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OPTIMAL PLACEMENT OF INDUCTION GENERATORS BASED WIND POWER PLANTS IN POWER SYSTEM BASED SMALL SIGNAL AND TRANSIENT STABILITY ANALYSIS

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ABSTRACT

As a result of increasing amounts of electricity are generated from renewable sources such as wind turbines with induction generators, due to differences in the dynamics and relationships between the parameters of synchronous and induction generators, the power system surrounded by synchronous generators now, experience the changes in your dynamic profile. This dynamic changes in power system, affects transient and small signal stability of the system, following a disturbance. In a vast country like Iran, many places may have potential of establish the wind power plants. After the survey locations potential and determine the appropriate number of the points as the candidate of the establish of wind power plants, the greatest problem is regarding the power system stability with presenting of this power plants. this paper, at first evaluate the effect of fixed speed Squirrel cage induction generator and variable speed doubly fed induction generators on power system stability and then with the perform simulation on a standard IEEE test system, the oscillatory modes of the system that are affected by induction generator will be assess. To evaluate the transient stability, the oscillatory modes are known in the small signal evaluation, will be excited by a great disturbance. To specify the location of the great disturbance that excites the specific oscillatory mode, we will use participation matrix. And disturbance will be located close to the generator having the largest participation factors in the oscillatory mode. After the evaluation of impact of induction generators in small signal and transient stability of power system, the best place between candidates will be suggested.

KEYWORDS: Optimal Placement, Induction Generator, Wind Power Plant, Small Signal Stability, Transient Stability

As a result of increasing environmental concern, the impact of conventional electricity generation on the environment is being minimized and efforts are made to generate electricity from renewable sources. The main advantages of electricity generation from renewable sources are the absence of harmful emissions and the infinite availability of the prime mover that is converted into electricity. Among the various renewable energy sources, wind energy is one of the most important energy sources in power systems and expanding the wind power plants and its technology has demonstrated it (h. hemati et al., 2014). On the other hand, safe and stable operation of power is the basic requirement of a modern society. In such circumstances, the addition of clean and renewable power to a system requires to consideration of the stability of the system. With the penetration of induction generators in wind power plants, and connect them to the power system, the power system which is surrounded by the synchronous generators now, experiences a change in your dynamic properties. This changes in the dynamic characteristic, depends on the location of the induction generators and shift of the network topology. As in many countries that wind power has great penetration on them, there are requirements for wind power plants in connect to the grid Issue. One of the requirements is capabilities of generator during disturbance and its impact on the performance of power system. Impact of wind power on power system stability can be studied from multiple perspectives. With the increase penetration of induction generators based wind farms and connecting them to the power system, due to differences in the dynamics and relationships between the parameters of synchronous and induction generators, the power system surrounded by synchronous generators, experience the changes in your dynamic profile. Although generators are used in wind power plants do not participate in the oscillations of the power system J. G. Slootweg, et al. 2003), but their placement in the system and change the operation conditions, will affect on the fluctuations of system.

Wind farms are usually far from the load centers and it cause to transport of power to distant intervals And may be crossing of the power from the compress lines. That may seriously change the system load flow and will affect on the small signal stability of system. For reach to purposes of this paper, a systematic approach is taken step by step. At first, the effect of fixed speed Squirrel cage induction generators and variable speed doubly fed induction generator on the stability of power systems will be discuss and evaluate. After wards, The 14 bus IEEE standard system as the test system will introduce. And then, identify some point as the candidates of wind power

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plants Construction optionally. That be Assumed due to regional conditions have the potential of wind power plants Construction. At each step of the simulation, select one of the candidate points, and with the participation of wind power in the system, evaluate the influence of oscillating modes that are affected by induction generators. To investigate of the transient stability, the oscillatory modes known in the small signal evaluation, are excited by a large disturbance, we use from the participation matrix of the system. And the disturbance wills located close to the machine that have greatest participation factors. After investigation of the effect of the induction generator on small signal and transient stability of power system, in this respect, the best place will be offered, among the possible points.

