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Dynamic DFIG wind farm model with an aggregation technique

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***Abstract*— Wind farms begin to influence the power systems with the increasing amount of wind power penetration. The study of such influence justifies the need of a dynamic wind farm model comprising of a large number of generators, but detail models require high simulation computation time. An aggregation technique is required to reduce the model order while maintaining its accuracy. In this paper, a complete and an aggregated wind farm model with Doubly Fed Induction Generator (DFIG) are presented. Simulations have been carried out for both models and compared to demonstrate effectiveness of the aggregated model in terms of accuracy in approximation of the dynamic collective responses at the Point of Common Connection (PCC) and reduction in simulation computation time.**

***Keywords*— Doubly fed induction generator, Wind farm, Dynamic response, Aggregated model.**

I. INTRODUCTION

Wind power has been the fastest growing energy source since the last decade. Wind power capacity has reached 159,213 MW (2% of global electricity consumption) worldwide with a growth rate of 31.7% in 2009 and a foreseeable penetration of 12% of global electricity demand (1,900,000 MW) is predicted by the year 2020 [1]. With the increasing amount of wind power penetration in the power systems, the wind farms begin to influence the power systems. This justifies the need of adequate models for wind farms in order to represent overall power system dynamic behaviour of grid-connected wind farms.

With the recent progress in modern power electronics, Doubly Fed Induction Generator (DFIG) is receiving increasing attention due to a number of its advantages stated in [2]. Hence, DFIG based wind turbine has become the most recent and widely used technology for wind farms.

Full aggregation techniques have been followed considering identical winds received by all the individual wind turbines of a wind farm in [3]-[5]. Full aggregated model during different wind incidents gives poor approximations of the collective response of the wind farm at the Point of Common Connection (PCC) [6]. Semi aggregation approach has drawn attention since then. Aggregated mechanical model with non-aggregated electrical model have shown some good results in [7]. Aggregated electrical model has been combined with non-aggregated mechanical model for better approximations of the collective response of the wind farm at the PCC in [2], [8].

This paper presents a new approach of simplified, reduced order aggregated model of a complete DFIG wind farm model. Due to having different operating conditions of wind turbines for different incoming winds, the aggregated model includes dynamic simplified model of each of the wind turbines with rescaled power capacity to feed equivalent mechanical torque into the aggregated generator system. The aggregated model includes lesser number of differential equations compared to the aggregated models introduced by [2] and [6]. Then, the effectiveness of the aggregated model is demonstrated in terms of approximation of the collective response at the PCC and simulation computation time comparing with those of the complete wind farm model.

II. COMPLETE WIND FARM MODEL

DFIG wind farm comprises of wound rotor induction generators connected to wind turbines through drive train in between. The generator stator is directly connected to the grid and the generator rotor is connected to the grid through two back-to-back IGBT PWM converters with an intermediate DC link capacitor. In this paper, the wind farm model is represented in terms of behavior equations of each of the subsystems, mainly the turbine, the drive train, the induction generator, the control system and the grid (Fig. 1).

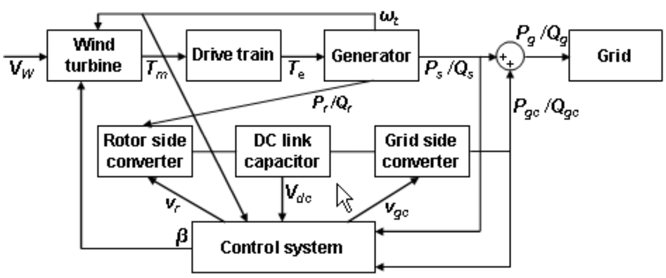

Fig. 1 Components of a DFIG wind farm

A. *Wind turbine model*

C_p-λ-β curve demonstrates the characteristics of the aerodynamic model of a wind turbine [9]. The mechanical torque (T_m) produced by the wind turbine is given by [10],

$$T_m = \frac{1}{2\lambda} \rho ARC_p(\lambda, \beta) V_W^2 \qquad (1)$$

ρ is the air density, A is the sweep area of the blades, R is the blade length, Cp is the power coefficient, λ is the tip speed ratio, β is the pitch angle and V_W is the wind speed.

