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Validation of multi-machine and single-machine equivalent models for wind farm transient stability studies

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ABSTRACT

Stability study of power system with wind farm is challenging task due to collection of system data, computation burden in case of system order and long simulation time. An aggregated representation of fixed speed wind turbine generator (WTG) is proposed for an actual wind farm which is a part of the Indian utility system. The stability study of actual system and equivalent system are simulated in MATLAB software package. Multi-machine and single-machine equivalent wind farm models are developed based on simple aggregation technique. The transient stability responses of these two equivalent wind farm models that are compared with actual wind farm system at point of common coupling (PCC). The two equivalent wind farm models response provides a satisfactory accuracy with actual system response for the three phase fault and varying wind speed. Also equivalent wind farm model responses are validated with actual system response for different dynamic conditions.

Indexing terms/Keywords

Wind farm; Fixed speed wind turbine generator; Simple aggregation; Transient stability; Indian utility system

Academic Discipline And Sub-Disciplines

Electrical Engineering, Wind energy

SUBJECT CLASSIFICATION

Power system stability, Wind energy conversion system

TYPE (METHOD/APPROACH)

Simulation investigation

INTRODUCTION

Incredible growth of wind energy harvesting technology is introduced for the use of different types of grid integrated wind turbine generator at distribution end and it is predominantly needed because of the diminution of fossil fuels. In India, installed capacity of wind power was 25.088 GW (as on Dec 31, 2015). India is ranked fourth in the world for wind power installed capacity and one of the major players in the global wind energy market [1]. An Indian Wind Energy Association (INWEA) has forecasted the 'on-shore' potential of wind energy in the order of 65 GW. In Tamil Nadu, the installed capacity of wind power in Tirunelveli and Udumalapet region is 7200 MW [2]. Presently it has been added in the capacity of 3000 MW. The evolving very large scale wind farm enforces utilities to do planning for evacuating wind power into grid and assessment of stability of the system. The large scale wind farms penetrated power into the grid can influence the power system, affects steady state and dynamics stability condition of the system [3]. Steady state and dynamic stability analysis of large scale wind farm become more tedious work for utility due to increased size of different wind turbine generators and repowering of wind turbine generators. Aggregated equivalent wind farm model reduces simulation time and effort while investigating transient stability analysis for a power system. Hence, utilities and researchers need the accurate equivalent model of large-scale wind farm.

An equivalent wind farm model has been obtained by aggregating the wind turbine generators present in the wind farm. In paper [4], aggregating turbines with and without identical incoming wind speed is discussed. The equivalent models are validated by detailed wind farms responses. In this [5, 6], an equivalent models of wind farms of both Squirrel Cage Induction Generator (SCIG) and Doubly Fed Induction generator (DFIG) with two equivalent models are considered. The average wind speed is used for the aggregated wind turbines, and an equivalent incoming wind speed is derived from the power curve if wind speed is non-uniform in wind farm. The effectiveness of the equivalent models provides the good collective response of the wind farm at the PCC to grid during wind fluctuations and a grid disturbance. In this paper, a simple method of aggregation of fixed speed wind turbine generators for a wind farm is presented [7]. An aggregated equivalent system response is compared with actual representation of wind farm during steady state and dynamic conditions at PCC.

This paper is organized as follows, Section 2 discusses briefly about the modelling of wind energy conversion system (WECS), Section 3 contains multi machine and single machine equivalent wind farm models; also aggregation methodology for a wind farm is explained. In Section 4, the simulation results are compared between two equivalent wind farm models with actual system. The conclusion of the paper is present in Section 5.

2. MODELLING OF WIND ENERGY CONVERSION SYSTEM

The main components of fixed speed wind turbine generator are wind turbine and generator. The drive drain influence and pitch angle controller of a generator are not considered in this paper. Hence the stiff model of wind turbine and generator is used for simulation.