SQUIRREL CAGE AND DFIG BASED WIND TURBINE MATHEMATICAL MODEL

The following is assumed when deriving the equations describing each of the systems:

a. Flux distribution is sinusoidal

b. Converter losses are neglected

c. Magnetic saturation is neglected in the generator models.

Turbine Model

Wind energy is transformed into mechanical energy by means of a wind turbine whose rotation is transmitted to the generator by means of a mechanical drive train. The wind-power equation is given by (A. Tapia, et al. 2003)

$$p_m = \frac{1}{2} p c_P V^3 \tag{1}$$

V: wind speed
P: density of air
Cp: aerodynamic wind turbine power factor

Wind turbine aerodynamic power factor depending on the tip speed ratio and blade angle is changed. Here the following equation is used to calculate Cp in the simulations (T.Sun, et al. 2003).

$$C_p = 0.22(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{\frac{-12.5}{\lambda_i}} \tag{2}$$

β And λ are the angle of the blades and tip speed respectively. The Turbine output torque is obtained using following relation.

$$T_{m_{(pu)}} = \frac{p_m(pu)}{\omega_r(pu)} \tag{3}$$

Squirrel cage induction machine model

Dq model of the Squirrel cage induction machine at steady state is as follows (N.W. Miller, et al. 2003).

$$V_{ds} = R_s i_{ds} - \omega_b \phi_{ds} + \frac{d}{dt}\phi_{qs} \tag{4}$$

$$V_{qs} = R_s i_{qs} - \omega_b \phi_{ds} + \frac{d}{dt}\phi_{qs} \tag{5}$$

$$0 = R_r i_{dr} - (\omega_b - \omega_r)\phi_{dr} + \frac{d}{dt}\phi_{qr} \tag{6}$$

$$0 = R_r i_{qr} + (\omega_b - \omega_r)\phi_{dr} + \frac{d}{dt}\phi_{qr} \tag{7}$$

$$\begin{aligned} \psi_{qs} &= L_{ls} i_{qs} + \psi_{mq} \\ \psi_{ds} &= L_{ls} i_{ds} + \psi_{md} \\ \psi_{mq} &= L_{mq}(i_{qs} + i_{qr}) \\ \psi_{md} &= L_{md}(i_{ds} + i_{dr}) \end{aligned} \tag{8}$$

$$\psi_{qr} = L_{lr} i_{qr} + \psi_{md}$$

$$\psi_{dr} = L_{lr} i_{dr} + \psi_{md} \tag{9}$$

$$Te = 1/5p(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}) \tag{10}$$

$$\frac{d}{dt}\omega_m = \frac{1}{2H}(T_e - F\omega_m - T_m) \tag{11}$$

In this relationships, V_{ds} , i_{ds} , V_{qs} and i_{qs} are the voltages and currents of d and q axes of stator, i_{dr} and i_{qr} are the currents of d and q axes of rotor, ϕ_{ds} , ϕ_{qs} , ϕ_{dr} and ϕ_{qr} are flow of d and q axes of the stator and rotor, R_s and R_r are resistances stator and rotor, L_{md} and L_{mq} are the mutual inductance of d and q axes between stator and rotor, L_{ls} and L_{lr} are the stator and rotor leakage inductance·

The Active and reactive power will be as follows.

$$P = v_{ds} i_{ds} + v_{qs} i_{qs} \quad (12)$$

$$Q = v_{ds} i_{ds} - v_{qs} i_{qs} \quad (13)$$

DFIG model

The Equations in dq space and in synchronous field reference frame are as follows (R. Pena, et al. 1996).