B. Drive train model

Conventionally, the rotor is treated as two lumped masses, i.e. turbine mass and generator mass are connected together by shaft with a certain damping and stiffness coefficient values.

After simplifications by neglecting the turbine and generator self-damping, shaft stiffness and torsional oscillations, the mathematical equation can be expressed according to [11]

$$2\left(H_t + H_g\right)\frac{d\omega_t}{dt} = T_m - T_e \qquad (2)$$

H is the inertia constant, ω is the rotor angular speed and T_e is the electromagnetic torque. Suffix t and g denote the turbine and the generator respectively.

C. Generator model

A synchronously rotating d-q reference frame is chosen and generation convention is considered during modeling the induction generator. Neglecting the calculation of external capacitor sets to the generator, stator and rotor voltages in both d and q axes are given by [11],

$$v_{ds} = -R_s i_{ds} - \varphi_{qs} + \frac{1}{\omega_b}\frac{d\varphi_{ds}}{dt} \qquad (3)$$

$$v_{qs} = -R_s i_{qs} + \varphi_{ds} + \frac{1}{\omega_b}\frac{d\varphi_{qs}}{dt} \qquad (4)$$

$$v_{dr} = R_r i_{dr} + s\varphi_{qr} + \frac{1}{\omega_b}\frac{d\varphi_{dr}}{dt} \qquad (5)$$

$$v_{qr} = R_r i_{qr} + s\varphi_{dr} + \frac{1}{\omega_b}\frac{d\varphi_{qr}}{dt} \qquad (6)$$

R_s and R_r are the resistances of the stator and rotor windings respectively. v_{ds}, v_{qs}, v_{dr}, v_{qr}, i_{ds}, i_{qs}, i_{dr}, i_{qr}, φ_{ds}, ,φ_{qs}, φ_{dr} and φ_{qr} are the d and q components of the stator and rotor voltages, currents and flux and ω_b is the angular frequency.

The electromagnetic torque, T_e is expressed in [12] as:

$$T_e = p\left(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}\right) \qquad (7)$$

where p is the number of pole pairs.

The real and reactive powers at the stator winding, rotor winding and power converter are calculated in [11] as:

$$P_s = -v_{ds} i_{ds} + v_{qs} i_{qs} \qquad (8)$$

$$Q_s = v_{qs} i_{ds} + v_{ds} i_{qs} \qquad (9)$$

$$P_r = -\left(v_{dr} i_{dr} + v_{qr} i_{qr}\right) \qquad (10)$$

$$Q_r = -\left(v_{qr} i_{dr} + v_{dr} i_{qr}\right) \qquad (11)$$

$$P_{gc} = P_r \qquad (12)$$

$$Q_{gc} = 0 \qquad (13)$$

The real and reactive powers delivered to the grid are given by [2],

$$P_g = P_s + P_r \qquad (14)$$

$$Q_g = Q_s \qquad (15)$$

D. Control system model

The control system generates pitch angle command signal, β for temporary reduction of wind turbine mechanical power when the rotor speed is over 1.21 p.u. It also generates the voltage command signal v_r and v_{gc} for the rotor and grid side converters respectively in order to control the DC voltage and the reactive power or the voltage at the grid terminals.

E. Grid model

An infinite bus is implemented by a voltage source which maintains the grid voltage and frequency to a constant value.

The block diagram of the complete wind farm model is depicted in Fig. 2.

