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Comparison between Wind Farm Aggregation Techniques to Analyze Power System Dynamics

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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 a large number of generators, but detail models require high simulation computation time. Wind farm aggregation technique is required to reduce the model order while maintaining its accuracy. Different wind farm techniques have been proposed to simulate and analysis wind farm dynamics. In this paper a comparison between some of these techniques are presented. Simulation have been carried out for these techniques and compare them using different effects such as wind farm power, reactive power and system dynamics, besides the effect of varying variance on these techniques.

Index Terms - Wind farm aggregation, dynamic wind farm model, wind speed variance and doubly fed induction generators.

I. INTRODUCTION

Wind power has been the fastest growing energy source since the last decade. Wind power capacity has reached 159.213 GW (2% of global electricity consumption) worldwide with a growth rate of 31.7% in 2009. A foreseeable penetration of 12% of global electricity demand (1900 GW) is predicted by the year 2020 [1]. With the increasing amount of wind power penetration in power systems; wind farms begin to influence power systems. This justifies the need of adequate models for wind farms in order to represent overall power system dynamic behavior for grid connected wind farms.

There are different generators in use for wind power applications today. The main distinction can be made between fixed speed and variable speed wind generator concepts. A fixed speed wind generator is usually equipped with a squirrel cage induction generator whose speed variations are only very limited. The two variable speed wind generator concepts are the doubly fed induction generator and the converter driven synchronous generator [1]. Doubly fed induction generator (DFIG) wind turbine has recently become the most widely used wind turbine for wind farms [2], since it presents noticeable advantages such as: the variable speed generation, the decoupled control of active and reactive powers, the reduction of mechanical stresses, less noise, improvement of power quality, and use of smaller power converter (rated power of only 25% of total wind system power).

A wind farm may consist of tens to hundreds of wind turbines. This leads to model complexity and computation burden. Fig. 1 shows a complete wind farm model with n number of wind turbines equipped with doubly fed induction generator (DFIG). To simplify the complete wind farm model, an aggregated wind farm (AWF) model is required to reduce the size of the power system model, the data requirement and the simulation computation time. This aggregated model can first represent the behavior (active and reactive power exchanged with the grid) during normal operation, characterized by small deviations and the changes of wind speed. Secondly it represents the behavior of wind farm during grid disturbances, such as voltage drops and frequency deviations [3].

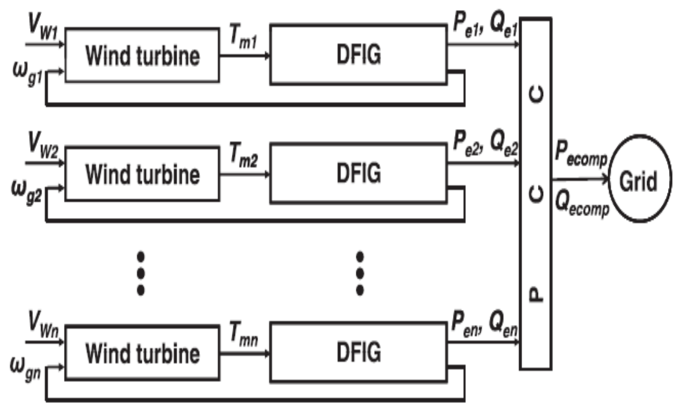
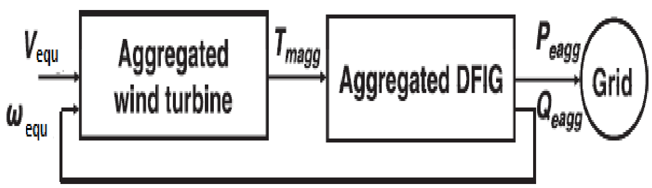


Fig. 1. Block diagram of a complete DFIG wind farm model.

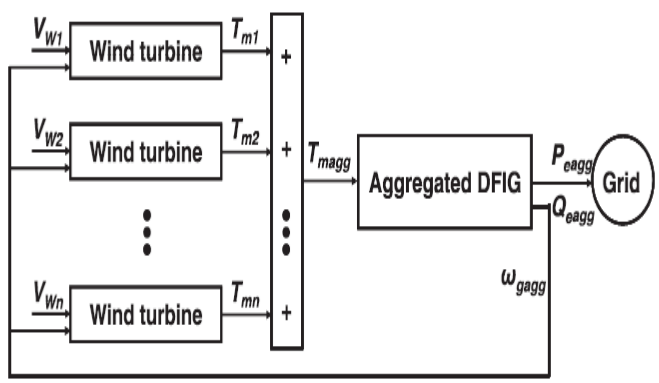
In this paper we have chosen three techniques and compared them between the complete model as a reference. These techniques are:

1- Full aggregated model using average wind speed technique [3].
2- Full aggregated model using equivalent wind speed method (EWM) [4].
3- Semi aggregated model [5].