$$V_{ds} = R_s i_{ds} - \omega_b \phi_{ds} + \frac{d}{dt}\phi_{qs} \quad (14)$$

$$V_{qs} = R_s i_{qs} - \omega_b \phi_{ds} + \frac{d}{dt}\phi_{qs} \quad (15)$$

$$V_{dr} = R_r i_{dr} - (\omega_b - \omega_r)\phi_{dr} + \frac{d}{dt}\phi_{qr} \quad (16)$$

$$V_{qr} = R_r i_{qr} + (\omega_b - \omega_r)\phi_{dr} + \frac{d}{dt}\phi_{qr} \quad (17)$$

$$\begin{aligned} \psi_{qs} &= L_{ls} i_{qs} + \psi_{mq} \\ \psi_{ds} &= L_{ls} i_{ds} + \psi_{md} \\ \psi_{mq} &= L_{mq}(i_{qs} + i_{qr}) \\ \psi_{md} &= L_{md}(i_{ds} + i_{dr}) \end{aligned} \quad (18)$$

$$\psi_{qr} = L_{lr} i_{qr} + \psi_{md}$$

$$\psi_{dr} = L_{lr} i_{dr} + \psi_{md} \quad (19)$$

$$Te = 1/5p(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}) \quad (20)$$

$$\frac{d}{dt}\omega_m = \frac{1}{2H}(T_e - F\omega_m - T_m) \quad (21)$$

Shaft model

In the case of a wind turbine with DFIG, the shaft can be neglected, because the power electronic converter decouples the electrical and mechanical behavior of power plant. Therefore, the turbine shaft dynamic are hardly reflected in the wind turbines response to wind speed changes or grid faults. Therefore, no equations describing the wind turbine shaft will be taken into account.

But In the case of a wind turbine with Squirrel cage induction generator, the following per unit equation describes the wind turbine shaft, in steady state.

$$\gamma = \frac{T_e}{K_s} = \frac{T_e}{K_s} \quad (22)$$

in which K_s, is the shaft stiffness, γ is the angle between the both ends of the shaft [el. rad] and T_e is torque in P.u.

IMPACT ON POWER SYSTEM

Under steady-state conditions, there is balance between the mechanical and the electrical torque of each generator in the power system, and the speed remains constant. If the system is disturbed, this balance is disruption resulting in acceleration or deceleration of the rotors of the generators according to the laws of motion of a rotating mass. If one generator temporarily runs faster than another, the angular resulting position of its rotor relative to that of the slower machine will advance. The resulting angular difference transfers load from the slow machine to the fast machine, depending On the power-angle relationship. This tends to reduce the speed difference and hence the angular separation. According to swing equation, speed changes due to differences between electrical and mechanical torques, depends on the inertia of the machine. In the constant speed wind turbine with non controllable Squirrel cage generators, the inertia of the system is automatically accessible. With the increase of rotor angular and therefore transferred power from the generator, the speed of rotor will be decreasing and part of the energy stored in rotating rotor, injected to the power system. But In the case of a DFIG, for special control of converter to have maximum active power in specific wind speed, the inertia of the turbine is effectively decoupled from the system. Therefore the system can't restitute the electric power losing by the energy stored in rotor of these generators. And the other generators of power system should be restituting this losing. However, portion of each generator to restitute this losing, depending on system Topology, Operation conditions and type and location of the error. And power-angle relationship of each generator during Operation, identify their portion to restitute the losing.

SIMULATION AND RESULTS

The test system for this study is derived from IEEE test system. This network consists of 14 buses, 83 branches, 11 loads and 5 generators. The transformers connecting generators to the grid are adjusted accordingly. This system is shown in Fig. 1.