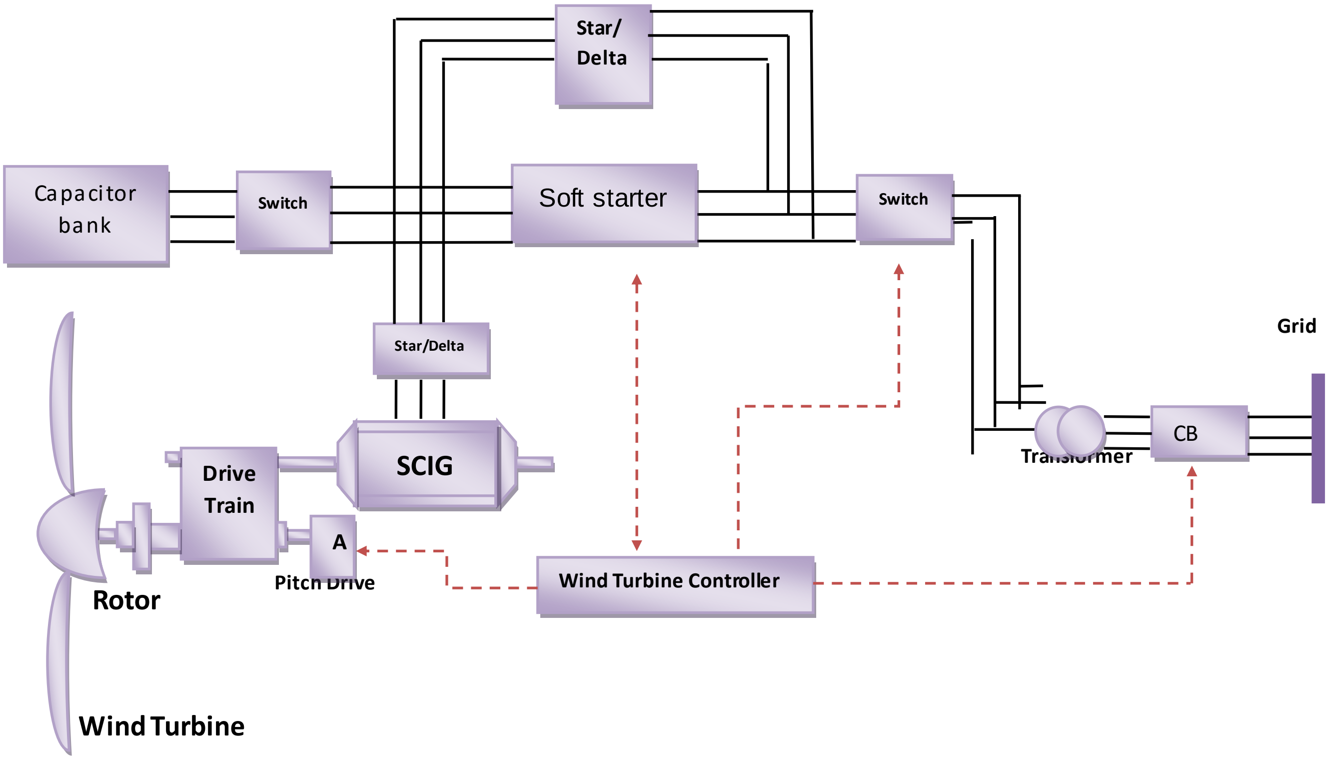

Fig.1 General structure of fixed speed wind turbine generator

The main driving force of any kind of wind turbine is wind speed and it is briefly explained in this section. The general structure of the WECS is shown in Fig.1. The modelling of each of components is presented in the following sections.

2.1 Wind speed model

The wind speed can be modeled as a deterministic and stochastic process [8]. This resultant expression of wind speed $V_w(t)$ is given by,

$$V_w(t) = V_a + V_r(t) + V_g(t) + V_{tc}(t) \tag{1}$$

where, V_a, $V_r(t)$, $V_g(t)$, $V_{tc}(t)$ are average, ramp, gust and turbulence component of wind velocity respectively.

In this paper, the power loss is very less due to wake effect and tower shadow effects compared to the power generated by the wind turbine generator at rated wind velocity. Hence, they are not taken in the simulation study.

2.2 Model of Wind Turbine

The aerodynamic rotor model gives the coupling between the wind turbine mechanical power and the rotational speed. Here, the passive stall mechanism is considered for wind turbine blades. The simple aerodynamic model commonly used to represent the turbine is based on power coefficient, C_P versus tip-speed ratio, λ. The tip-speed ratio is given by,

$$\lambda = \frac{\omega_t R}{V_W} \tag{2}$$

where, R is the radius of the turbine rotor in meters and ω_t is the turbine rotational speed in RPM. The power extracted from the WECS varies as the cube of wind speed. The turbine torque, τ_t is obtained by dividing turbine power, P_t by turbine angular speed, ω_t. It is given by,

$$\tau_t(V_w, \omega_t) = \frac{P_t}{\omega_t} = \frac{\frac{1}{2}\rho A V_W{}^3 C_P}{\omega_t} \tag{3}$$

where, C_P is performance power coefficient, decided by the tip speed ratio and the pitch angle.

The power coefficient is expressed [8] as,

$$C_p = C_1(C_2 \frac{1}{\Lambda} - C_3\theta - C_4\theta^x - C_5)e^{(-\frac{C_6}{\Lambda})} \tag{4}$$

where,

$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.008\theta} - \frac{0.035}{1-\theta^3} \tag{5}$$

and C_1 to C_6, x are constants.

The C_P versus λ curve is provided by wind turbine manufacturer. The procedure for finding wind turbine blade constants C_1 to C_6 and x is discussed in reference [8]. The wind turbine mechanical torque can be obtained by substituting ω_t from Equ.(2) in Equ.(3) and simplifying yields,

$$\tau_t(V_w, \omega_t) = \frac{1}{2}\rho\, A\, V_W{}^2\, RC_t \tag{6}$$

where, ρ is the air density in kg/m^3 , C_t is the torque coefficient of the wind turbine and it is given by,

$$C_t(\lambda,\theta) = \frac{C_p(\lambda,\theta)}{\lambda} \tag{7}$$

The wind turbine generator captures the wind energy through the blades, and converts it into the mechanical power P_m on the shaft. The power extracted from the wind is given by,

$$P_m = \frac{1}{2}\rho\pi R^2 V_W{}^3 C_P(\lambda,\theta) \tag{8}$$

Hence, given an empirical power coefficient curve, an analytical expression for the power curve (P versus V_w) of the wind turbine can be obtained using Equ. (4) and (8). In this paper, an identical turbine data are used for 200 kW and 250 kW. So, the turbine data of 250 kW are used in simulation for 200 kW rated turbines.

