\lambda\) as given by Equation 2:

\[
\lambda = \left( \frac{R \omega_m}{v} \right),
\]

with:
- \(R\): radius of the turbine blades
- \(\omega_m\): angular speed of the turbine rotor

As can be derived from (1), the power coefficient \(C_p\) is given in terms of the blade pitch angle \(\beta\) and the tip-speed ratio \(\lambda\). Since the wind turbine can operate over a wide range of rotor speeds, the aerodynamic system results very complex to be analytically determined. Consequently, numerical approximations have been developed in order to calculate the mechanical power characteristic of the wind turbine as follows [9]:
The maximum value of $C_p$ is achieved at a specific $\lambda_{opt}$, thus resulting in the point of optimal efficiency where the maximum power is captured from wind by the wind turbine.

### 2.2. Mechanical Shaft System

In the case of direct-in-line variable speed wind power systems, because the wind turbine is connected to the electric grid through a full-scale converter, the shaft properties are hardly reflected at the grid connection side due to the decoupling effect of the PCS [10]. In this way, the turbine rotor is modeled as a lumped mass and the shaft dynamics is neglected. Even more, since a multi-pole PMSG is used, the gearbox can be omitted.

The wind turbine rotor dynamics is modeled as:

$$T_c = T_l + B_f \omega_m + J_c \frac{d\omega_m}{dt},$$

where:

- $T_c$: electromagnetic torque of the electric machine
- $T_l$: load torque
- $B_f$: viscous friction coefficient
- $J_c$: combined inertia moment of the WTG rotor and PMSG
- $\omega_m$: rotor mechanical speed, which is related to the rotor angular speed of the electric machine $\omega_s$, through:

$$\omega_m = \frac{\omega_s}{p_p},$$

with $p_p$ being the number of pole-pairs of the generator.

### 2.3. Permanent Magnet Synchronous Generator

The permanent magnet synchronous machine can be electrically described in steady-state using a simple equivalent circuit with an armature equation including back electromotive forces (emfs). In this way, the state equation for the PMSG in the rotor $dq$ frame is given by:

$$s \begin{bmatrix} i_{dm} \\ i_{qm} \end{bmatrix} = \begin{bmatrix} -R_m & 0 \\ L_d & -L_q \end{bmatrix} \begin{bmatrix} \omega_s \\ \omega_m \end{bmatrix} + \begin{bmatrix} \frac{u_{dm}}{L_d} \\ \frac{u_{qm} - u_d}{L_q} \end{bmatrix},$$

where:

- $u_{im}$ ($i=d,q$): stator phase voltages in $dq$ coord.
- $u_d$; back emfs in $dq$ coordinates
- $i_{im}$: stator currents in $dq$ coordinates
- $L_i$: stator winding inductances, in $dq$ coord.

Fig. 1 shows the detailed model of a modern direct-in-line variable-speed direct-driven PMSG wind turbine connected to the utility distribution grid, which is used here to develop the proposed simplified models [3], [4]. This PCS is composed of a back-to-back AC/DC/AC converter that fulfills all the requirements stated above. Since the variable speed rotor of the WTG is directly coupled to the synchronous generator, this later produces an output voltage with variable...
amplitude and frequency. This condition demands the use of an extra conditioner to meet the amplitude and frequency requirements of the utility grid, resulting in a back-to-back converter topology [8]. Two voltage source inverters (VSIs) compose the core of the back-to-back converter, i.e. a machine-side inverter and a grid-side one.

The grid-side three-phase three-level VSI essentially consists of a DC/AC three-phase VSI built with insulated gate bipolar transistors (IGBTs). The output voltage control of the VSI is achieved through sinusoidal pulse width modulation (SPWM) techniques. The connection to the utility grid is made by means of a step-up $\Delta$–Y coupling transformer, and low pass sine wave filters. The VSI structure uses a three-level twelve pulse pole structure, also called neutral point clamped (NPC), instead of a standard two-level six pulse inverter structure [11]. This three-level VSI topology generates a more smoothly sinusoidal output voltage waveform than conventional two-level structures without increasing the switching frequency and effectively doubles the power rating of the VSI for a given semiconductor device. In this way, the harmonic performance of the inverter is improved, also obtaining better efficiency and reliability.

3. CONTROL STRATEGY OF THE WIND TURBINE GENERATORS

The multi-level control scheme for the grid-connected individual direct-in-line wind power system consists of three distinct blocks, namely the external, middle and internal level [12].

The external level control (left side of Fig. 2) is responsible for determining the active and reactive power exchange between the WTG system and the utility grid. The proposed external level control scheme is designed for performing simultaneously two major control objectives, that is the active power control mode (APCM) and the voltage control mode (VCM).

The VCM is designed to control the voltage at the point of common coupling (PCC) of the grid-side VSI through the modulation of the reactive component of the output current. The main purpose of a grid-connected wind power system is to transfer the maximum available wind generator power into the electric system. In this way, the APCM aims at matching the active power to be injected into the electric grid with the maximum instant power capable of being generated by the WTG. Maximum power point tracking means that the wind turbine is always supposed to be operated at maximum output voltage/current rating. To this aim, the APCM of the wind turbine is achieved by two coordinated controllers: a power controller and a speed controller. The turbine power is directly controlled by the machine-side converter, while the generator speed in critical conditions is regulated by the pitch angle of the turbine blades. The pitch angle controller is only active in high wind speeds.

