Effect of Wind Speed, Slip and Field Excitation on Dynamic Behavior of Multi-Machine Power Systems with Doubly Fed Induction Generator

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Abstract— This paper work presents a study on the effect of wind speed, slip and field excitation on dynamic behaviour of multi-machine power systems installed with Doubly Fed Induction Generator (DFIG) based Wind Energy Conversion System (WECS). A method to construct linear model of DFIG, a framework for interfacing DFIG with multi-machine power systems, formation of system matrix and eigen-value analysis for the investigation of small signal stability are presented in this paper. A MATLAB program is developed and effectiveness of developed program is tested in a test system interfaced with DFIG. The impact of varying wind speed, slip and field excitation on the small signal stability analysis of multi-machine power system interfaced with DFIG is studied and the results are presented.

Index Terms— Doubly Fed Induction Generator, Wind Energy Conversion System, Multi-Machine System, Small Signal Stability Analysis, Eigen-value Analysis

I. INTRODUCTION

With improving techniques, low environmental impact and reducing costs, wind energy play a major role in the world's energy. As the wind power penetration continually increases, power utilities are shifting the focus from power quality issue to the stability problem caused by the wind power [1]. With increasing penetration of the wind generations, the impacts on dynamic characteristic and performance of the overall system should be properly investigated.

Several types of wind turbine generators (WTG) are available today which includes squirrel cage induction generators (SCIG), doubly fed induction generators (DFIG) and permanent magnet synchronous generators (PMSG). Initially squirrel cage induction generators were used along with wind turbines to tap wind power .However, the doubly fed induction generators are being preferred nowadays because it has the capacity to operate in sub-synchronous and super-synchronous speed regime extracting maximum power from wind [2, 3]. The advantages of DFIGs are given in [4]-[7].

The modern DFIG as described in [2] and [3] uses back to back converter which controls the rotor voltage and the speed of wound rotor induction machine. The grid side converter of the rotor circuit exchanges real power with the grid and maintains the DC voltage across the capacitor. The rotor side converter is controlled to extract maximum wind power and Constant torque. The model of the mechanical part (drive train) may be lumped mass, two mass or a three mass model are described in [8].

Modal analysis is carried out in [1] for DFIG based wind farm. Large power oscillations can occur in power system. These oscillations are slow and it is possible to damp the oscillations with help of wind power [10]. Eigen-value analysis of the DFIG wind turbine system has been discussed in [15]–[18]. The location of eigen-values in the complex plane gives information about presence of weekly damped oscillations [19].

This paper presents a modelling of DFIG for small signal stability analysis, step by step procedure for small signal stability analysis of DFIG interfaced with multi-machine system and state space model for multi-machine system with DFIG. The small signal stability analysis of multi-machine system with DFIG is presented using eigen-value analysis. A program is developed in MATLAB environment to achieve the above mentioned objectives and the effectiveness of the program is tested by applying it to a standard test system.

This paper comprises of the following sections: Section 2 deals with the modeling of power system. In section 3, the small signal stability analysis of multi-machine system with DFIG is presented. In section 4, the results and discussion of the test system are presented. The eigen-values are determined for the test system considered. Conclusion and future scope are presented in Section 5 and Section 6.

II. POWER SYSTEM MODELLING

In this section, modelling of synchronous generator, DFIG and load for small signal stability analysis is presented.

A. Synchronous Generator Model

Synchronous generator are represented by variable voltage behind transient reactance with effect of excitation system. Neglecting saliency, the stator of a synchronous machine is represented by the equivalent circuit shown in Fig 1. The block diagram of excitation system is shown in Fig 2.

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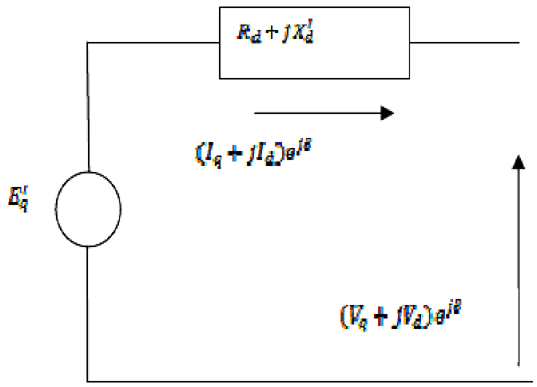