2.3 Modelling of Squirrel Cage Induction Generator

Squirrel cage induction generator (SCIG) is used for wind power generation a decade ago widely that can be directly connected to the grid [9]. The dynamic modeling of induction generator is derived from the dq synchronous reference frame [10,11]. Induction generator is represented by means of a third order model with neglected stator transients. The winding rotor and stator leaving currents are taken as positive when generator convention is adopted. The dynamics of a SCIG with passive stall mechanism are described by the following differential equations

$$\frac{dE'_{qs}}{dt} = -\frac{1}{T'_o}[E'_{qs} + (X_0 - X')\, i_{ds}] + s\,\omega_0\, E'_{ds} \tag{9}$$

$$\frac{dE'_{ds}}{dt} = -\frac{1}{T'_o}[E'_{ds} - (X_0 - X')\, i_{qs}] - s\,\omega_0\, E'_{qs} \tag{10}$$

$$\frac{ds}{dt} = \frac{1}{2H}[\tau_e - \tau_m(V_w, \omega_t)] \tag{11}$$

where, E'_{ds} and E'_{qs} are transient *dq* axis rotor voltages respectively, i_{ds} and i_{qs} are d and q axis stator currents respectively. T'_o is the rotor open circuit time constant equal to L_r/R_r, H is combined inertia of induction generator and wind turbine (H_t+H_g), X_0, X' are denotes self-reactance of stator and transient reactance of induction generator, s represents slip of the induction generator. ω_0 is synchronous speed of the induction generator in rad/s.

The general expression for electromagnetic torque is $\tau_e = E_{qs}'i_{qs} + E_{ds}'\, i_{ds}$ (12)

The p.u voltage equations for a single rotor winding induction generator in d, q coordinates with d-axis 90^0 ahead of q-axis with respect to the direction of rotation. The following algebraic equations are describing the model of SCIG.

$$V_{qs} = -R_s\, i_{qs} - X'\, i_{ds} + E'_{qs} \tag{13}$$

$$V_{ds} = -R_s\, i_{ds} + X'\, i_{qs} + E'_{ds} \tag{14}$$

$$E'_{qs} = \frac{\omega_0 M}{L_{22}}\lambda_{dr}\,, E'_{ds} = \frac{\omega_0 M}{L_{22}}\lambda_{qr} \tag{15}$$

where, V_{ds} and V_{qs} are stator voltages in d and q axis respectively. R_s is stator resistance, $L_{22} = L_2 + M$, L_2 represents rotor leakage inductance, M denotes the magnetizing inductance and λ_{qr} , λ_{dr} represent the rotor winding flux linkage on real and imaginary axis respectively.

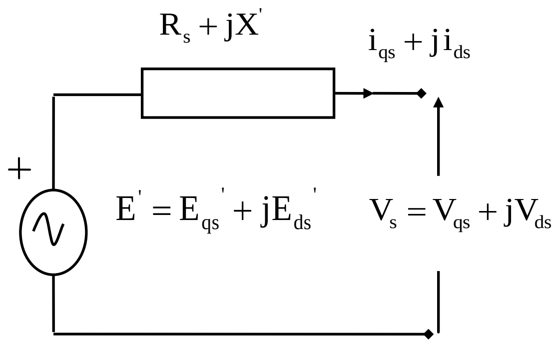

Fig.2. Thevenin's equivalent circuit of SCIG

The Fig.2 shows the transient stability representation of SCIG and the resultant equation in phasor form is

$$E' = V_s + (R_s + j\,X')\, I_s \tag{16}$$

Where E' is phasor of constant voltage behind transient reactance and V_s , I_s are represents phasors of stator terminal voltage and stator output current respectively.

3. EQUIVALENT WIND FARM MODELS

A wind farm may have different types of grid integrated generators. In this paper, the aggregation of fixed speed induction generators in a wind farm is analyzed. Aggregations of wind farm of the wind turbine generators (WTG) according to multi-machine equivalent WTG, single-machine equivalent WTG are presented in this section. It is possible to aggregate the induction generators in the wind farm, consisting of NG parallel WTGs, by a single machine equivalent with a re-scaled power capacity. The following assumptions are taken:

I. Wind speeds at the wind farm are uniform row wise. If not the average wind speed is calculated for a row.

II. The wind turbines in the wind farm are identical row wise. If not the weighted average value is used for a row.

III. Each wind turbine runs at the same operating condition at all times. Thus the voltage, current and power of each WTG are identical.

IV. With the aggregation procedure, the equivalent wind turbine of the entire wind farm is a scale up of a single wi nd turbine, i.e., the base power becomes NG times the base power of a single wind turbine in the farm.

