NONLINEAR MODAL ANALYSIS OF WIND FARM IN STRESSED WIND FARMS IN STRESSED POWER SYSTES: EFECTS OF DFIG CONTROLLERS

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ABSTRACT

This paper deals with the problems of nonlinear interaction of large capacity wind farm in stressed power systems in the presence of FACTS controllers. The study is performed on an IEEE modified test system using the nonlinear modal analysis based on the Modal Series (MS) method. As the installed capacity of renewable energy especially the wind energy increases, the connection of the wind farms to the grid should be studied from different viewpoints. The dynamic performance of this composite power system is an important issue and should be investigated carefully especially in stressed conditions and different operating points of DFIG controllers. The nonlinear interactions will complicate the dynamic behavior of power systems. If such interaction exists between wind farms and other system components such as FACTS controllers and is quantitatively significant, the stability of wind plant is jeopardized.

INTRODUCTION

The growing demand for electrical energy, limitation of fossil resources and the worries about environmental pollution lead to new challenge for utilization of clean energies such as wind in power systems [1]. Nowadays the use of wind energy resources as connecting to the main network or supplying the far loads and also to use in urban areas has been extended [2]-[4]. When the penetration of wind generation is high, the online operation of generators during grid disturbances becomes very important regarding the grid code requirements. Therefore, investigating the dynamic performance of a power system integrated with wind farms having high penetration levels is quite necessary.

In this respect one problem needs to be analyzed is the possibility of adverse interactions between modes associated with wind farms and other system modes. In [5]-[8] using the time domain simulations and linear modal analysis, the interaction between the wind turbine-generator set and system modes such as inter-area, local and control modes are studied. The results of these papers show that when the wind farm capacity increases the interaction level between wind farm turbine-generator units and other system components increases.

In time-domain simulations, the required information corresponding to the system modal structure is not provided. On the other hand, the linear analysis is only valid for small variations around the operating points and cannot demonstrate the nonlinear interaction phenomenon [9]. Therefore, in case of nonlinear interaction the nonlinear modal analysis approaches such as the Modal Series (MS) method should be used to investigate the dynamic behavior of power systems. In recent years, Modal Series (MS) method has been used to study the power system dynamic phenomena [9]-[13]. These papers have concluded that in stressed power systems, due to the increase of nonlinear interactions the linear modal analysis is not able to analyze their dynamic behaviors accurately, so the nonlinear analysis techniques should be employed.

Regarding the important role of wind power energy in modern power systems and the common use of DFIG’s, their stability is crucial to operators. In present paper, the MS method is used to analyze the nonlinear interactions between Wind Turbine Generator (WTG) units in wind farms and other system components especially the Flexible AC Transmission System (FACTS) devices. To do so, at first, the power system is modeled and the governed dynamic equations are provided. Then, the second-order Taylor expansion of these equations is performed around the stable operating point and using the MS method the nonlinear interactions of wind farm are studied under different conditions. The paper is organized as follows. Some interaction problems of the wind farms are demonstrated in section 2. In Section 3, the modal analysis of nonlinear systems based on MS method is outlined. The adopted model of the studied power system is presented in Section 4. The case study and the obtained results are shown in Section 5. Conclusions are given in Section 6.

INTERACTION PROBLEMS OF WIND FARMS

In modern power systems, attempts have been made to provide the reliable electricity services and cleaner environments for customers by shifting the generations from centralized to combination of centralized and distributed ones. For this purpose, the renewable resources such as wind energy are introduced in power systems. Due to economic, environmental, and technological issues, the wind energy has grown rapidly and taken a better position among resources.