Fig 1: Stator Equivalent Circuit

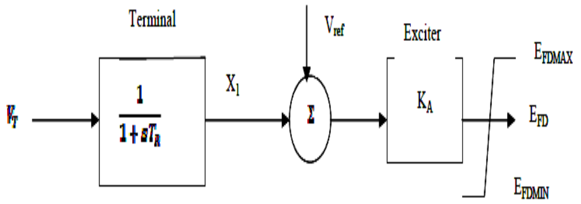

Fig 2: Simplified Block Diagram of Excitation System

The linearized equations for the small signal stability analysis in state variable form are represented by the following equations [11, 13, 14] :

$$p\Delta\omega_{12} = \frac{-K_D}{2H}\Delta\omega_{12} - \left(\frac{T_{12}}{2H_1} - \frac{T_{22}}{2H_2}\right)\Delta\delta_{12} - \left(\frac{T_{11}}{2H_1} - \frac{T_{21}}{2H_2}\right)\Delta E'_{q1} \quad (1)$$

$$p\Delta\delta_{12} = \omega_s\Delta\omega_{12} \quad (2)$$

$$p\Delta E'_{q1} = E_1\Delta\delta_{12} + E_{11}\Delta E'_{q1} - \frac{K_A}{T'_{d01}}\Delta X_1 \quad (3)$$

$$p\Delta X_1 = \frac{p_{12}}{T_R}\Delta\delta_{12} + \frac{p_{11}}{T_R}\Delta E'_{q1} - \frac{1}{T_R}\Delta X_1 \quad (4)$$

Where δ and ω refers rotor angle and speed, E'_q is quadrature voltage behind transient reactance, X_1 is terminal voltage transducer, H is inertia constant.

Where

$$E_{11} = -\frac{1}{T'_{d01}}[1 - B_{11}(X_{d1} - X'_{d1})] \quad (5)$$

$$E_{13} = -\frac{1}{T'_{d01}}(X_{d1} - X'_{d1})(G_{12}\cos\delta_{12,0} + B_{12}\sin\delta_{12,0})E'_{q10}$$

(6)

$$p_{11} = \left(\frac{V_{q10}}{V_{T10}}\right)(1 + d_{11}X'_{d1}) - \left(\frac{V_{d10}}{V_{T10}}\right)q_{11}X_{q1} \quad (7)$$

$$p_{13} = \left(\frac{V_{q10}}{V_{T10}}\right)(d_{13}X'_{d1}) - \left(\frac{V_{d10}}{V_{T10}}\right)q_{13}X_{q1} \quad (8)$$

$$d_{11} = B_{11} \quad (9)$$

$$d_{12} = -(G_{12}\cos\delta_{12,0} + B_{12}\sin\delta_{12,0})E'_{q10} \quad (10)$$

Where X_{d1} refers direct axis synchronous reactance, X'_{d1} is direct axis transient reactance, T'_{d01} is direct axis open circuit transient time constant and X_{q1} refers quadrature axis synchronous reactance.

B. Doubly Fed Induction Generator Model

Basically, DFIG is an induction-type generator. This modeling methodology is similar to standard d–q axes representation of induction generator. This model uses seven state variables, three for the drive train and four for the DFIG. The equivalent circuit of DFIG is shown in Fig 3.