V. Similarly, the equivalent generator impedance becomes 1/ NG times the impedance of the generator in the individual turbine.

VI. The resistance, reactance parameters of transmission line and transformer of the equivalent wind farm system can be found as per reference[7]

VII. Reactive power required by WTG is uniformly compensated by each capacitor bank present in WTG at all conditions.

The steady state and transient stability investigations are executed on the assumption that all the wind turbines in the wind farm are identical and have the same operating condition row wise.

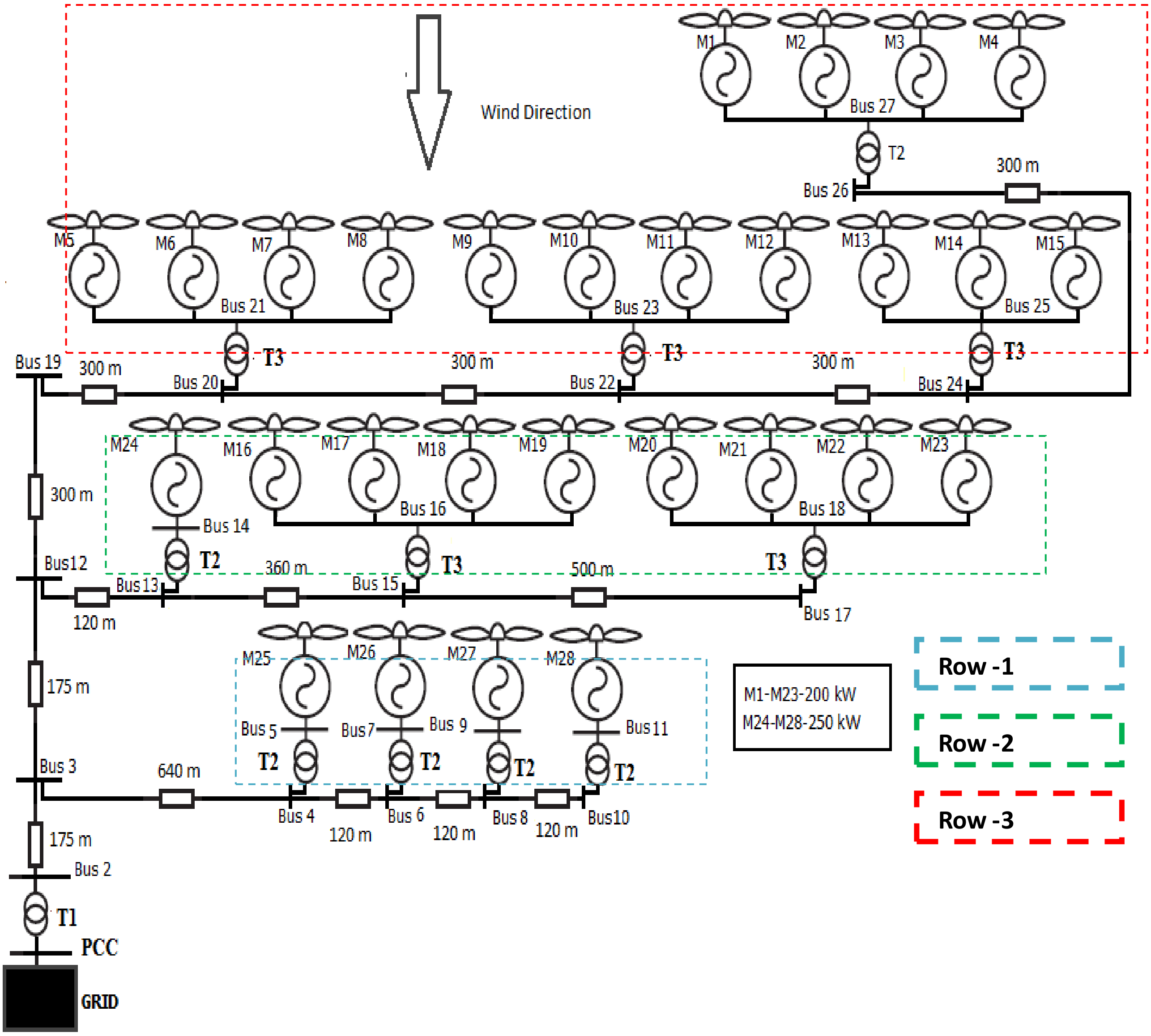

Fig.3. Actual wind farm system

3.1 Actual System

An Indian utility system of wind farm is used, and it is located in Tamilnadu with total installed capacity of 15 MW and shown in Fig.3. The system has 28 numbers of fixed speed WTGs with five numbers of Vestas make machines rating of 250 kW each and 23 numbers of NEG Micon machines rating 200 kW each, respectively. The actual wind farm, which consists of many small power rated wind turbines, is represented by an equivalent larger WTG. It reduces simulation time to a greater extent. The advantage of this is that it eliminates the need of developing detailed model of wind farm. The wind farm data of 27-bus system, wind turbines, SCIG are presented in Appendix.