The full aggregated model of wind farms with DFIG wind turbines represent the whole wind farm by one single equivalent wind turbine without using a dynamic simplified model of each individual wind turbine. It consists of one equivalent wind turbine and one equivalent generator for a wind farm with average wind speed or with equivalent wind speed as shown in Fig. 2(a). To obtain the equivalent wind speed, the output power of each wind turbine is derived from its power curve and the incoming wind. The sum of the output power of each wind turbine is the total output power. Assuming the per unit power curve of the equivalent wind turbine is equal to that one of the individual wind turbine; the equivalent wind can be calculated from the total output power, using the equivalent wind speed power curve. The semi aggregated model is based on using a dynamic simplified model of each individual wind turbine to approximate the generator mechanical torque according to the incoming wind. The generator mechanical torques of each individual wind turbines is aggregated and the resulting torque is applied to an equivalent generator system as shown in Fig. 2(b).



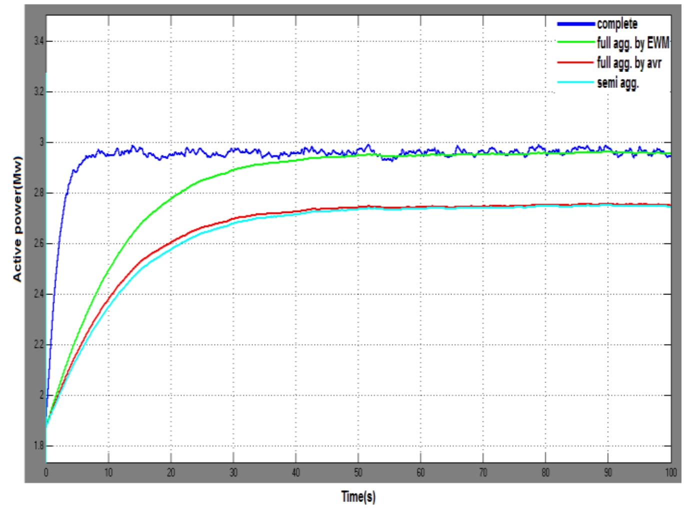
(a)



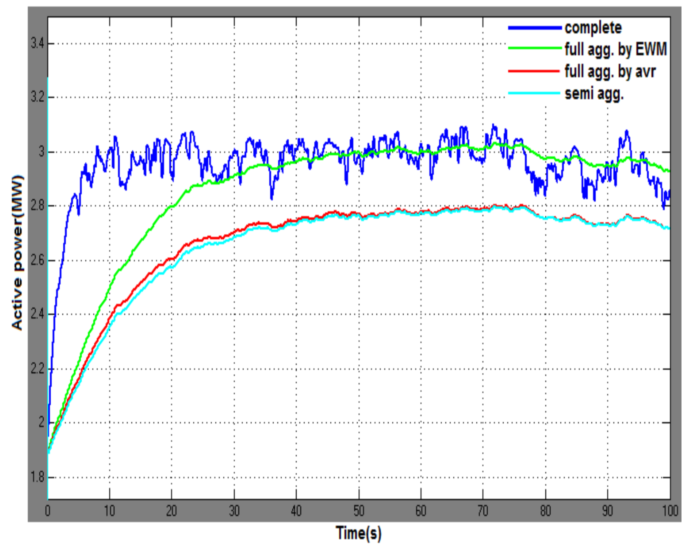
(b)

Fig. 2. Block diagram of (a) full aggregated and (b) semi aggregated DFIG wind farm models.

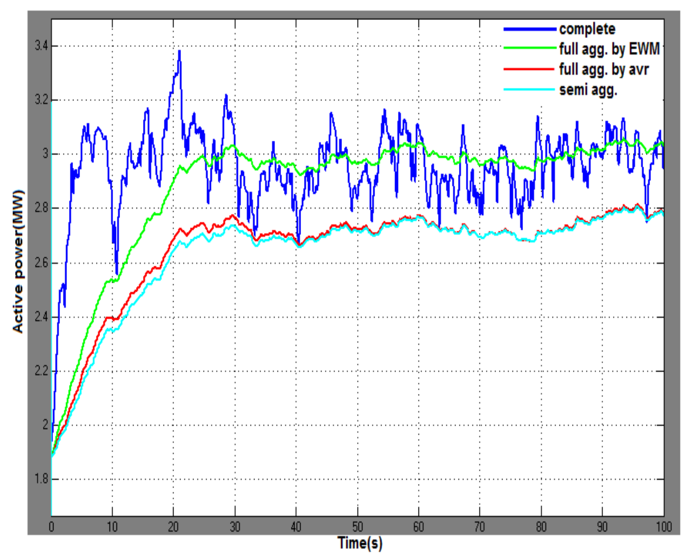
Also we have compared the active power using these techniques for different speed variances (speed variances are 0.1, 0.5, and 1) where the whole wind farm have the same variance in each case as shown in Fig. 3(a,b,c). We can conclude that the effect of variance on the closeness of any aggregated method to the complete solution can not be seen. The same results are found in Fig. 4(a,b,c) when comparing reactive powers.