In connection of large-scale wind farms with power grid, the High Voltage DC (HVDC) and FACTS devices can be used to support the grid and protect the equipments during severe grid disturbances [14]. In this situation, the problems corresponding to the interactions between wind farms and other system controllers such as HVDC or FACTS controllers are our great concern considering the stability and safe operation of a power system. These interactions may originate from nonlinear effects and known as nonlinear interactions [9]. The nonlinear interactions between WTG’s in the wind farms and system controllers become more vigorous and can adversely affect the dynamic behavior of the system leading to the damage of some system components [15]. To study these types of interactions the nonlinear modal analysis methods such as MS method can be used.

APPROXIMATE SOLUTION BASED ON MODAL SERIES METHOD

The nonlinear interactions, which arise from nonlinear factors, will contribute in complicating the dynamic behavior of nonlinear systems. To study these interactions the nonlinear modal analysis methods such as MS method can be used. The MS method is based on Taylor's expansion of nonlinear system equations around the stable equilibrium point. If (1) exhibits the nonlinear dynamic equations of a power system with n variables, (2) will be the Taylor expansion of (1) around a stable equilibrium point.

$$\dot{\boldsymbol{X}} = \boldsymbol{F}(\boldsymbol{X}) \tag{1}$$

$$\dot{x}_{\mathrm{i}} = \boldsymbol{A}_{\mathrm{i}}\boldsymbol{X} + \frac{1}{2}\boldsymbol{X}^{\mathrm{t}}\boldsymbol{H}^{\mathrm{i}}\boldsymbol{X} + \ldots \qquad \mathrm{i} = 1,2,\ldots,n \tag{2}$$

In (2), A and H are Jacobian and Hessian matrices respectively. If U and V denote the matrices of right and left eigenvectors of A respectively, by applying the linear transformation X=UY to the first and second-order terms of (2), yields,

$$\begin{aligned}\dot{\mathrm{y}}_{\mathrm{j}} &= \lambda_{\mathrm{j}}\mathrm{y}_{\mathrm{j}} + \mathrm{Y}^{\mathrm{t}}\mathrm{C}^{\mathrm{j}}\mathrm{Y} \\ &= \lambda_{\mathrm{j}}\mathrm{y}_{\mathrm{j}} + \sum_{\mathrm{k}=1}^{\mathrm{n}}\sum_{\mathrm{l}=1}^{\mathrm{n}}\mathrm{C}_{\mathrm{kl}}^{\mathrm{j}}\mathrm{y}_{\mathrm{k}}\mathrm{y}_{\mathrm{l}} \qquad \mathrm{j}=1,2,\ldots,\mathrm{n}\end{aligned} \tag{3}$$

Where

$$\boldsymbol{C}^{\mathrm{j}} = \frac{1}{2}\sum_{\mathrm{p}=1}^{\mathrm{n}}\mathrm{V}_{\mathrm{jp}}^{\mathrm{t}}\left(\boldsymbol{U}^{\mathrm{t}}\boldsymbol{H}^{\mathrm{p}}\boldsymbol{U}\right) \tag{4}$$

Approximate Linear Method

If in (3) only the first term is considered, and the higher-order terms are neglected, the linear approximate solution of (1) becomes [10]:

$$x_{\mathrm{i}}(\mathrm{t}) = \sum_{\mathrm{j}=1}^{n}u_{\mathrm{ij}}\mathrm{y}_{\mathrm{j0}}e^{\lambda_{\mathrm{j}}t} \tag{5}$$

Modal Series Method

In (3), by considering up to second-order terms and assumption for not existence of second-order resonance ($\lambda_k + \lambda_l \neq \lambda_j$), the MS second-order approximate solution of (1) is given by [10]:

$$\begin{aligned}x_i(t) &= \sum_{\mathrm{j}=1}^{n}u_{ij}\left(y_{\mathrm{j0}} - \left\{\sum_{\mathrm{k}=1}^{n}\sum_{\mathrm{l}=1}^{n}h2_{\mathrm{kl}}^{\mathrm{j}}y_{\mathrm{k0}}y_{\mathrm{l0}}\right\}\right)e^{\lambda_{\mathrm{j}}t} \\ &+ \sum_{\mathrm{k}=1}^{n}\sum_{\mathrm{l}=1}^{n}\left(y_{\mathrm{k0}}y_{\mathrm{l0}}\sum_{\mathrm{j}=1}^{n}u_{ij}h2_{\mathrm{kl}}^{\mathrm{j}}\right)e^{(\lambda_{\mathrm{k}}+\lambda_{\mathrm{l}})t}\end{aligned} \tag{6}$$