3.2 Multi-machine equivalent model

Wind speed is not uniform in a wind farm due to wake effect. Therefore it is convenient to represent a wind farm as multiple equivalents of wind turbine generators. The wind speed with wake effect for multi equivalent and detailed wind farm is taken as 12 m/s, 11.5 m/s, and 11 m/s from top to bottom row wise.

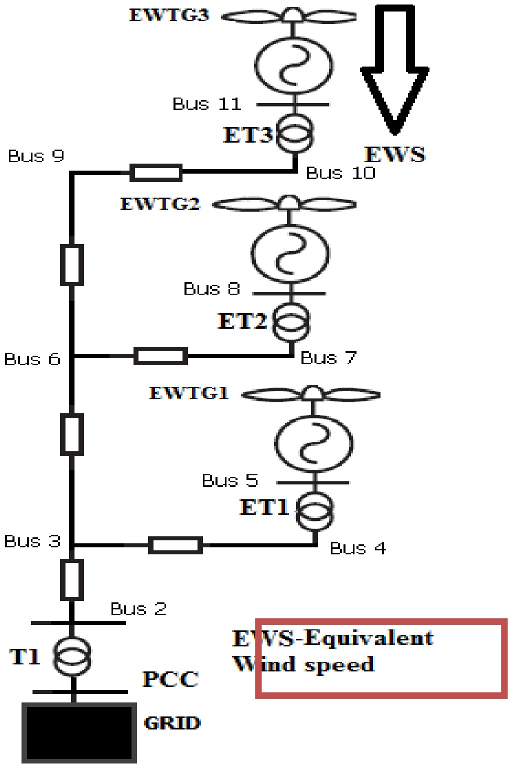

Fig.4.Multi-machine equivalent of wind farm- aggregated model of wind farm

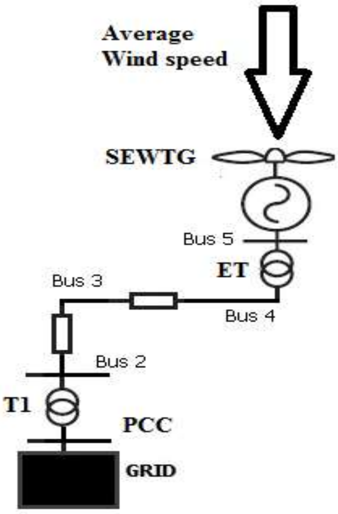

Fig.5. Single-machine equivalent of wind farm- aggregated model of wind farm

As per the assumptions stated in section 3, the whole wind farm is represented by the multi wind turbine generator model as shown in Fig.4. In this equivalent representation, row wise wind turbine generators, transformers `are aggregated to form an equivalent WTG. The aggregated equivalent wind farm model has been developed and the whole wind farm is represented by the multi machine and single equivalent model as shown in Fig.4 and Fig.5.

3.3 Single-machine equivalent model

Average wind speed is calculated from the multi machine equivalent WTG model. The whole wind farm is represented by the single equivalent model arrived from multi equivalent wind turbine generators as shown in Fig.5 and the system data is present in Appendix.

4. SIMULATION RESULTS AND DISCUSSION

Simulation studies are carried out to evaluate the steady state and dynamic condition of different equivalent wind farm models. The differential and algebraic equations of wind farm system are given in Eqs. (9-11), Eqs.(12-14) are solved together by Runge-Kutta method. The equivalent aggregated models are implemented in MATLAB software package using M-files [12] and compared with the actual wind farm model under different operating conditions. In this case, the multi machine and single machine equivalents are applicable for less computational time.

4.1 Steady state operating conditions of actual system and equivalent model

Steady state operating conditions of the wind farm system is obtained from power flow solution. Power flow analysis is conducted for actual, multi machine equivalent and single machine equivalent wind farm system. The results were taken at PCC for all wind farm models for comparison.

Table 1 – Steady state values of actual wind farm and equivalent wind farm systems at the rated wind speed operating condition (12 m/s)

Measured Variables at PCC	**Actual System**	**Multi-Machine Equivalent system**	**Single-Machine Equivalent system**
Real power P (MW)	4.7709	4.7723	4.8061
Reactive Power Q (Mvar)	-4.0891	-4.1001	-3.8073
Voltage (p.u.)	1.0000	1.0000	1.0000

Table 2 – Percentage error of steady state values of equivalent wind farm systems at rated wind speed (12 m/s)

Measured Variables at PCC	**% Error between Actual and multi machine equivalent system**	**% Error between Actual and Single machine equivalent**
Real power P(MW)	-0.0293	-0.7378
Reactive Power Q(Mvar)	-0.2690	6.8914

The real power, reactive power and voltage values at PCC of actual wind farm, multi-machine equivalent and single machine equivalent system are shown in Table 1. In this, the multi machine equivalent system values are very close to actual system. Percentage error of real power, reactive power and voltage variables are also computed for multi machine equivalent and single machine equivalent system with respect to actual system. In Table 2, the percentage error of multi machine equivalent system with respect to actual wind farm system is very small compared to single machine equivalent system. The percentage voltage error is zero for multi-machine and single-machine equivalent system with respect to actual system.