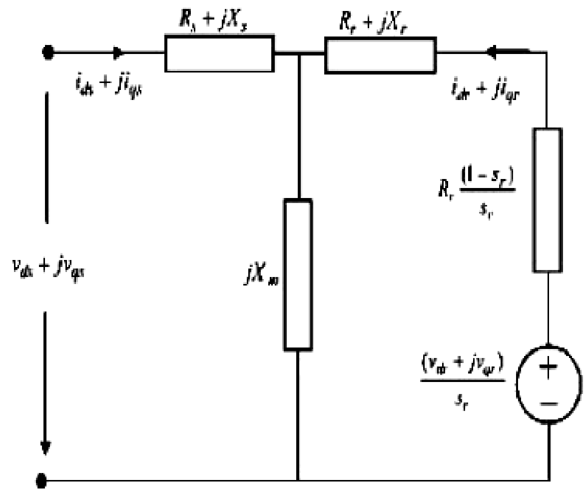

Fig 3: Equivalent Circuit of DFIG

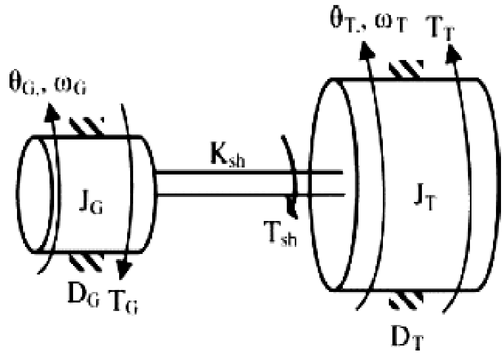

Fig 4: Two Mass Drive Train Model

A two-mass drive train model is used to get a more accurate response from the wind turbine and to have a more accurate prediction of the impact on the power system. Two mass drive train model is shown in Fig 4. The linearized differential equations of DFIG [12] for small signal stability analysis in state variable form are represented by the following equations

$$\frac{d\Delta i_{qsi}}{dt} = \frac{\omega_{elB}}{L_{si}}\left[-(R_{1i} + R_s)\Delta i_{qsi} + \left(\frac{\omega_r}{\omega_s} - 1\right)\Delta e'_{qsi} - \frac{\Delta e'_{dsi}}{T_{ri}\omega_s} + K_{mrri}\Delta v_{qri}\right] \quad (11)$$

$$\frac{d\Delta i_{dsi}}{dt} = \frac{\omega_{elB}}{L_{si}}\left[-(R_{1i} + R_s)\Delta i_{dsi} + \left(\frac{\omega_r}{\omega_s} - 1\right)\Delta e'_{dsi} + \frac{\Delta e'_{qsi}}{T_{ri}\omega_s} - v_{dsi} + K_{mrri\Delta}v_{dri}\right] \quad (12)$$

$$\frac{d\Delta e'_{qsi}}{dt} = \omega_{elB}\omega_s\left(R_{2i}\Delta i_{dsi} - \frac{\Delta e'_{qsi}}{T_{ri}\omega_s} + \left(1 - \frac{\omega_{ri}}{\omega_s}\right)\Delta e'_{dsi} + K_{mrri}\Delta v_{dri}\right. \quad (13)$$

$$\frac{d\Delta e'_{dsi}}{dt} = \omega_{elB}\omega_s\left(-R_{2i}\Delta i_{qsi} - \frac{\Delta e'_{dsi}}{T_{ri}\omega_s} - \left(1 - \frac{\omega_{ri}}{\omega_s}\right)\Delta e'_{qsi} + K_{mrri}\Delta v_{qri}\right. \quad (14)$$

$$\frac{d\Delta\omega_{gi}}{dt} = \frac{1}{2H_{gi}}\left(K_{shi}\Delta\theta_{tgi} + D_{shi}\omega_{elB}(\Delta\omega_{ti} - \Delta\omega_{gi}) - \Delta T_{ei}\right) \quad (15)$$

$$\frac{d\Delta\theta_{tgi}}{dt} = \left(\omega_{elB}\left(\Delta\omega_{ti} - \Delta\omega_{gi}\right)\right) \quad (16)$$

$$\frac{d\Delta\omega_{ti}}{dt} = \frac{1}{2H_{ti}}\left(\Delta T_{mi} - K_{shi}\Delta\theta_{tgi} + K_{shi}\omega_{elB}\left(\Delta\omega_{ti} - \Delta\omega_{gi}\right)\right) \quad (17)$$

The mechanical torque generated by turbine is taken from [19] and represented as equation (18)

$$T_m = \frac{0.5\rho\pi R^2 C_p(\lambda,\beta) v_w^3}{\omega_t} \quad (18)$$

Where R refers the blade length of the wind turbine, $C_p(\lambda,\beta)$ is the coefficient of performance and ρ refers air density, λ is the ratio of rotor blade tip speed to wind speed, β is the blade pitch angle, A is the turbine sweep area.