where

$$h2_{\mathrm{kl}}^{\mathrm{j}} = C_{\mathrm{kl}}^{\mathrm{j}}\Big/\left(\lambda_{\mathrm{k}}+\lambda_{\mathrm{l}}-\lambda_{\mathrm{j}}\right) \qquad \mathrm{j,k,l} = 1,2,\ldots,n \tag{7}$$

In (5) and (6), e^{λ_j} and $e^{(\lambda_k+\lambda_l)}$ respectively defined as linear and nonlinear modes.

Nonlinear Interaction Index Based on Modal Series Method

To analyze the nonlinear behavior of a power system using the MS method, the nonlinear interaction indices should be used. By comparison the linear solution (5) and MS solution (6), it is seen that by considering the nonlinear factors the nonlinear modes are appeared in the time responses of the system. This phenomenon is defined as nonlinear interaction [9]. As seen from (6), the amplitudes and the damping of nonlinear modes are the two important affected factors in the time responses. Therefore, the index $I2_{K1}^{i}$ defined in (8) is used as a criterion to study the nonlinear interactions in the nonlinear systems.

$$\mathrm{I2}_{\mathrm{kl}}^{\mathrm{j}} = \left| y_{\mathrm{k0}}y_{\mathrm{l0}}\sum_{\mathrm{j}=1}^{n}u_{ij}h2_{\mathrm{kl}}^{\mathrm{j}} \Big/ \mathrm{real}(\lambda_{\mathrm{k}}+\lambda_{\mathrm{l}})\right| \tag{8}$$

$I2_{K1}^{i}$ provides n2 values for jth state variable. By comparing these values, it is found that which nonlinear mode has most effect on the time response of this state variable. The high value of this index implies the existence of severe nonlinear interaction between system components related to jth mode with system components related to kth and lth modes.

MODELING THE POWER SYSTEM FOR MODAL ANALYSIS

The study system comprises the synchronous generators, the wind farm, and the FACTS device. In this paper, the Static VAr Compensator (SVC) is considered as one of the well-known FACTS controllers.

Synchronous Generator

The simple d-q axes model is used to represent the synchronous generator. In addition, the excitation system is modeled as a thyristor with a high transient gain. The synchronous generator equations are obtained as follows [16]:

$$\dot{E}'_{q_i} = \left(E_{fd_i} - E'_{q_i} + \left(x_{d_i} - x'_{d_i}\right) I_{q_i}\right) \Big/ \tau'_{d0_i}$$

$$\dot{E}'_{d_i} = \left(-E'_{d_i} - \left(x_{q_i} - x'_{q_i}\right) I_{d_i}\right) \Big/ \tau'_{q0_i}$$

$$\dot{E}_{fd_i} = \left(-E_{fd_i} + K_{exc_i}\left(V_{ref_i} - V_{t_i} + V_{s_i}\right)\right) \Big/ T_{exc_i} \quad (9)$$

$$\dot{\delta}_i = \omega_S\,(\omega - 1)$$

$$\dot{\omega}_i = \left(T_m - T_e - D\,(\omega - 1)\right) \Big/ 2H$$

Wind Farm

A wind farm comprises many WTGs connected to each other via an internal network. The electric power generated by WTGs is injected to the main network at the point of common coupling (PCC). To extract the electrical energy from wind energy different types of wind turbines are used. Type A and B are based on the induction generator, which respectively provide fixed and limited variable speed operation. Type C and D provide a variable speed operation and respectively are based on the DFIG and synchronous generator. In types C and D, the maximum output power with lower fluctuation is extracted from wind. Regarding the benefit and characteristics of type C, it is the most common use in the current wind farm projects [17]. So in this paper, the WTG based on the DFIG is considered. The following equations describe the electrical model of the DFIG [18]:

$$\dot{\psi}_{qs} = \omega_s\left(V_{qs} + R_s I_{qs} - \psi_{ds}\right)$$

$$\dot{\psi}_{ds} = \omega_s\left(V_{ds} + R_s I_{ds} + \psi_{qs}\right)$$

$$\dot{\psi}_{qr} = \omega_s\left(V_{qr} - R_r I_{qr} - \frac{(\omega_s - \omega_r)}{\omega_s}\psi_{dr}\right) \quad (10)$$

$$\dot{\psi}_{dr} = \omega_s\left(V_{dr} - R_r I_{dr} + \frac{(\omega_s - \omega_r)}{\omega_s}\psi_{qr}\right)$$

In addition, a two-mass model is considered for the wind turbine-generator. The mechanical equations of DFIG are as bellow:

$$\dot{\omega}_T = \left(T_m - K_{TG}\theta_{TG} - D_T\,(\omega_T - \omega_0)\right) \Big/ 2H_T$$

$$\dot{\omega}_r = \left(-K_{TG}\theta_{TG} - D_G\,(\omega_r - \omega_0) - T_e\right) \Big/ 2H_G \quad (11)$$

$$\dot{\theta}_{TG} = \omega_s\,(\omega_T - \omega_G)$$

Where ω_T and ω_G respectively denote the speed of turbine and generator and θ_{TG} denotes the angular displacement between these masses.

Three controllers are considered for turbine-generator based DFIG as pitch angle controller, active and reactive power controllers [19]. The wind speed is assumed to be in its technical limit, the pitch angle controller is not taken into account. The block diagram of active and reactive controllers is shown in Fig. 1.

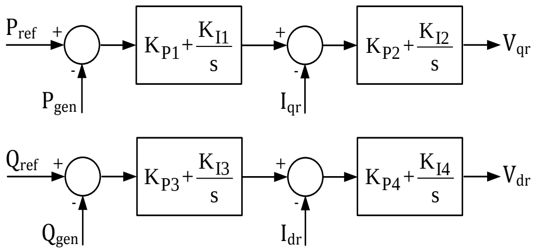

Fig. 1. Active and reactive power controllers

SVC Representation

SVC is one of the FACTS devices that installed in transmission lines to improve the voltage profile and increase the dynamic and transient stability limits [20]. The SVC control system is presented by a variable susceptance model. The block diagram of this model is shown in Fig. 2 [21].

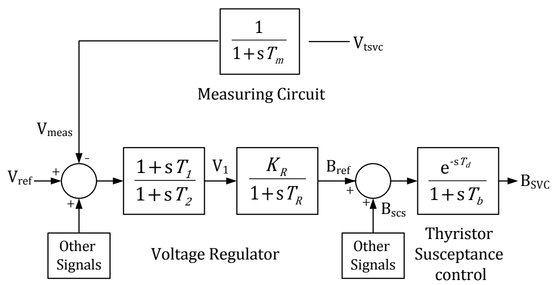

Fig. 2. The block diagram of SVC control system

CASE STUDY

The modified IEEE 2-areas 4-gen test system is considered to study the nonlinear interactions of the wind farm. This system contains a SVC and one of the synchronous generators replaced with the wind farm. The single-line diagram of the test system is shown in Fig. 3. The wind farm included 20×5MW WTGs based DFIG. For simplicity, the wind farm is modeled by only one WTG having 100MW capacity. The test system parameters are listed in Appendix.