4.2 Dynamic response of actual system and equivalent models

In the real time wind farm, the wind speed keeps on varying. To compare the dynamic response of aggregated model with the actual system model, two different scenarios are considered for analysis:

(1) Three phase to ground fault disturbance at the PCC with rated wind speed condition.

(2) Step change in wind speed disturbance applied to all WTGs.

CASE (1) Three Phase to ground fault at the PCC with rated wind speed of 12 m/s

At PCC, a three phase fault is applied with rated wind speed of 12 m/s to actual wind farm, multi-machine and single-machine equivalent system at 1.0 second with duration of 100 milli seconds. The dynamic responses of real power, reactive power, magnitude of voltage and angle, current of actual system, multi-machine equivalent and single-machine equivalent are shown in Fig. 6 (b)-(f). These responses are taken at PCC of actual, multi-machine equivalent and single-machine equivalent, respectively.

Before the disturbance, the actual, multi-machine and single machine equivalent wind farm systems are stable and operating at steady state point. The three phase fault disturbance at 1.0 second, the electrical variables of real power, reactive power, magnitude of voltage and angle, current of actual system, multi-machine equivalent and single-machine equivalent are suddenly changing. Due to this disturbance, the real power, voltage angle and current responses decrease as shown in Fig.6 (a), (e), and (f). During the disturbance, a close match between the responses of multi-machine equivalent wind farm and actual wind farm is obtained as shown in Fig.6.(b) to (f). But except voltage response the single machine equivalent all other responses are not matching with actual wind farm.

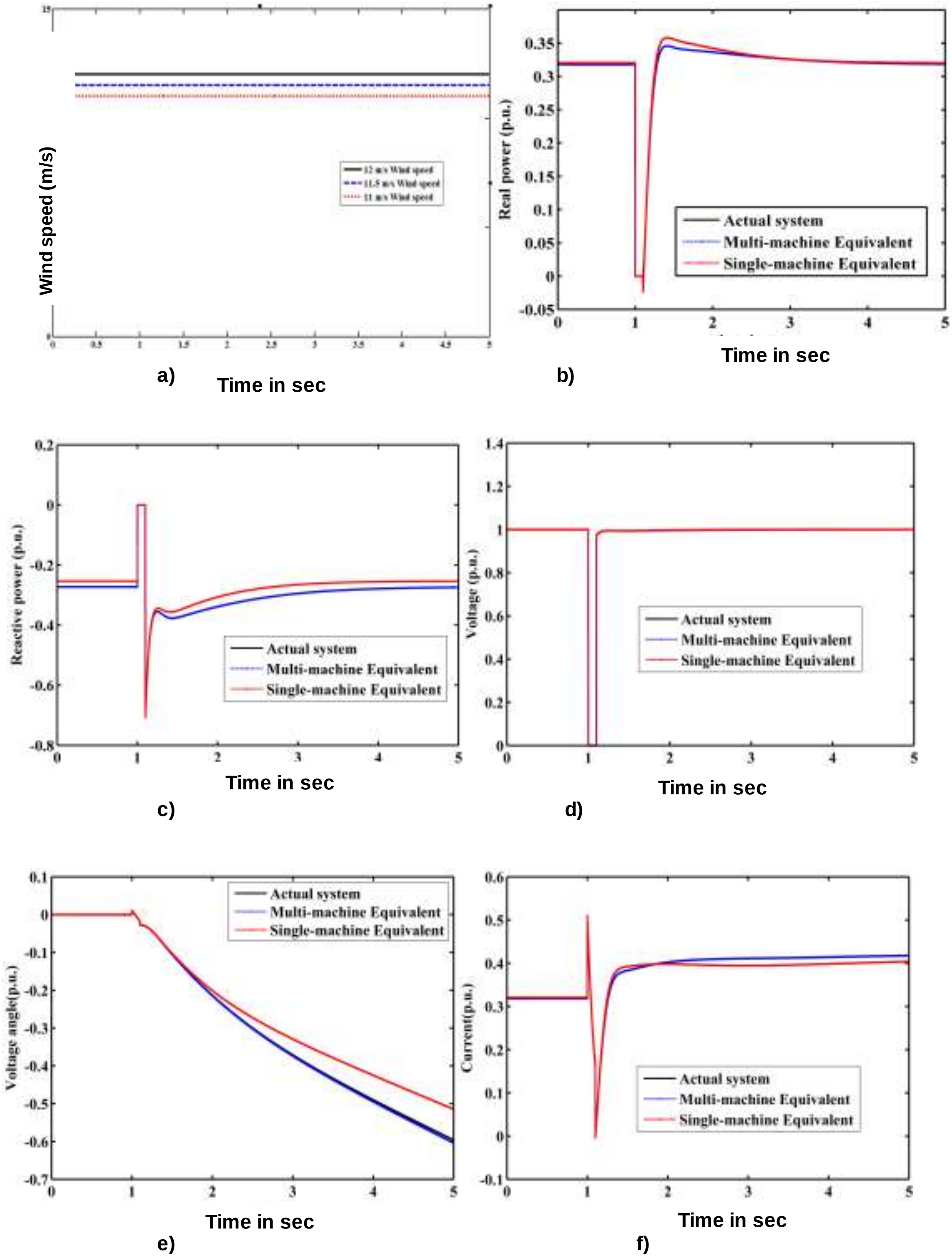

Fig.6. Actual, multi-machine and single-machine equivalent system responses at the BUS 1 (PCC) during three phase to ground fault a) wind speed curve b) Response of real power c) Response of reactive power responses d) Voltage response e) voltage angle response f) Response of current