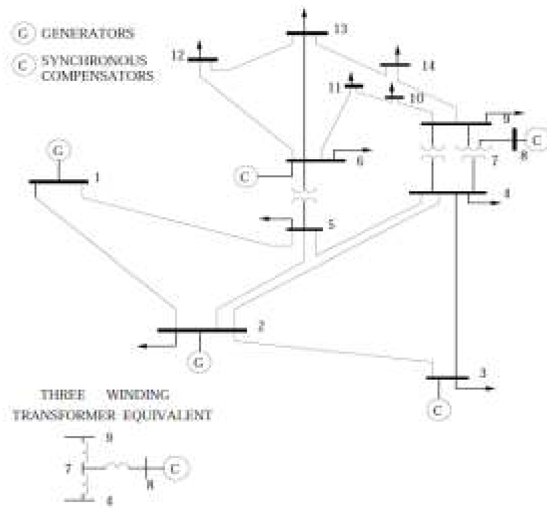

Figure 1: 14 buses IEEE test system

In this test system the generators do not a single machine but represent a group of coupled generators and the total power is divided as follow:

Table 1: Generators Power

Generator	1	2	3	4	5
Power(mw)	615	60	60	25	25

For answer to the 5 percent load growth prediction, the generation of the system should be increase. We want add wind power to the system. In this power system due to regional conditions is assumed in the vicinity of buses 3, 6, 12 and 14, there is potential to build wind farms. The choices are completely optional. Capacity of wind farm is 16 MW that consisting of 8 wind turbine with 2 MW power. This power is 6.1 percent of total power of the system. The wind farm is connected to the adjacent bus using a transmission line.

The simulation performed in three cases to verify Small signal stability, transient stability and therefore optimal placement of induction generators as follow:

Base case: The original base case.

Case1: wind power plant with Squirrel cage induction generator adds to the system.

Case2: wind power plant with doubly fed induction generator adds to the system.

At each step of the simulation, select one of the candidates' points, and with the participation of wind power in the system, evaluate the influence of oscillating modes that are affected by induction generators. To investigate of the transient stability, the oscillatory modes known in the small signal evaluation, are excited by a large disturbance, we use from the participation matrix of the system.

Investigation of small signal stability

Although the generators used in the wind power plant do not take part in oscillations of power systems [12], their location in the system and changes in the operational conditions affect the oscillations of synchronous generators of the system. Wind farms are usually far from the load centers, and hence the power may be transmitted to far distances while crossing from congested lines. This may drastically change the load distribution pattern of the system and affect the small signal stability. For investigation of small signal stability, first the oscillatory modes of system are considered before the load growth and addition of wind power to the power system. The corresponding damping coefficients are then calculated. After that, by introduction of squirrel cage and doubly-fed induction generators into cases 1 and 2 in different buses, the oscillatory modes of the system are reevaluated. In each case, the modes with the most positive and negative changes are known. Those modes which move in the negative direction of real axis increase the system stability and have positive variations, whereas the modes which move in the positive direction of the real axis have negative variations and reduce the system stability. Therefore, positive and negative effects of using wind power in different locations on the synchronous generators of the system are well defined. Table 2 represents the system's oscillatory modes with the largest negative variations before and after the introduction of wind power generators.

Table 2: Oscillatory modes with the largest negative changes

Bus number	Operation condition	mode	Most Participation	Frequency	damping coefficient
3	Base case	-3.9811+j10.8501	ω 5- delta5	1.8394	0.3445
	Case1	-3.8732+j11.0711	ω 5- delta5	1.8667	0.3302
	Case2	-3.8919+j11.0625	ω 5- delta5	1.8664	0.3319
6	Base case	-1.037+j1.0927	ω 1- delta1	0.23976	0.9204
	Case1	-	-	-	
	Case2	-0.90163+j1.1463	ω 1- delta1	0.23211	0.5245
12	Base case	-3.9811+j10.8501	ω 5- delta5	1.8394	0.3445
	Case1	-3.8732+j11.0711	ω 5- delta5	1.8667	0.3302
	Case2	-3.8732+j11.0711	ω 5- delta5	1.8667	0.3302
14	Base case	-3.1111+j9.6955	ω 4- delta4	1.6206	0.3719
	Case1	-3.0846+j9.8937	ω 4- delta4	1.6494	0.2976
	Case2	-3.0846+j9.8937	ω 4- delta4	1.6494	0.2976