(a) Speed variance 0.1

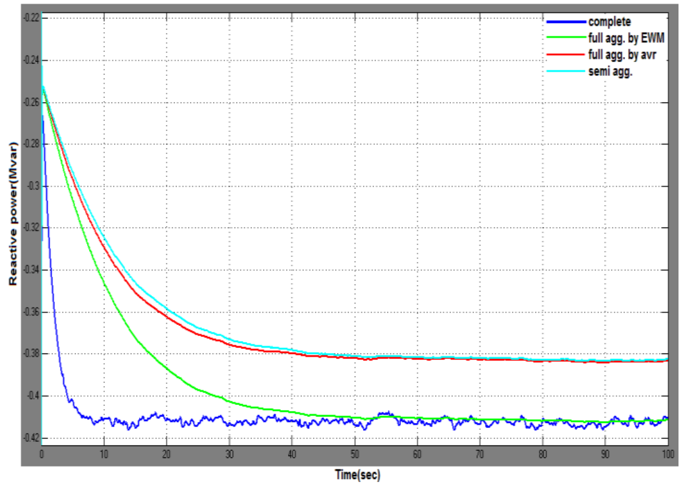


(b) Speed variance 0.5

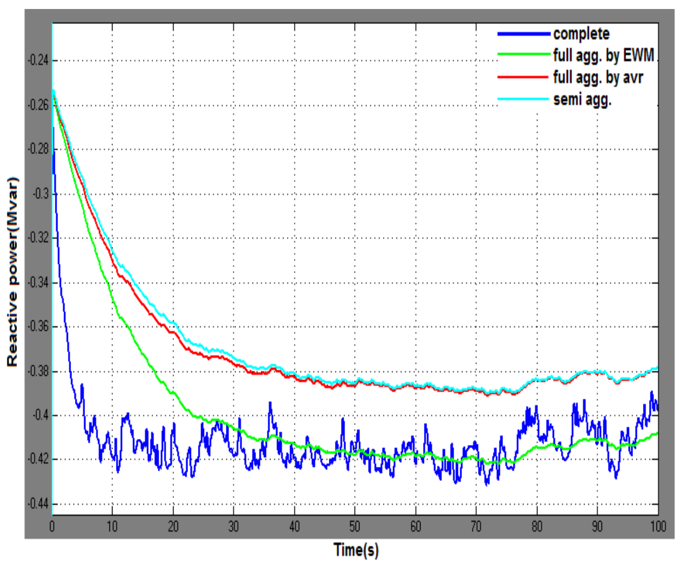


(c) Speed variance 1

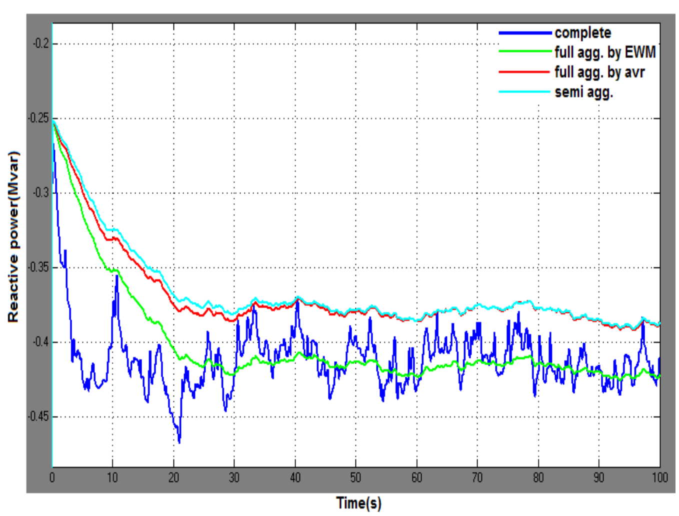
Fig. 3. Active power with different variance speed



(a) Speed variance 0.1



(b) Speed variance 0.5



(c) Speed variance 1

Fig. 4. Reactive power with different variance speed

II. Complete Wind Farm Model

A DFIG wind farm is composed of several DFIG wind turbines operating at an internal electrical network (lines and transformers) which enables the generated power to be delivered to grid, as depicted in Fig. 5. The dynamic response of a DFIG wind farm can be represented by a complete model, in which all the wind turbines and internal electrical network are modeled.

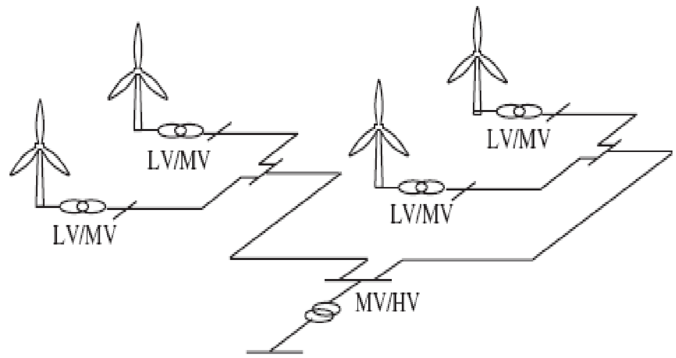


Fig. 5. DFIG wind farm.