CASE (2) Step change in wind speed

A step change in wind speed is applied to actual wind farm system, multi-machine and single-machine equivalent system at 1.0 second with duration of 200 milli seconds. The dynamic responses of real power, reactive power, magnitude and angle of voltage, current of actual system, multi-machine equivalent and single-machine equivalent are shown in Fig. 7 (b) to (f).

Due to this step change in wind speed disturbance, the real power, voltage angle and current responses decrease after 1 second as shown in Fig.7 (b) to (f). These responses can be controlled by passive stall mechanism of the turbine. On the other hand, the reactive power absorption from the grid increases. After the clearing step change in wind speed at 3 seconds, the wind speed retains the original speed. The real power, reactive power, voltage, voltage angle and current values of actual, multi-machine and single-machine equivalent wind farms moving to new operating point. The multi machine equivalent WTG system responses match accurately with actual system for both cases as shown in Fig.6 (b) to (f) and Fig.7 (b) to (f). But the single machine equivalent responses are failed to capture the actual wind farm system dynamics due to its average input wind speed and single-machine equivalent.

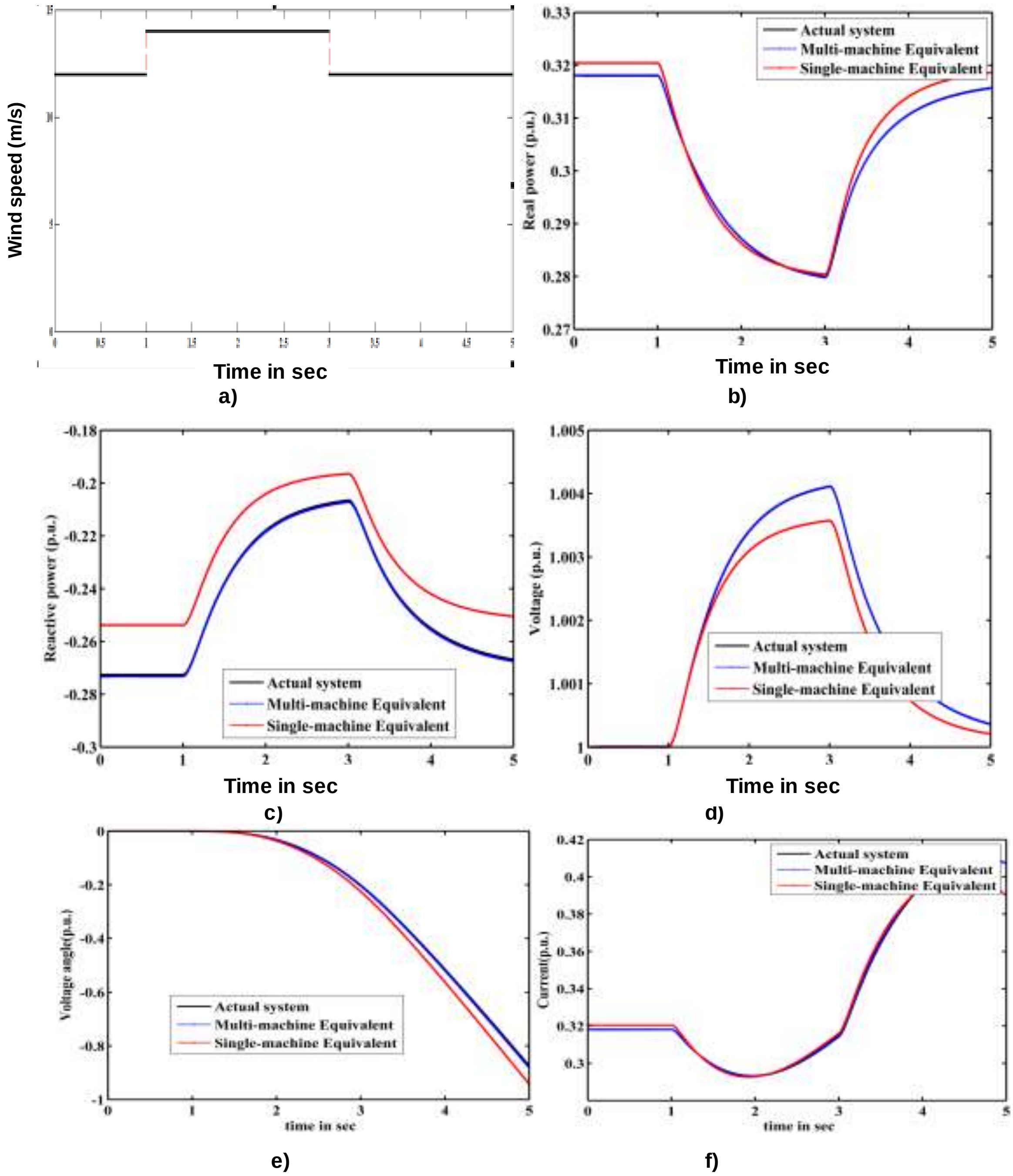

Fig.7. Actual, Multi-macl Time in sec **e-machine equivalent syst** Time in sec **; at the BUS 1 (PCC)**