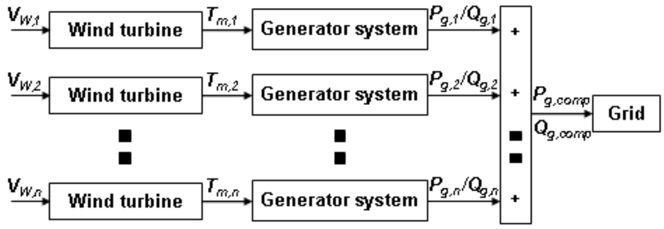

Fig. 2 Block diagram of the complete wind farm model

III. AGGREGATED WIND FARM MODEL

Aggregated model represents the collective response of a DFIG wind farm at the PCC with the highest possible accuracy. For system impact studies like impact of the wind farms to the power transmission system or interaction of wind farms with other power plants, complete model requires a significantly high computation time. Aggregated model enables important reduction in model order and simulation computation time.

In this paper, a new semi aggregation technique is approached considering different wind incident on each row of the wind turbines in the wind farm. Mechanical torque with proper system base from each of the individual wind turbines for their corresponding incoming wind speed is approximated and aggregated. This equivalent torque is then fed into the aggregated generator system comprising of induction generator and power converters (Fig. 3).

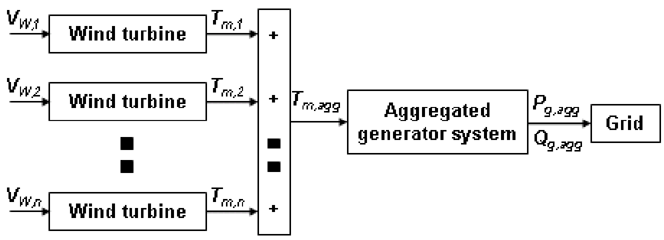

Fig. 3 Block diagram of the aggregated wind farm model

The aggregated generator system is represented by the same equations (2)-(15) with the same mechanical and electrical (in p.u.) parameters used for the individual wind turbines. The DC link capacitor, C and Inertia constant, H are mathematically formulated as:

$$C_{agg} = \sum_{i=1}^{n} C_i \quad (16)$$

$$H_{agg} = \frac{1}{n} \sum_{i} H_i \quad (17)$$

IV. SIMULATION RESULTS

The wind farm models have been implemented and simulated by using Matlab v.7.8.0 (Simulink and SimPowerSystems library browsers). Several simulation cases have been developed in order to present the dynamic responses of the complete wind farm model and validate the proposed aggregated model.

A. Dynamic responses of the complete wind farm model

The wind farm under consideration comprises of six grid connected DFIG wind turbines (index 1 to 6 has been used for identification), each of 1.5 MW, 575 V. The effective fluctuating wind speed is considered to be reduced by 1 m/s per row of wind turbines due to shadowing effect and turbulence (Fig. 4a) [4].

Wind turbines 2 to 5 receive wind below the nominal speed value (12 m/s). So, the rotor speed never exceeds the control speed value 1.21 p.u. (Fig. 4b). So, there is no generation of pitch angle, β (Fig. 4c) and hence C_p remains constant. So the power curve follows the wind speed curve proportionally (Fig. 4e) followed by generation of mechanical torque (Fig. 4d).

Wind turbine 1 eventually receives wind above the nominal speed value. Wind speed reaches 14.5m/s and 14m/s at t=14.3s and t=36.3s respectively, which causes rotor speed exceeding 1.21 p.u. So, the pitch angle controller is activated limiting the mechanical power extraction and hence maintains the rotor speed to the control speed value. Therefore, C_p remains no more constant, rather become a non-linear function of λ and β. This is how mechanical torque is limited to -0.74 p.u. and active power to 1.2 p.u. During remaining period, it behaves like other wind turbines.

Due to having capacitive loads, all of the generators absorb same average reactive power (being negative) of 0.08 p.u. to the grid over 50s period during normal operation.

B. Evaluation of the aggregated model

The effectiveness of the proposed aggregated model has been evaluated through comparing the collective responses of the complete and aggregated wind farm models at the PCC. The parameters used for comparison are active and reactive power at the PCC. The simulations have been carried out under two operating conditions: (1) normal operation and (2) grid disturbance.