A. DFIG Wind Turbine

DFIG wind turbine includes a wound rotor induction generator connected to the wind turbine rotor through a gearbox. This generator presents the stator winding directly grid coupled and a bidirectional power converter feeding the rotor winding, made of two back to back IGBT bridges based voltage source converters linked by a DC bus. This power converter decouples the electrical grid frequency and the mechanical rotor frequency, thus enabling variable speed wind turbine generation. The wind turbine rotor presents blade pitch angle control limiting the power and the rotational speed for high winds. Fig. 6 shows DFIG wind turbine configuration [1].

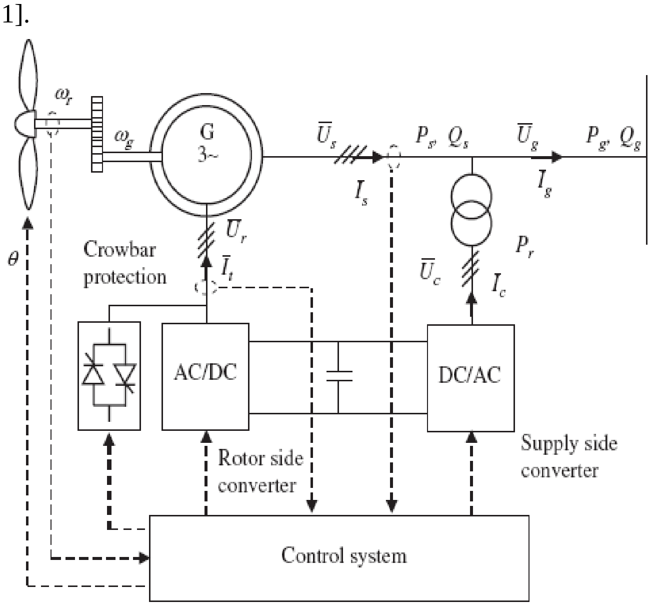


Fig. 6. DFIG wind turbine.

The DFIG wind turbine has been represented by modeling the rotor, drive train, induction generator, power converter and the protection system. The parameters of the DFIG wind turbine used in this paper are shown in Table 1 [9].

Table 1. DFIG wind turbine parameters.

Parameter	Symbol	Value	Unit
Nominal mechanical output power	P_{mec}	1.5	MW
Nominal electrical power	P_e	1.5/.9	MW
Nominal voltage (L-L)	V_{nom}	575	V
Stator resistance	R_s	0.00706	p.u.
Stator leakage inductance	L_s	0.171	p.u.
Rotor resistance	R_r	0.0058	p.u.
Rotor leakage inductance	L_r	0.156	p.u.
Magnetizing inductance	L_m	2.9	p.u.
Base frequency	f	60	Hz
Inertia constant	H	0.84	s
Friction factor	F	3	p.u.
Pair of poles	p	0.01	-

1. Rotor model

The rotor model expresses the mechanical power extracted from the wind by the rotor, given as [1].

$$p_w = 0.5\rho A u^3 c_p(\lambda,\theta). \tag{1}$$

where P_w(W) is the aerodynamic power, ρ(kg/m^3) the air density, A(m^2) the rotor disk area, R(m) the rotor radius, u(m/s) the wind speed, and C_p the turbine coefficient of performance which is a function of the tip speed ratio λ (ratio between blade tip speed and wind speed) and θ the pitch angle of rotor blades. The power extracted from the wind is maximized if the rotor speed is such that C_p is maximum, which occurs for a determined tip speed ratio.

2. Drive train model

The drive train of DFIG wind turbine has been represented in this paper by the two masses model [1]:

$$T_{wt} - T_m = 2H_r \frac{d\omega_r}{dt}. \tag{3}$$

$$T_m = D_m(\omega_r - \omega_g) + K_m \int (\omega_r - \omega_g)dt. \tag{4}$$

$$T_m - T_g = 2H_g \frac{d\omega_g}{dt}. \tag{5}$$

where T_{wt} & T_m are the mechanical torque from the wind turbine rotor shaft and from the generator shaft, T_g is the generator electrical torque, H_r & H_g are the rotor and generator inertia, K_m and D_m are the stiffness and damping of the mechanical coupling.