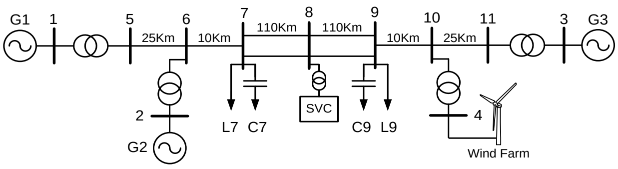

Fig. 3. Single line diagram of test system

The test system has 31 modes, in which 11 modes are related to the wind farm, 15 modes related to synchronous generators, and 5 modes related to SVC. The Eigenvalues of the test system can be found in Table 1.

To study the effect of DFIG controllers on the nonlinear interactions of the wind farm the second-order Taylor expansion of test system is provided. A fault is applied on bus 9, which is cleared in 10ms. According to the MS nonlinear interaction index presented in section 3, the nonlinear interaction between DFIG, and other system components are investigated in the base case and the results for some state variables of DFIG are shown in Fig. 4. In the base case, the proportional and integral parameters of DFIG controllers are considered as:

KP1=KP2= KP3=KP4=1 KI1=KI2= KI3=KI4=5

Table 1. Eigenvalues of the test system

Mode Number	Eigenvalue	Source	Mode Number	Eigenvalue	Source
1,2	$-5710.6 \pm j1269$	Wind Farm	16,17	$-0.096 \pm j10.03$	Wind Farm
3	-1984.4	SVC	18,19	$-0.635 \pm j7.5$	G1-G2
4	-530.6	SVC	20,21	$-0.086 \pm j4.6$	G1-G2-G3
5,6	$-11.8 \pm j357.1$	Wind Farm	22	0	Reference
7,8	$-5.6 \pm j216.5$	SVC	23	-0.185	G1,G2,G3
9	-90.2	G1,G2	24	-0.2	Wind Farm
10	-81	G3	25,26	$-2.39 \pm j0.43$	Wind Farm
11	-76.2	G1,G2	27	-3.8	Wind Farm
12	-33.1	SVC	28	-4.97	G1
13	-23.6	G1,G2	29	-4.14	G2
14	-19.1	G3	30	-4.3	G3
15	-11.1	G1,G2	31	-4.63	Wind Farm