C_p is related to λ and β as

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\beta^{C_5} - C_6\right)e^{\frac{-C_7}{\lambda_i}} \quad (19)$$

The electromagnetic torque is taken from [20] and represented as equation (20)

$$T_e = \frac{e'_{qs} i_{qs}}{\omega_s} + \frac{e'_{ds} i_{ds}}{\omega_s} \quad (20)$$

C. Load Model

The load is modelled as constant impedance load. The load (P + jQ) is represented as constant impedance load. The equation of load for small signal stability analysis are represented by equation (21).

$$Z_L = V_L / I_L \quad (21)$$

Where V_L = Load Voltage

I_L = Load Current

Z_L = *Load impedance*

III. Small Signal Stability Analysis

Small signal stability analysis is performed using the concepts of Linearizing the system equations at the operating point and eigen-value analysis. The system equations are described in the following general form:

$$\dot{\mathbf{x}} = f(x,z,u), \mathbf{z} = g(x,u) \quad (22)$$

Where x, z and u are the vectors of state variables, control variables and input variables respectively. After performing the linearization procedure around the current operating point, the following relation is derived.

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B} \quad (23)$$

Equations (1) - (4) and Equations (11) – (17) represents the state equations for small signal stability analysis of multi-machine system with DFIG.

The state variable x is given as

$$\mathbf{x} = [\omega_1\ \delta_1\ E'_{q1}\ X_1\ \omega_2\ \delta_2\ E'_{q2}\ X_2\ i_{qs}\ i_{ds}\ e'_{qs}\ e'_{ds}\ \omega_g\ \theta_{tg}\ \omega_t]^T$$

Where A is the system state matrix. This matrix is then used for calculating the system eigen-values.

IV. RESULTS AND DISCUSSION

A. Test System

The sample power system considered in this paper is shown in Fig 5. All parameters are given in the Appendix. The first and second generators are identical. They send power to the load at bus 3. The load is assumed to be static and is represented by constant impedance. The DFIG is connected between bus 2 and 3. The losses in transmission lines are neglected and mechanical power is assumed to be constant. The disturbance is given by interfacing DFIG bus into the sample power system.

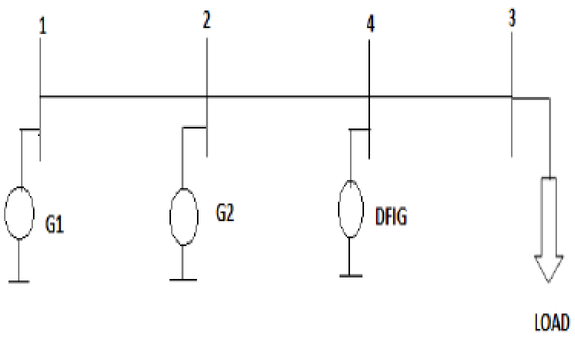

Fig 5: Sample Power System

B. Numerical Results

Linearized model of DFIG is interfaced to the linearized multi-machine power system network and state space modelling of the multi-machine power system with DFIG is developed. Eigen-value analysis is performed for the test system whose data as furnished in Appendix and the results are presented in Table 1.

Table 1: Eigen-values for test system.

$\lambda_1 = 0$
$\lambda_{2,3} = -0.0001 \pm 0.0245i$
$\lambda_4 = -0.0154$
$\lambda_5 = -0.0146$
$\lambda_6 = -0.0025$
$\lambda_7 = -0.0015$
$\lambda_8 = 0$
$\lambda_9 = -5.9403$
$\lambda_{10} = -0.7685$
$\lambda_{11} = -0.4410$
$\lambda_{12} = -0.3267$
$\lambda_{13,14} = -0.0006 \pm 0.0076i$
$\lambda_{15} = -0.1332$

From Table 1 it is clear that when both the machine are considered as IEEE type I excitation model, the system with DFIG remained stable. There is only one dominant mode in this system, namely the mechanical mode $\lambda_{2,3}$. The damping ratio for the dominant mode is 0.0041.

To study the impact of wind speed, slip and field excitation on the dynamic behaviour of multi-machine power system interfaced with DFIG, the small signal stability analysis is extended for the following cases:

Case 1: Effect of wind speed

Case 2: Effect of slip

Case 3: Effect of field excitation

Case 1. Effect of Wind Speed

Wind speed is varied from 8 to 14 m/s and the corresponding eigen-values are tabulated in Table 2 to 5.