3. Generator model

The wound rotor induction generator has been represented by the third-order model for stability transient studies of power systems. This model is obtained by neglecting the stator transients for the fifth order model of induction generator. It presents three differential equations [6]: two are electrical equations and the third equation is mechanical, given by (5). The model is expressed into a direct and quadrature reference frame rotating at synchronous speed with the position of the direct axis aligned with the maximum of the stator flux. It enables the decoupled control of active and reactive powers of DFIG [7]. Equations (6-9) are electrical differential expressed per unit and use generator convention, which means that the currents are positive when flowing towards the grid.

$$\frac{de'_d}{dt} = -\frac{1}{T'_o}(e'_d - (X_s - X'_s)i_{qs}) + s\omega_s e'_q - \omega_s \frac{L_m}{L_{\sigma r} + L_m} u_{qr}. \tag{6}$$

$$\frac{de'_q}{dt} = -\frac{1}{T'_o}(e'_q - (X_s - X'_s)i_{ds}) + s\omega_s e'_d + \omega_s \frac{L_m}{L_{\sigma r} + L_m} u_{dr}. \tag{7}$$

$$T_g = L_m(i_{ds}i_{qr} - i_{qs}i_{dr}). \tag{8}$$

where u denotes voltage, i denotes current, indexes d and q, the direct and quadrature components, indexes s and r refers to stator and rotor, e'_d and e'_q are the internal voltage components of induction generator, ω_s is the synchronous speed, s is the generator slip, T'_o is the transient open circuit time constant, T_g is the generator electrical torque, X_s is the stator reactance and X'_s is the transient reactance, expressed as

$$T'_o = \frac{L_{\sigma r} + L_m}{L_m}, X_s = \omega_s(L_{\sigma s} + L_m), X'_s = X_s - \omega_s \frac{L_m^2}{L_{\sigma r} + L_m}. \tag{9}$$

with R_s and R_r are the stator and rotor resistances, $L_{\sigma s}$ and $L_{\sigma r}$ the stator and rotor leakage inductances and L_m the magnetizing inductance.

The bidirectional frequency converter is made up of two back to back IGBT bridges linked by a DC bus. A converter is connected to the rotor winding (rotor side converter) and the other converter to the grid (supply side converter) [8]. The rotor side converter controls the rotor voltage, and thus the wind turbine can operate with optimum efficiency below nominal winds or with the output power limited to rated power above nominal winds with the desired power factor. The supply side converter maintains the exchange power from the rotor circuit to the grid and operates at unity power factor. It is assumed in this paper that these converters are considered ideals and the DC link voltage between the converters is constant, as usual for power system simulations [7]. The rotor side converter is modeled as a controlled voltage source with the q-axis rotor voltage u_{qr} controlling the rotor speed and d-axis rotor voltage u_{dr} controlling the reactive power. The supply side converter is represented by a controlled current source, which provides the exchange of active power from the rotor circuit to the grid with unity power factor. The DFIG generation system can be represented by the equivalent circuit shown in Fig. 7.

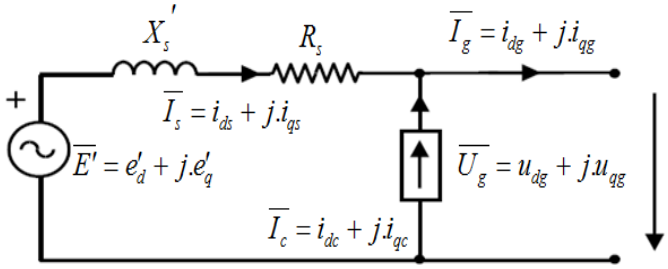


Fig. 7. Equivalent circuit of DFIG wind turbine.

4. Control system

The control system of DFIG wind turbine is composed of three controllers: rotor speed, blade pitch angle and reactive power controller as shown in Fig. 8(a,b,c). The wind turbine control is based on the following control strategies [8]:

1. Power optimization below rated wind speed. In this case, the wind turbine generates the optimum power corresponding to the maximum power coefficient. The blade pitch angle controller keeps the pitch angle to its optimal, whereas the tip speed ratio is driven to its optimal value by the rotor speed controller acting on the rotor speed/generator torque.

2. Power limitation above rated wind speed. The wind turbine operates with the power limited to the rated value. In this case, the rotor speed controller assures the rated power by acting on the rotor voltage, whereas the blade pitch angle keeps the generator speed limited to the control value by acting on the pitch angle.

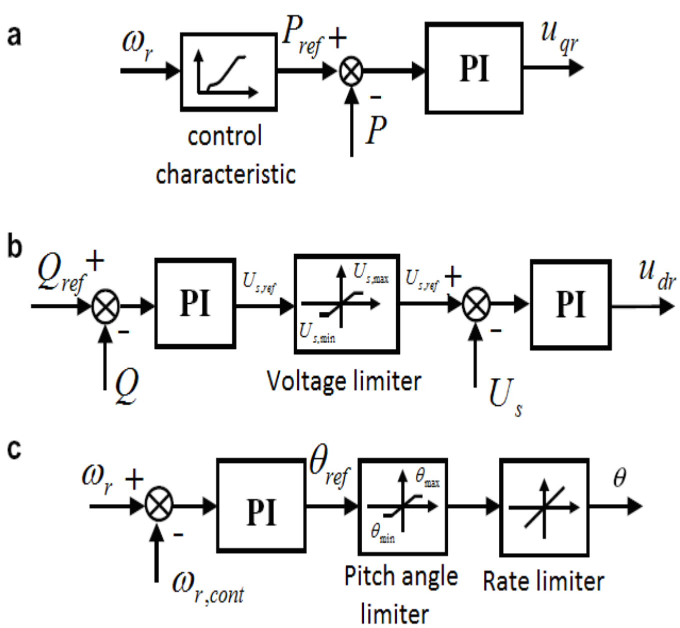


Fig. 8. Controllers of a DFIG wind turbine: (a) rotor speed controller, (b) reactive power controller and (c) blade pitch angle controller.