As shown in this table, addition of wind power generators to the system in the buses 3 and 12 exerts a destructive effect on the stability of generator 5. Concerning bus 3, this destructive effect is more obvious for Squirrel cage induction generator, while in bus 12 the destructive effects on both generators are similar. Addition of wind power to bus 14 also produces a damaging effect on the stability of generator 4, which is again similar for both types of generators. Introduction of the doubly-fed induction generator into bus 6 has the largest destructive effect on generator 1 and increases its electromechanical oscillations. Obviously, introduction of squirrel cage induction generator to the system in bus 6 does not worsen the electromechanical oscillatory modes but rather increases their damping and significantly contributes to system stability.

In the analysis of small signal stability, the next step is to determine the positive effect of the presence of squirrel cage and doubly-fed induction generators on the damping of power system's oscillations. In this analysis, the modes with the most positive changes in the presence of squirrel cage and doubly-fed induction generators are represented in Table 3.

Table 3: Oscillatory modes with the largest positive variations

Bus number	Operation condition	Mode	Most Participation	Frequency	damping coefficient
3	Base case	-2.3659+j7.8262	ω 2- delta2	1.3013	0.2893
	Case1	-	-	-	-
	Case2	-2.599+j7.8198	ω 2- delta2	1.3115	0.3154
6	Base case	-3.9811+j10.8501	ω 5- delta5	1.8394	0.3445
	Case1	-4.8098+j10.6555	ω 5- delta5	1.8606	0.4114
	Case2	-4.0882+j10.9841	ω 5- delta5	1.8653	0.3488
12	Base case	-2.3659+j7.8262	ω 2- delta2	1.3013	0.2893
	Case1	-2.4356+j7.9367	ω 2- delta2	1.3213	0.2934
	Case2	-2.4356+j7.9367	ω 2- delta2	1.3213	0.2934
14	Base case	-2.3659+j7.8262	ω 2- delta2	1.3013	0.2893
	Case1	-2.4356+j7.9367	ω 2- delta2	1.3213	0.2934
	Case2	-2.4356+j7.9367	ω 2- delta2	1.3213	0.2934

As it can be seen from the above table, in three points out of the four points which have potential for establishment of wind power plant, the power plant establishment brings about positive effect on the stability of generator 2. However, in bus 6, application of wind power generators produces much desired effect on the stability of generator 5, and hence the introduction of the doubly-fed induction generator into the system in bus 6 develops the damping coefficient of oscillatory mode of generator 5 from 0.3445 to 0.3488. Positive effect of application of squirrel cage induction generator is even better than the previous case and develops the damping from 0.3445 to 0.4114. It can be understood that introduction of wind power into the system exerts the largest negative effect on the generator 1 in bus 6 and the largest positive effect on the generator 5 in bus 6.

Transient Stability

By the investigation of transient stability, the oscillatory modes with low damping characterized through the analysis of the small signal are excited by a large disturbance such as a three-phase short link. Error is eliminated in due time depending on the voltage level of the network. In order to determine the position of disturbance, which excites a given mode, the disturbance close to the machines with the largest participation factor in this mode is taken into account.

Error in a region with negative effect on transient stability

In the formation of the destructive oscillatory mode in the presence of induction generators listed in Table 1, the largest participation coefficient is due to the machines 1, 4, and 5. Therefore, for excitation of these oscillatory modes in all four cases, a three-phase error close to the relevant generator is applied. When wind power generators are introduced into bus 3, the largest participation factor in the formation of destructive mode can be ascribed to generator 5. Fig. 2 shows the diagram for the speed of this generator when an error occurs in bus 6.