Table 2
Eigen-values for wind speed 8m/s

$\lambda_1 = 0$
$\lambda_{2,3} = -0.0001 \pm 0.0245i$
$\lambda_4 = -0.0154$
$\lambda_5 = -0.0146$
$\lambda_6 = -0.0025$
$\lambda_7 = -0.0015$
$\lambda_8 = 0$
$\lambda_9 = -5.9403$
$\lambda_{10} = -0.7685$
$\lambda_{11} = -0.4410$
$\lambda_{12} = -0.3267$
$\lambda_{13,14} = -0.0006 \pm 0.0076i$
$\lambda_{15} = -0.1332$

Table 3
Eigen-values for wind speed 10m/s

$\lambda_1 = 0$
$\lambda_{2,3} = -0.0001 \pm 0.0245i$
$\lambda_4 = -0.0154$
$\lambda_5 = -0.0146$
$\lambda_6 = -0.0025$
$\lambda_7 = -0.0015$
$\lambda_8 = 0$
$\lambda_9 = -5.9403$
$\lambda_{10} = -0.7685$
$\lambda_{11} = -0.4410$
$\lambda_{12} = -0.3267$
$\lambda_{13,14} = -0.0006 \pm 0.0076i$
$\lambda_{15} = -0.4266$

Table 4
Eigen-values for wind speed12m/s

$\lambda_1 = 0$
$\lambda_{2,3} = -0.0001 \pm 0.0245i$
$\lambda_4 = -0.0154$
$\lambda_5 = -0.0146$
$\lambda_6 = -0.0025$
$\lambda_7 = -0.0015$
$\lambda_8 = 0$
$\lambda_9 = -5.9403$
$\lambda_{10} = -0.7685$
$\lambda_{11} = -0.4410$
$\lambda_{12} = -0.3267$
$\lambda_{13,14} = -0.0006 \pm 0.0076i$
$\lambda_{15} = -0.9805$

Table 5
Eigen-values for wind speed 14m/s

$\lambda_1 = 0$
$\lambda_{2,3} = -0.0001 \pm 0.0245i$
$\lambda_4 = -0.0154$
$\lambda_5 = -0.0146$
$\lambda_6 = -0.0025$
$\lambda_7 = -0.0015$
$\lambda_8 = 0$
$\lambda_9 = -5.9403$
$\lambda_{10} = -0.7685$
$\lambda_{11} = -0.4410$
$\lambda_{12} = -0.3267$
$\lambda_{13,14} = -0.0006 \pm 0.0076i$
$\lambda_{15} = -1.8428$

From Table 2 to 5 it is seen that by varying the wind speed, there is no variation in the dominant eigen-value and the mechanical mode is also not affected by the wind speed and hence it can be inferred that the dynamic behaviour is not affected by the range of wind speed variation considered.

Case 2. Effect of Slip

To analyze the effect of slip, the small signal stability analysis is performed for slip ranging from 0.2 to 0.8. Table 6 to 9 shows the eigen-values obtained for different values of slip.

Table 6
Eigen-values for slip 0.2

$\lambda_1 = 0$
$\lambda_{2,3} = -0.0001 \pm 0.0245i$
$\lambda_4 = -0.0154$
$\lambda_5 = -0.0146$
$\lambda_6 = -0.0025$
$\lambda_7 = -0.0015$
$\lambda_8 = 0$
$\lambda_9 = -5.9403$
$\lambda_{10} = -0.7685$
$\lambda_{11} = -0.4410$
$\lambda_{12} = -0.3267$
$\lambda_{13,14} = -0.0006 \pm 0.0076i$
$\lambda_{15} = -0.1332$

Table 7
Eigen-values for slip 0.4

$\lambda_1 = 0$
$\lambda_{2,3} = -0.0001 \pm 0.0245i$
$\lambda_4 = -0.0154$
$\lambda_5 = -0.0146$
$\lambda_6 = -0.0025$
$\lambda_7 = -0.0015$
$\lambda_8 = 0$
$\lambda_9 = -6.112$
$\lambda_{10} = -0.6678$
$\lambda_{11} = -0.4362$
$\lambda_{12} = -0.1096$
$\lambda_{13,14} = -0.0006 \pm 0.0076i$
$\lambda_{15} = -0.2444$

Table 8
Eigen-values for slip 0.6

$\lambda_1 = 0$
$\lambda_{2,3} = -0.0001 \pm 0.0245i$
$\lambda_4 = -0.0154$
$\lambda_5 = -0.0146$
$\lambda_6 = -0.0025$
$\lambda_7 = -0.0015$
$\lambda_8 = 0$
$\lambda_9 = -6.0185$
$\lambda_{10} = -0.8118$
$\lambda_{11} = -0.4312$
$\lambda_{12} = -0.1396$
$\lambda_{13,14} = -0.0006 \pm 0.0076i$
$\lambda_{15} = -0.3795$