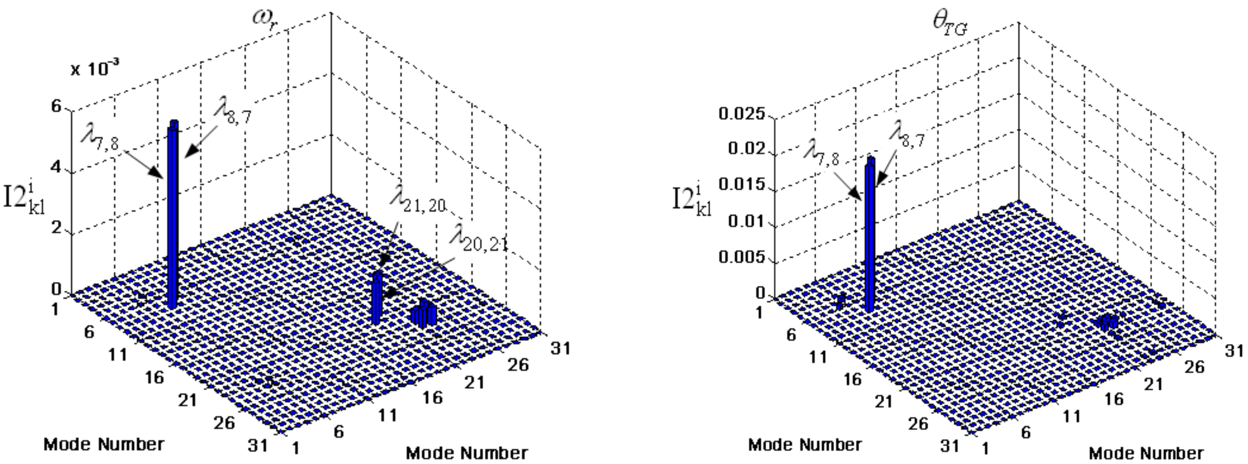

Fig. 4. Nonlinear interaction index of DFIG state variables in base case

As seen from Fig. 4, the most important nonlinear modes that appeared in the output responses of DFIG are $\lambda_{7,8}(\lambda_7+\lambda_8)$ and $\lambda_{8,7}(\lambda_8+\lambda_7)$ that are related to SVC, $\lambda_{20,21}(\lambda_{20}+\lambda_{21})$ and $\lambda_{21,20}(\lambda_{21}+\lambda_{20})$ related to inter area mode. With reference to the Table 1, the modes 7 and 8 correspond to SVC, the modes 20 and 21 correspond to inter area mode.

In what follows of the paper, the effect of DFIG controllers on the nonlinear interaction between DFIG and other system components are studied. As seen from Fig. 1, the active and reactive controllers of DFIG are included from two PI controllers. As shown in (12), using an increasing or decreasing factor the proportional and integral parameters of PI controllers are changed such that their relation to be fixed.

$$\begin{cases} Kp_{i,new} = factor \times Kp_{i,base} \\ KI_{i,new} = factor \times KI_{i,base} \end{cases} \quad i = \{1,2,3,4\} \qquad (12)$$

Effect of DFIG active power controller on the nonlinear interaction

To investigate the effect of active power controller on the nonlinear interaction between DFIG and other system components, by considering larger values for proportional KP1 and KP2 and integral KI1 and KI2 parameters, the nonlinear interaction index $I2^i_{K1}$ is obtained and the results are shown in Fig. 5. In this case, the parameter factor (eq. 12) is selected equal to 5. In addition, by selecting smaller values for active power controller parameters, the nonlinear interaction of DFIG is obtained and the results are shown in Fig. 6. In this case, the parameter factor is considered equal to 0.2.

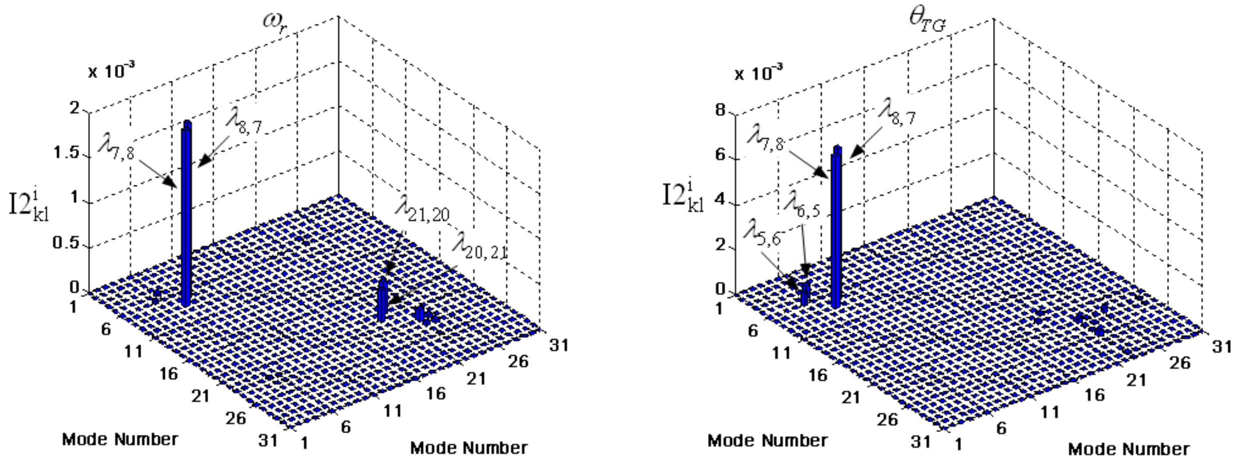

Fig. 5. Nonlinear interaction index of DFIG state variables when selecting high values for active power controller parameters (factor=5)