5. Protection system

To limit the rotor voltage and current, and to protect the electronic devices used in the power converter, DFIG wind turbine presents a crowbar [7], which protects the rotor and power converter against over-current. The crowbar protection is external rotor impedance, coupled via the slip-rings to the generator rotor instead of the converter. When a grid disturbance occurs and the control system detects a rotor current value above the current protection limit, the rotor side converter is disabled and bypassed by the crowbar protection. Therefore, DFIG is turned into squirrel cage induction generator, and the independent controllability of active and reactive power gets lost.

B. Wind Farm Electrical Network

The wind farm electrical network is modeled by the static model of electric lines and transformers, represented by constant impedance, as usual for power systems simulations [6].

A matlab simulation has been done to present the proposed systems.

III. Power Curve of DFIG Wind Turbine

Fig. 9 shows the power curve of the DFIG wind turbine model from SimPowerSystems [9]. Each point on the power curve has three values, namely turbine output power, wind speed, and turbine speed. When incoming wind is less than the nominal wind speed (NWS), DFIG uses the optimal tracking strategy (OPTS) to capture maximum wind energy, which corresponds to the curve between B and C. When incoming wind is greater than NWS, the blade pitch control is used to reduce the mechanical power to the equipment rating, which corresponds to the horizontal line starting from D. The curve between C and D is introduced to smooth the power fluctuations occurring near the NWS. When the incoming wind speed is lower than that of A, the mechanical power of the DFIG is zero, and the curve between A and B is introduced to smooth the power fluctuations occurring near point A.

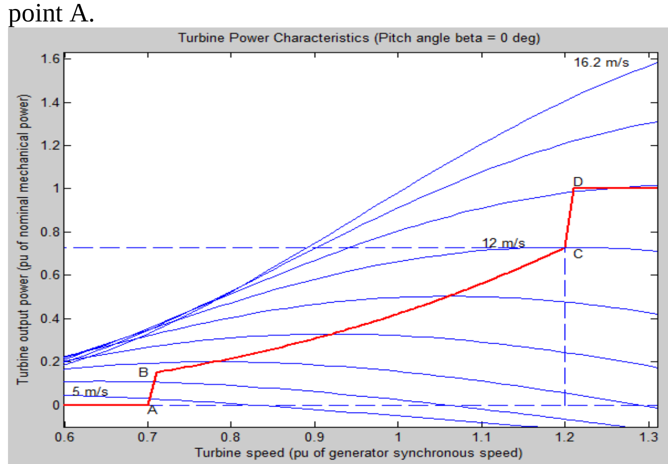


Fig. 9. Power curve of DFIG from SimPowerSystems

Table 2 shows the data regarding the four points A-D of the power curve.

Table 2. Data of point A-D

Points	Wind speed (m/s)	Turbine speed (p.u.)	Turbine output power (p.u.)
A	4.23	0.7	0
B	7.1	0.71	0.151
C	12	1.2	0.73
D	13.48	1.21	1

IV. Equivalent Wind Method (EWM)

The EWM from [10] is used for the aggregation of DFIG wind turbines. This equivalent wind is derived from the power curve of the wind turbine, according to the following procedure:

1. The output power of each wind turbine P_j is derived from its power curve corresponding to the incoming wind.

$$P_j^{wt} = PC_{wt}(v_j). \tag{10}$$

where $PC_{wt}(v_j)$ is a function which represents the power curve of the wind turbine against wind speed and the super index wt represents the value in p.u., expressed in the individual wind turbine base.

2. The equivalent power P_{eq} is the sum of the output power of all wind turbines power,

$$P_{eq}^{wt} = \sum_{j=1}^{n} P_j^{wt}. \tag{11}$$

3. After that, P_{eq}^{wt} is expressed in the equivalent wind turbine base as P_{eq}^{ewt}. Where the resulting power curve expressed in the equivalent wind turbine base is the same as the individual wind turbines,

$$P_{eq}^{ewt} = PC_{ewt}(v_{eq}). \tag{12}$$

$$PC_{ewt} = PC_{wt}. \tag{13}$$

4. The equivalent wind speed of the whole aggregated system is derived from the inverse function of the power curve.

$$v_{eq} = PC_{ewt}^{-1}(P_{eq}^{ewt}). \tag{14}$$

5. If all aggregated DFIG wind turbines faced above nominal winds, the equivalent wind is the average wind speed.

V. Simulatin Results

A 9 MW wind farm from SimPowerSystems has been used for simulation studies. As shown in Fig. 10, the wind farm consists of six 1.5 MW wind turbines connected to a 25 kV distribution system, and a 500 kW load is connected on the 575 V bus of the wind farm. The parameters of this studies system can be found in [9].