Table 9
Eigen-values for slip 0.8

$\lambda_1 = \mathbf{0}$
$\lambda_{2,3} = -0.0001 \pm 0.0245i$
$\lambda_4 = -0.0154$
$\lambda_5 = -0.0146$
$\lambda_6 = -0.0025$
$\lambda_7 = -0.0015$
$\lambda_8 = 0$
$\lambda_9 = -5.9184$
$\lambda_{10} = -0.9718$
$\lambda_{11} = -0.4261$
$\lambda_{12} = -0.1604$
$\lambda_{13,14} = -0.0006 \pm 0.0076i$
$\lambda_{15} = -0.3428$

Table 6 to 9 shows that there is no change in dominant eigen-value when the slip ranges from 0.2 to 0.8. Hence, the mechanical mode of the system is not affected by slip .But the corresponding eigen-values of DFIG changes when slip varies from 0.2 to 0.8.

Case 3. Effect of Field Excitation

Excitation system should be capable of responding rapidly to a disturbance and modulating the generator field to enhance the small signal stability. The effects of different excitation values on small signal stability analysis are shown in table 10and 11

Table 10
Eigen-values for excitation 1.374

$\lambda_1 = 0$
$\lambda_{2,3}$ = - 0.0002 ± 0.0327i
λ_4 = - 0.0145
λ_5 = - 0.0110
λ_6 = - 0.0056
λ_7 = - 0.0012
$\lambda_8 = 0$
λ_9 = - 6.2
λ_{10} = - 0.5447
λ_{11} = - 0.4411
λ_{12} = - 0.0644
$\lambda_{13,14}$ = - 0.0006 ± 0.0076i
λ_{15} = - 0.1332

Table 11
Eigen-values for excitation 2.1437

$\lambda_1 = 0$
$\lambda_{2,3}$ = - 0.0003 ± 0.0457i
λ_4 = - 0.0145
$\lambda_{5,6}$ = - 0.0082±0.0021i
λ_7 = - 0.0012
$\lambda_8 = 0$
λ_9 = - 6.2
λ_{10} = - 0.5447
λ_{11} = - 0.4411
λ_{12} = - 0.0644
$\lambda_{13,14}$ = - 0.0006 ± 0.0076i
λ_{15} = - 0.1332

It is clear from the Table 10 and 11, the dominant eigen-value is varied by increasing the field excitation of the system. If the excitation is increased, the dominant eigen-value heads to left. Hence, the mechanical mode is affected and the stability of the system is increased.

V. CONCLUSION

This paper discusses a framework of small signal stability analysis of multi-machine system to include DFIG. Stepwise procedure for inclusion of DFIG in multi-machine small signal stability model has been presented. State space model is developed for the multi-machine system with DFIG. Numerical results based on eigen-value analysis are carried out to study the impact of DFIG when connected to a multi-machine power system. Effect of wind speed, effect of slip and effect of field excitation are studied in this paper. Observations in each analysis is summarized as,

Effect of Wind Speed

When the wind speed is varied from 8 to 14 m/s, it has been clear that there is no variation in dominant eigen-value, and hence the stability of the system is not affected.

Effect of Slip

When slip varies from 0.2 to 0.8, it is seen that there is change in DFIG eigen-values but there is no change in the dominant eigen-value. Hence the stability of the system is not affected.

Effect of Field Excitation

When the field excitation is increased, the dominant eigen-value changes and hence, the mechanical mode of the system gets affected and the system stability is improved.

APPENDIX

A. Data for Test System

A1. GENERATOR DATA

Gen No	P	Q	V_t	X_d
	(p.u.)	(p.u.)	(p.u.)	(p.u.)
1	0.5	0.3099	1	0.49
2	0.5	0.3099	1	0.49

A2. LINE DATA

From	To	R (p.u.)	X (p.u.)
1	2	0	0.8
2	4	0	0.4
4	3	0	0.4

A3. DFIG DATA

P (MW)	Q (MVAr)	Wind Speed (m/s)
0.5	0.33	8

A4.TURBINE SHAFT DATA

H_t	D_{sh}	K_{sh}	H_g
4.32	1.5	80.27	0.685

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