During normal operation, same wind incident has been considered for individual wind turbines as stated in section IV(A). Fig. 5 shows that, a very good agreement in dynamics is observed between the responses of the complete and aggregated wind farms with an average discrepancy of 5.35% in active power magnitude and 5.22% in reactive power magnitude during 50s period.

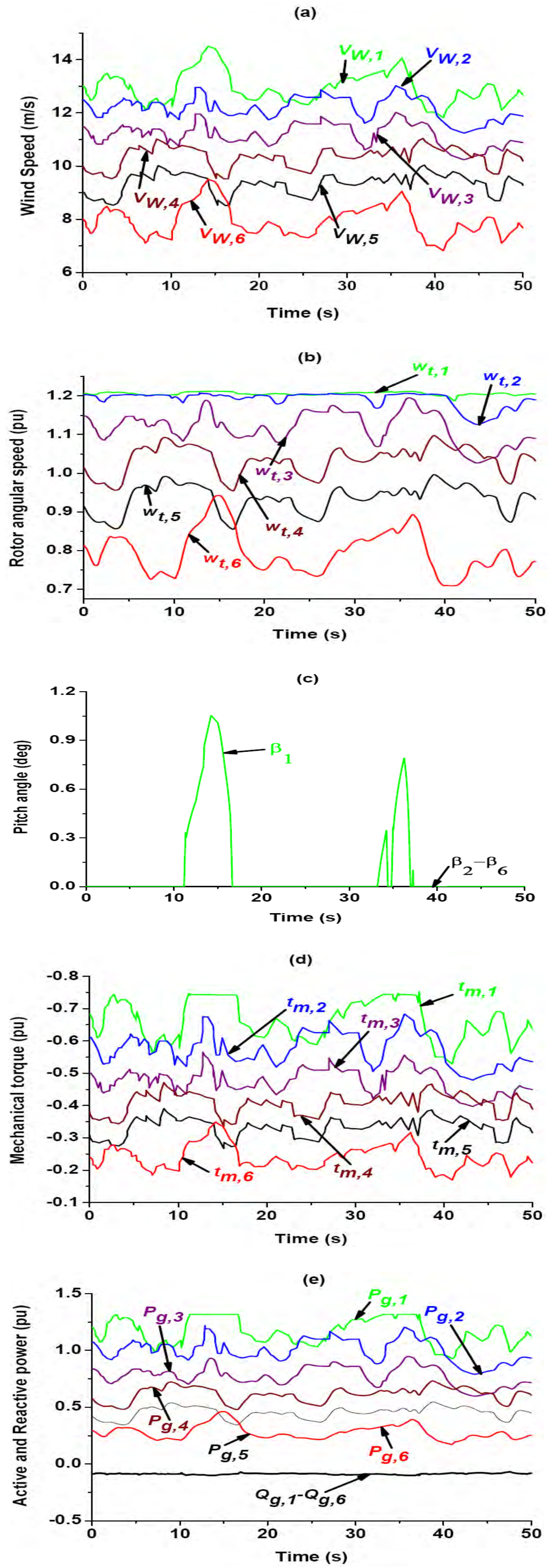

Fig. 4 Dynamic responses of each individual wind turbine in the complete wind farm model: (a) wind incident, (b) Rotor angular speed, (c) Pitch angle, (d) Mechanical torque and (e) Active and reactive power

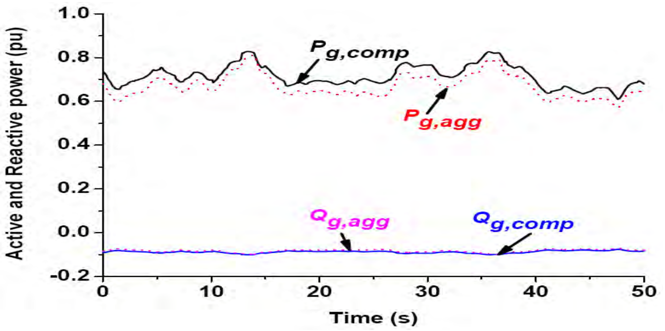

Fig. 5 Active and reactive powers at the PCC for complete and aggregated wind farm model during normal operation

The evaluation of the proposed aggregated model has also been carried out during grid disturbance. A voltage sag of 50% lasting for 100ms has been simulated at t=5s (Fig. 6a). Simulation results for both complete and aggregated wind farm model are presented in Fig. 6b.