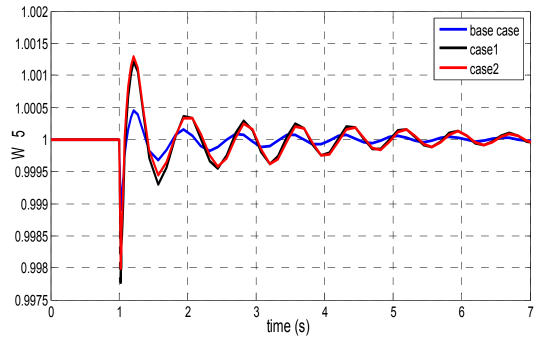

Figure 2: Speed of generator 5 in the presence of wind power in bus 3

According to the table, when adding the squirrel cage and doubly-fed induction generators to bus 14, these generators exerts the most destructive effect on generator 4.Fig. 3 shows the speed diagram of this generator when an error occurs in bus 8.

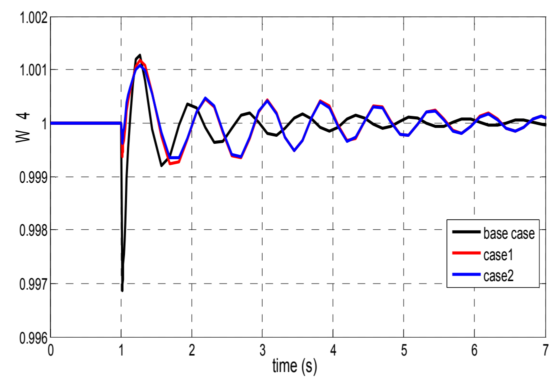

Figure 3: Speed of generator 4 in the presence of wind power in bus 14

Error in a region with positive effect on the transient stability

Similar to the aforementioned trend for excitation of oscillatory modes with positive effect on the transient stability, a three-phase error is applied to the buses of the generators with the most participation in the mode formation.

When adding wind power generators to bus 3, generator 2 has the largest participation factor in the beneficial mode formation. Fig. 4 shows the speed diagram of this generator when an error occurs in bus 3.

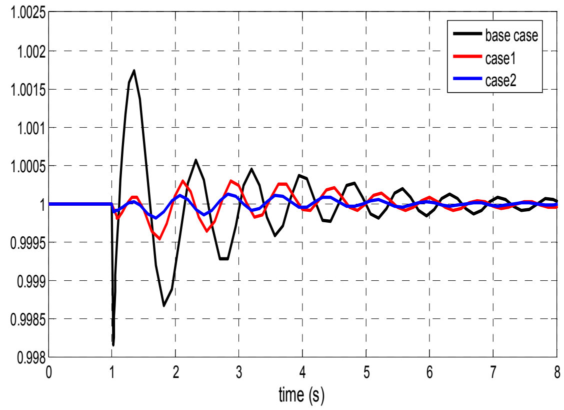

Figure 4: Speed of generator 2 in the presence of wind power in bus 3

As expected, addition of wind power generators to the system improves the system stability. Such improvement has been done more appropriately for the doubly-fed induction generator, which has the best damping coefficient among the three cases. It can be stated that addition of doubly-fed induction generator to bus 3 has a positive effect on the stability of synchronous generator 2.

By addition of wind power generators to bus 6, generator 5 has the most contribution in the beneficial mode formation. The speed diagram shows this generator as error occurs in the bus.

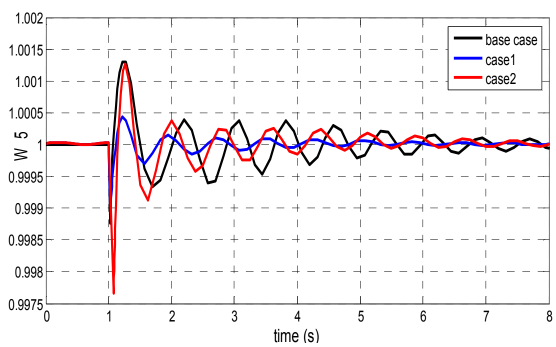

Figure 5: Speed of generator 5 in the presence of wind power in bus 6

As expected, based on the table, addition of induction generators in the form of wind power plant to bus 6 brings about desired effect on the stability of generator 5. This effect is more obvious in the case of squirrel cage induction generator. This issue has been justified by the diagram.