during step change in wind speed a) wind speed curve b) Response of real power c) Response of reactive power responses d) Voltage response e) Voltage angle response f) Response of current

It is inferred from Table 3 that simulation time required to simulate single machine equivalent system is very less compared to the actual and multi machine equivalent wind farms. But the dynamic responses of single machine equivalent wind farm model are not matching with actual wind farm for both the cases.

Table 3 -Transient stability simulation time comparison between Actual system and equivalent wind farm systems

Simulation Test cases	Actual system	Multi-machine Equivalent system	Single-machine equivalent system
Three phase to ground fault	128.15 sec	23.41 sec	11.30 sec
Step change in wind speed	139.42 sec	30.35 sec	17.85 sec

5. Conclusion

In this paper, the dynamic stability behavior of a wind farm containing fixed speed wind turbine generators subjected to equivalent model has been studied. Two different aggregated cases, i.e., multi-machine equivalent system and single-machine equivalent system has been validated with actual system response. For a three phase to ground fault, the aggregated system of multi-machine equivalent response at PCC exactly follows the actual system response. Also due to step change in wind speed, the multi-machine equivalent system response with actual system is indistinguishable. The multi-machine equivalent wind farm is more sufficient for stability studies and it significantly reduces the simulation time and data collection effort. But the single machine equivalent wind farm model responses are not matching with actual system for all the cases even with reduced simulation run time. So the multi machine equivalent wind farm model is chosen for equivalent representation of wind farm and it has remarkable less simulation time when compared to actual system. Thus the multi-machine equivalent wind farm model of the wind farm has been developed, whose dynamic responses follow the actual system wind farm during dynamics conditions.

Appendix

Wind Turbine data:

Power/Voltage: 225 kVA/200 kW, 433 V; Frequency: 50 Hz

Cut in and Cut out wind speed: 3m/s and 22 m/s

Rated wind speed: 12 m/s

Wind turbine data: Gear box ratio: 67.5

Blade radius: 26.1 m

Inertia of Turbine and generator: H_t=2.3 s, H_g=0.35 s,

Squirrel cage induction generator (SCIG):

R1=0.02375 Ω/phase, R2=0.029 Ω/phase, X1=0.225 Ω/phase, X2=0.431 Ω/phase, Xm=6 Ω/phase.

EWTG1: R1=0.006 Ω/phase, R2=0.007 Ω/phase, X1=0.056 Ω/phase, X2=0.108 Ω/phase, Xm=1.5 Ω/phase.

EWTG2: R1=0.003 Ω/phase, R2=0.003 Ω/phase, X1=0.025 Ω/phase, X2=0.048 Ω/phase, Xm=0.667 Ω/phase.

EWTG3: R1=0.0016 Ω/phase, R2=0.0019 Ω/phase, X1=0.015 Ω/phase, X2=0.0287 Ω/phase, Xm=0.4 Ω/phase.

SEWTG: R1=0.02375 Ω/phase , R2=0.029 Ω/phase, X1=0.225 Ω/phase, X2=0.431 Ω/phase, Xm=6 Ω/phase

Transformer data : T1: 500 kVA, 0.433/11 kV, Z=2.5 % **T2:** 1 MVA, 0.433/11 kV, Z=5.7 %

ET1: 2 MVA, 0.433/11 kV, Z=11.0 % **ET2:** 3 MVA, 0.433/11 kV, Z=16.1 %

ET3: 4 MVA, 0.433/11 kV, Z=22.8 % **ET:** 15 MVA, 0.433/11 kV, Z=50.9 %

Transmission line: 10 MVA; 11 kV; R: 0.13 Ω /km/ckt; X=0.0952 Ω/km/ckt

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Dr.R.P.Kumudini Devi has 16 years of teaching experience. She received the M.E. degree in Power Systems Engineering and has completed doctorate in Power Systems from Faculty of Electrical Engineering, College of Engineering, Guindy, Anna University, India, in 1992 and 2000, respectively. She has completed the NIWE funded project entitled as Power Evacuation studies of grid integrated wind energy conversion system worth of Rs. 16 lakhs. Currently she is handling transient studies project funded by TANGEDCO, Tamilnadu, India. She has been with Department of Electrical and Electronics Engineering, College of Engineering Guindy, Anna University, Chennai, India from 1995 where she is currently working as a Professor in-charge in the Power System Division. Her area of specialization is Power systems dynamics, stability and control, FACTS and Renewable energy. She is the member of IEEE.

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