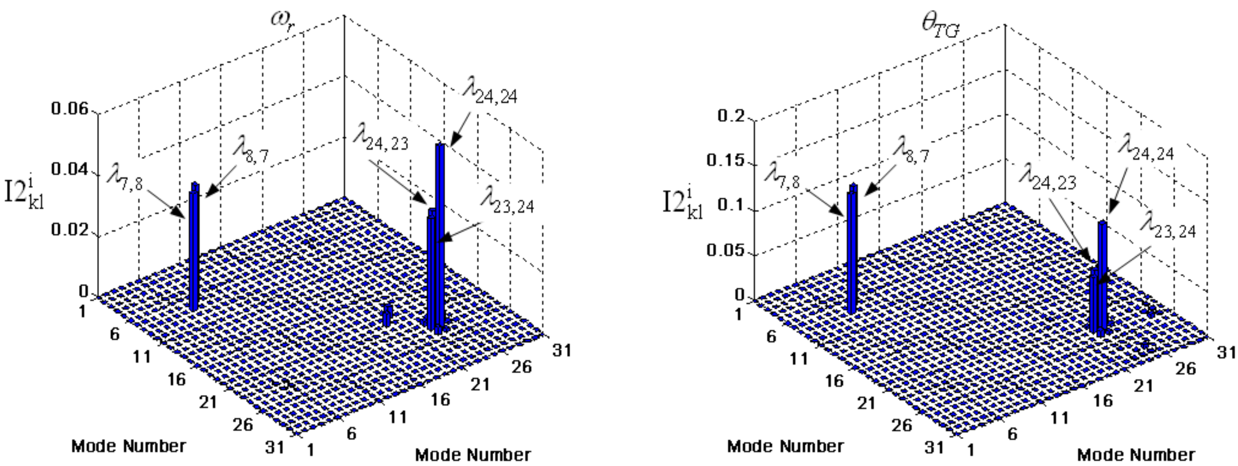

Fig. 6. Nonlinear interaction index of DFIG state variables when selecting small values for active power controller parameters (factor=0.2)

As seen from Figs. 5 & 6, by selecting smaller values for active power controller parameters, the nonlinear interaction between DFIG and other system components are increased. In addition, when high values of parameters are considered for active power controller the most nonlinear modes that appeared in the responses of DFIG are that combined from SVC ($\lambda_{7,8}$ and $\lambda_{8,7}$) and inter area mode ($\lambda_{20,21}$ and $\lambda_{21,20}$). While that when active power controller operates in less values of proportional and integral parameters, the most nonlinear interaction occurred between DFIG and synchronous generators (as seen from Table 1, mode 23 is related to synchronous generator and mode 24 correspond to DFIG).

Effect of DFIG reactive power controller on the nonlinear interaction

Similar to previous section, to study the effect of reactive power controller on the nonlinear interaction between DFIG and other system components, by considering different values for proportional KP3 and KP4 and integral KI3 and KI4 parameters, the nonlinear interaction index $I2^i_{K1}$ is obtained and the results are shown in Figs. 7 & 8.