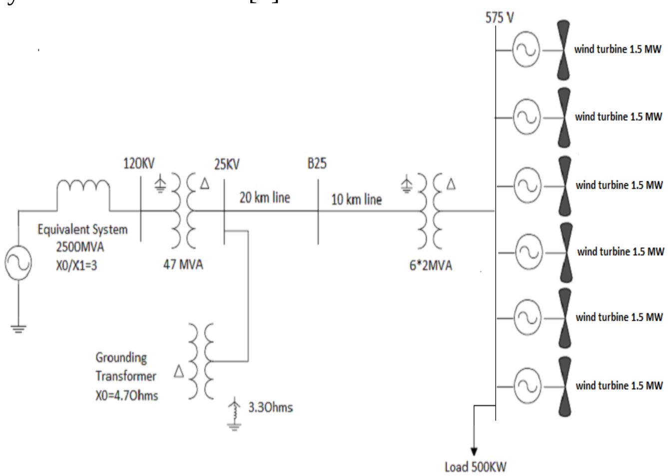


Fig. 10. A 9 MW wind farm connected to a distributed system

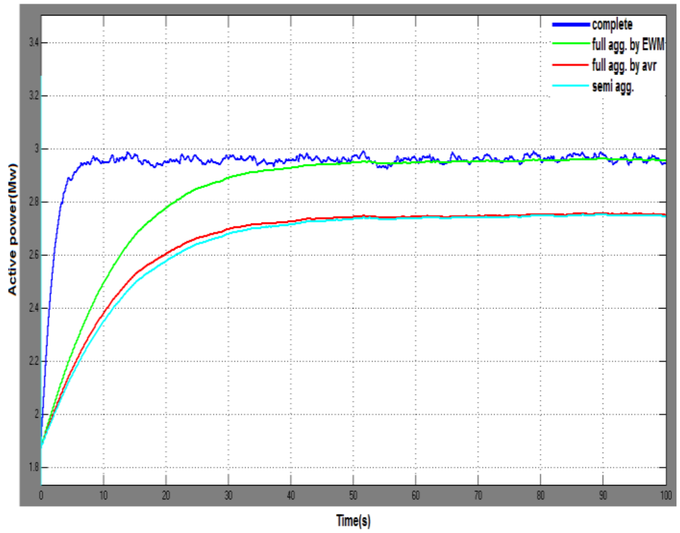
The complete, full aggregated and semi aggregated model are simulated using Matlab software to obtain the dynamic responses at the PCC under the following two conditions: 1- normal operation and 2- grid disturbance. The variables considered for the comparison are the active (P_e) and reactive power (Q_e) exchange between the wind farm and power system. Table 3 shows the speed of the wind received by the DFIG wind turbines.

Table 3. Wind speeds incident on the wind turbines

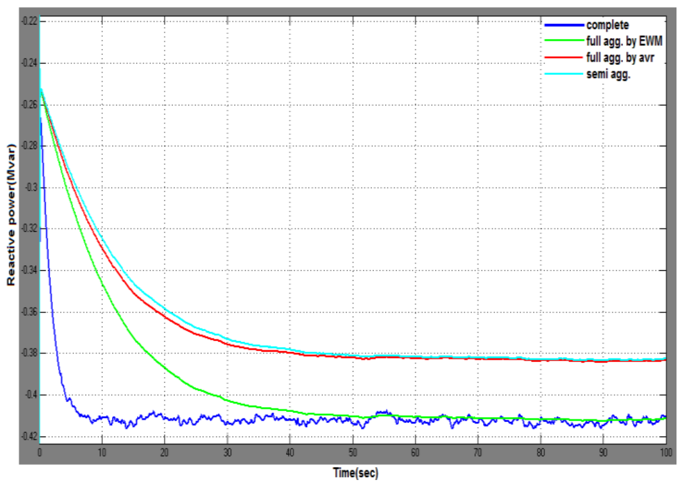
Wind turbine	WT1	WT2	WT3	WT4	WT5	WT6
Wind speed (m/s)	6.9	7.8	8.9	9.4	10.3	11.2

A. Normal Operation

During normal operation, the wind farm operates under wind speed fluctuations. In this case, the wind farm has been simulated with different incoming winds. The collective responses of the complete, two full aggregated and semi aggregated wind farm models at the PCC during normal operation are shown in Fig. 11.