The middle level control (middle side of Fig. 2) makes the expected output, to dynamically track the reference values set by the external level. In
order to derive the control laws for this block, the state-space averaged models of both, the machine- and grid-side inverters, described in [12] are employed. In order to achieve a full decoupled active and reactive power control, it is required to decouple the control of $i_d$ and $i_q$, as much in the machine-side as in the grid-side inverter. This condition is achieved by using two conventional PI controllers with proper feedback of the VSI output current components.

The internal level control (right side of Fig. 3) is responsible for generating the PCS control signals. Modeling wind farms requires the reduction of complex detailed WTG models, such as the one presented in Fig. 1, by simplified equivalent ones (as previously described) in order to reduce the simulation time. In this way, the PCS is modeled using an averaged model implemented using a pair of three controlled AC voltage sources connected to the electric grid on one side and to the PMSG on the other, through the corresponding coupling network. Thus, this level is simply composed of a couple of inverse coordinate transformation blocks, from $dq$ to $abc$ components for generating the inverter control signals. The grid-side inverter voltage signals are synchronized with the instantaneous positive sequence components of the ac voltage vector at the PCC using the phase $\theta_s$. On the other hand, the machine-side inverter voltage signals are synchronized with the instantaneous PMSG stator magneto-motive forces through $\theta_s$.

4. DYNAMIC MODEL OF THE WIND FARM

Fig. 3 shows the configuration of the wind farm used in this study. It consists of 3 units of 2 MW variable-speed PMSG WTGs. The total installed power capacity of the wind farm is 6 MW. The wind farm is organized into an internal network interconnected via underground power cables. Each WTG is equipped with a 0.69/15 kV step-up transformer. The entire wind farm is connected to the power network at the PCC through a 15/35 kV transformer and a 3 km underground power cable. The utility electric system is represented by a classical single machine-infinite bus type (SMIB) system interconnected through a 20 km tie-line. It operates at 120 kV/50 Hz in the bulk power system side and at 35 kV in the wind farm side, and implements a 100 MVA short circuit power level infinite bus using a Thevenin equivalent. The parameters of each WTG and the network components are given in [6].

Figure 3. Configuration of a wind farm with PMSG-WTGs connected to the utility grid.

If the incoming wind speed profile on each individual wind turbine is identical or similar, as is usually the case for the topology presented, it can be assumed that all the WTGs in the wind farm operate at the same operating point, to be precise, all the wind turbines and the PMSGs operate at the same rotational speed. Under this assumption, the entire wind farm can be simply represented by a single WTG equivalent model operating on an equivalent internal network. In this way, the proposed simplified wind farm modeling approach groups all WTGs that experiences similar wind velocities into an equivalent aggregated wind farm model, while the entire wind farm is represented by several equivalent turbines receiving different wind profiles.

The MVA-rating of the equivalent WTG is the sum of the MVA-rating of all the individual WTGs. The mathematical model of this equivalent WTG is exactly the same as each individual WTG described in previous sections. If the MVA-rating of the equivalent WTG is used as the base value, then the per-unit values of the equivalent WTG parameters and the internal network parameters, including the equivalent wind turbine parameters, equivalent shaft system parameters, equivalent PMSG parameters, equivalent transformer parameters, and equivalent cable impedance, are exactly the same as those for each individual WTG of Fig. 2.

5. DIGITAL SIMULATIONS RESULTS

In order to evaluate the dynamic responses of the proposed simplified equivalent models and control algorithms of the PMSG-WTG based
wind farm, phasor domain dynamic simulations were implemented using SimPowerSystems of MATLAB/Simulink environment [13]. Simulations depicted in Fig. 4 show the case with only active power exchange with the utility grid, using the 6 MW wind farm connected to the 15 kV/50Hz feeder. If the incoming wind is incident on the wind farm with the direction shown in Fig. 3, then the wind turbines will usually experience similar wind conditions. In this way, this neglects the effects of speed deviations between different WTGs and allows modeling the entire wind farm by an aggregated equivalent wind turbine model with the power capacity of 6 MW. The MVA-rating of the equivalent WTG is the sum of the MVA rating of the three individual WTGs. Using the MVA-rating (2 MVA) as the base value, the parameters in per-unit value of the equivalent WTG are the same as those for each individual WTG. As shown in Fig. 4(a), real data of wind speed profile during 300 s were used as input of the wind farm. Under these conditions, the wind farm produces the fluctuating active power profile shown in Fig. 4(b). Comparison of the wind farm detailed model (blue solid lines) and the simplified aggregated equivalent model (red dashed lines) under real wind fluctuations show nearly the same accuracy, but the simplified modeling approach greatly reduces the excessive computation effort of the detailed modeling approach. This occurs because all the WTGs in the same section are running at the same operating point and therefore can be exactly represented by one equivalent WTG.

6. CONCLUSIONS

The dynamic modeling and control approach of a wind farm with variable-speed direct-driven PMSG WTGs for dynamic studies in DG systems has been presented in this paper. The proposed wind farm modeling approach groups all WTGs that experiences similar wind velocities into an equivalent aggregated WTG model. This simplified modeling is developed using the state-space averaging technique. In addition, a three-level control scheme is designed. Simulation results demonstrate the effectiveness of the proposed simplified models and control systems for the individual WTGs and also for the entire wind farm, if the wind distribution across each WTG is regular.

7. REFERENCES


Figure 4. Comparison of the wind farm detailed model and the simplified equivalent model under real wind fluctuations with APCM.