Concerning the table, as squirrel cage and doubly-fed induction generators are added to bus 12, these generators have the largest positive effect on generator 2. The speed diagram shows this generator as error occurs in bus 3.

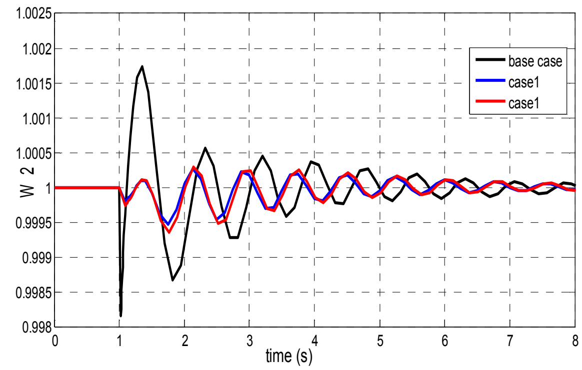

Figure 6: Speed of generator 2 in the presence of wind power in bus 12

As clear from the investigation of small signal in the table, placing of wind power in bus 12 improves the damping of oscillatory mode of generator 2. This is evident in the diagram.

By a little more attention to the table, it can be understood that addition of wind power to bus 14has again the most positive effect on generator 2, while improving the said generator's stability quite similar to the previous case. Thus, investigation of transient stability of this case is disregarded.

ANALYSIS OF TABLES AND DIAGRAMS

With regard to Table 1, addition of wind power to bus 3 produces a negative effect on the stability of generator 5 and such negative effect is quite similar for both kinds of generators. On the other hand, based on Table 3, positive effect of doubly-fed induction generator on the stability of generator 2 is greater than that of the squirrel cage induction generator. Therefore, if a wind power plant is to be established in this area, then the doubly-fed induction generator is a better candidate. Similar to bus 3, by addition of wind power to bus 12, the corresponding negative effect is directed to generator 5 while its positive effect is on generator 2. However, here the positive or negative impact of both kinds of induction generators on synchronous generators 2 and 5 is similar. Analyses for bus 14 are also similar to those in buses 3 and 12. But, regarding bus 6, addition of squirrel cage induction generator not only does not produce adverse effect on the stability of synchronous generators but also improves their stability. In this case, generator 5 is the most vulnerable and the damping coefficient of its electromechanical oscillatory mode develops from 0.3445 to 0.4114. In this context, it is obvious that establishment of wind power plant with squirrel cage induction generator in bus 6, is the best choice in terms of transient stability and small signal of system.

CONCLUSION

The present paper has offered the best choice among different potential alternatives for the siting of a wind power plant while considering thetransient stability and small signal of the system.For this purpose, through the study of the small signal of the system, all oscillatory modes of system are recognized. Then by addition of wind power generators to the system, their influence in the system oscillatory modes are determined. After that, modes which are most positively and negatively affected are determined and machines with the largest contribution in the mode formation are defined using the participation matrix of the system. Addition of wind power to system has the most positive and negative effect on these machines. In the study of transient stability, determined modes in the investigation of small signal are excited by a large disturbance such as a short link. The short link is placed close to the machines with most participation in the related oscillatory mode formation. While considering the IEEE 14-bus test system as the test system,the present study has assumed bus 6 to be the best candidate for establishment of wind power plant with squirrel cage induction generator. Besides, it has been shown that the results of transient stability and small signal analyses are in complete agreement – as it is shown in all the suggested diagrams.

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