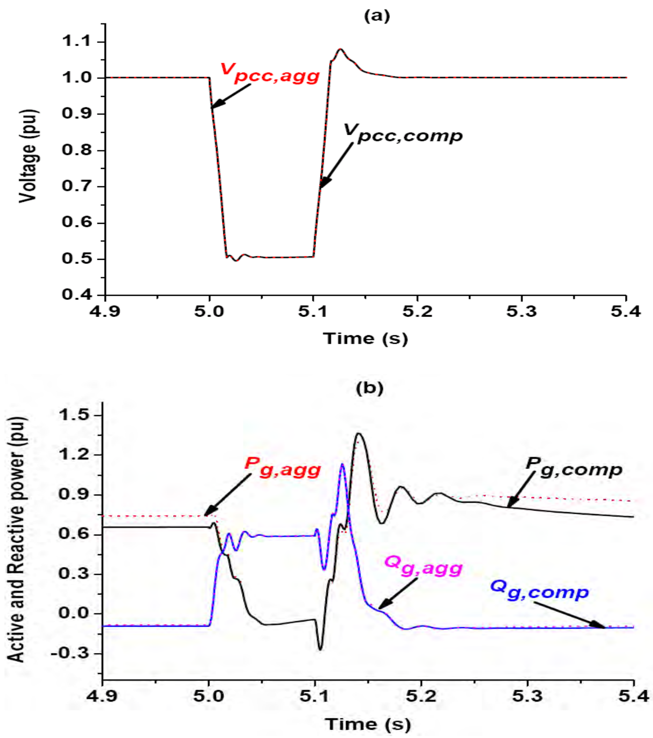

Fig. 6 Voltages, Active and reactive powers at the PCC for complete and aggregated wind farm model during grid disturbance

When there is a grid disturbance, the real power produced by the wind farm reduces and it goes to negative values for a short time (i.e. the grid supplies active power to the generator to keep it spinning). On the other hand, the reactive power which is normally negative (which means the wind farm takes reactive power from the grid) changes sign and increases during the disturbance (this means the wind farm supplies reactive power to the grid during the disturbance to feed the reactive loads on the grid. The responses (both active and reactive powers) of the aggregated wind farm model show good agreement with that of the complete wind farm model in terms of magnitude and dynamics, which demonstrates the effectiveness of the proposed aggregated model, even during grid disturbances.

An important reduction in simulation computation time has been achieved as well. The simulations have been carried out on a personal computer with the following specifications: Intel (R) Pentium (R) Dual CPU E2200 2.20 GHz 2.19 GHz 1.96 GB of RAM. The proposed aggregated wind farm model simulates the results in 35s compared with 234s for the complete model. This observation demonstrates that the simulation computation time is 87% faster when using the proposed aggregated model compared to the complete wind farm model.

V. CONCLUSIONS

In this paper, the dynamic responses of all individual wind turbines in the complete wind farm model have been shown. Then, the effectiveness of the proposed aggregated wind farm model has been evaluated in terms of accurate approximations of the collective responses at the Point of Common Connection (PCC) of the wind farm and the power grid. The advantage of the aggregated model to the complete model is the reduced simulation computation time, which will be important in system studies (where we have many generators connected to a common grid).

It is clearly shown that the proposed simplified aggregated model gives an accurate approximation of the collective responses at the PCC having minor discrepancies in magnitude with a faster simulation computation time.

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