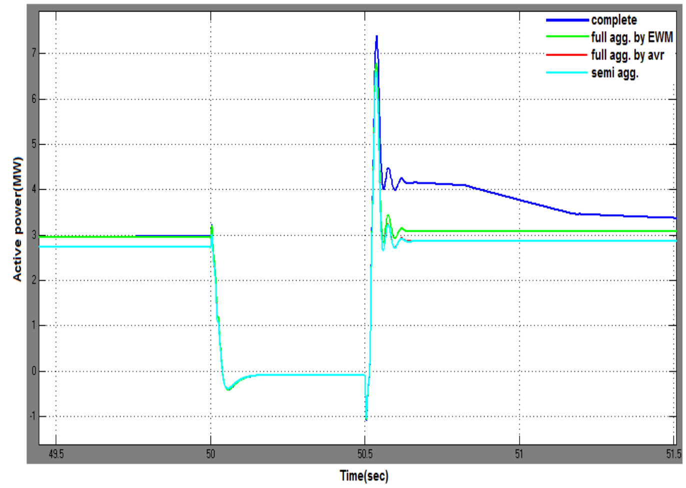


(a)



(b)

Fig. 11. (a) Active power at PCC during normal operation. , (b) Reactive power at PCC during normal operation.



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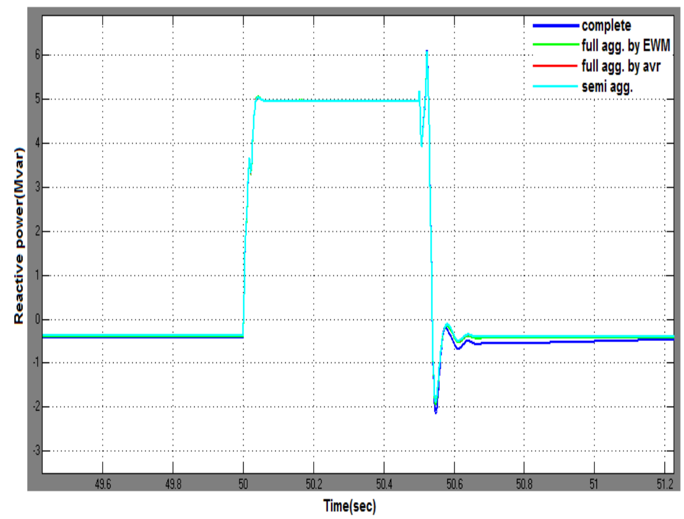

(b)

Fig. 12. (a) Active power at PCC during grid disturbance. , (b) Reactive power at PCC during grid disturbance.

The results depicted in Fig. 11 shows that the full aggregated model using EWM has a higher correspondence in approximating active and reactive power to the complete model. Unlike in ref [3] where he proposed aggregation technique with the incorporation of a mechanical torque compensation factor (MTCF) into the full AWF model. They compare between full aggregated model using average wind speed and semi aggregated model. But he did not use the full aggregated model with the equivalent wind speed which gives the best and closest results to the complete technique.

B. Grid Disturbance

A voltage sag of 50% lasting for 500 ms is originated at the PCC at t = 50 s to evaluate the collective responses of the complete, two full aggregated and semi aggregated wind farm models during grid disturbances at PCC as shown in Fig. 12.

From Fig. 12(a,b) we can conclude that the full aggregated model using EWM is also much closer in the results of the complete aggregated model during the simulation of grid disturbances. This means that we can relay on full aggregated model using EWM even at cases of system dynamic disturbances.

The simulations have been carried out on a personal computer with the following specifications: Intel (R) Core (TM) i5-2430M CPU @ 2.40 GHz 2.40 GHz 2.99 GB of RAM. The computation time takes 103, 89, and 85 second for full aggregated using EWM, full aggregated using average wind speed, and semi aggregated model compared with 924 second for the complete model. This observation demonstrates that any of the three techniques consume lesser time than the complete model for only 6 wind turbines.

VI. CONCLUSION

In this paper, the dynamic responses of all individual wind turbines in the complete wind farm model have been presented as reference. The aim is to simulate the dynamic responses of wind farm with an acceptable level of accuracy while reducing the simulation time considerably by using different aggregation techniques and compare each one with the (reference one) complete model. The advantage of the aggregated model to the complete model is the reduced simulation computation time, which is important in system studies where we have many generators connected to a common grid. The proposed full aggregated model consists of one equivalent wind turbine and one equivalent generator for a wind farm with average or equivalent wind speed which is derived from the power curve of the aggregated wind farm. The semi aggregated model consists of all wind turbines in the wind farm and one equivalent generator. A comparison between complete, two full aggregated and semi aggregated models are simulated using Matlab simulation program. First we examine the effect of varying the variance of the applied wind speeds on different proposed aggregated models and we found that no clear evidence that varying the variance effects differently on different aggregated models. Second the full aggregated model using EWM gives the accurate approximation of the collective responses at the PCC having minor discrepancies in magnitude with a fast simulation computation time. This result different than [3] which concluded that semi aggregated model is the closest to the complete model.

VII. REFEERNCE

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