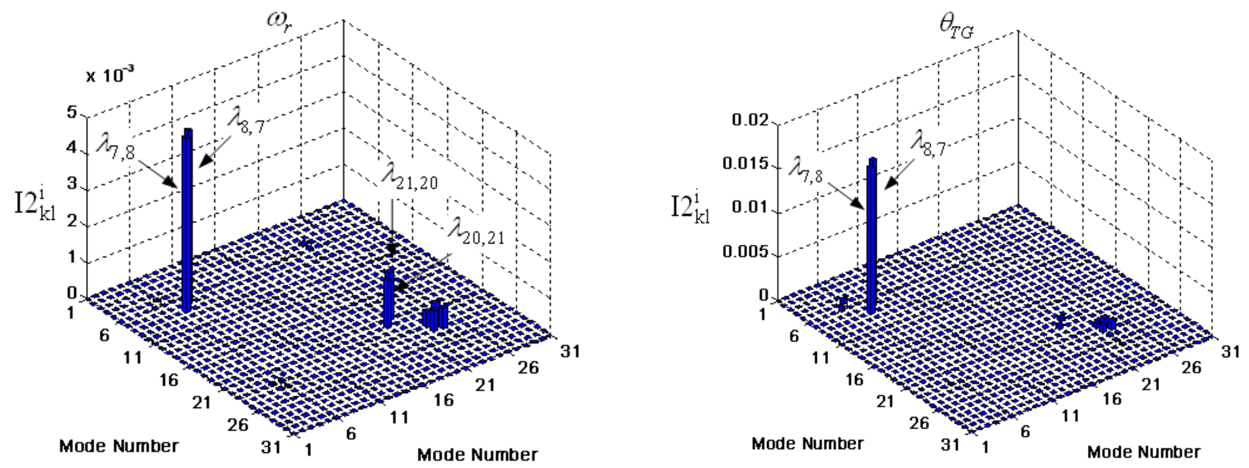

Fig. 7. Nonlinear interaction index of DFIG state variables when selecting high values for reactive power controller parameters (factor=5)

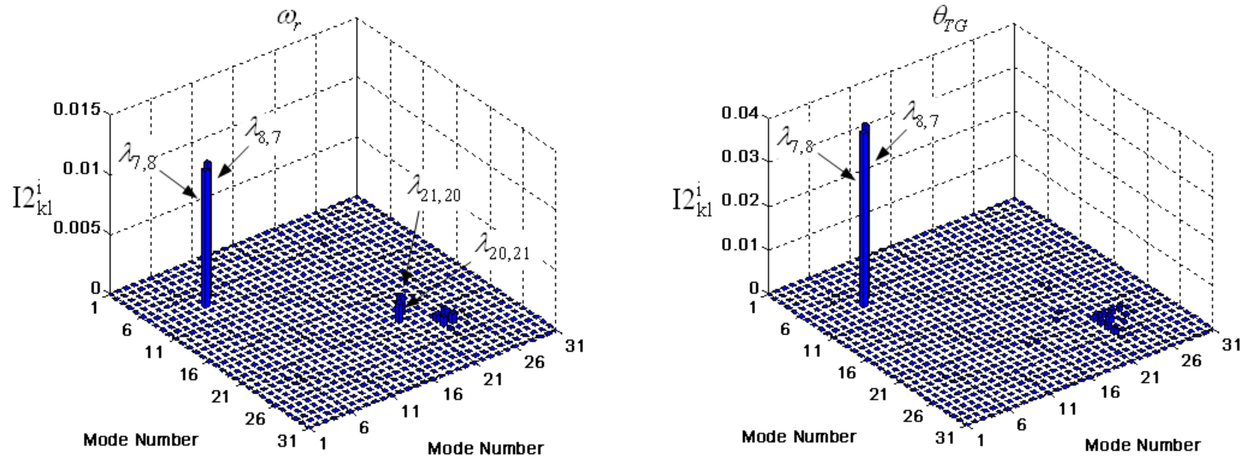

Fig. 8. Nonlinear interaction index of DFIG state variables when selecting small values for reactive power controller parameters (factor=0.2)

With reference to these Figs., by considering different parameters for the DFIG reactive power controller the considerable change is not to be seen in the nonlinear interaction of DFIG. In addition, the results show that the reactive power controller of DFIG has no effect on the most important nonlinear modes that appeared in the output response of DFIG (as seen from Figs. 7 & 8 for different parameters of reactive power controller the important nonlinear modes are $\lambda_{7,8}$ and $\lambda_{8,7}$).

CONCLUSION

The results of this paper show that the nonlinear interactions exist between wind farms based DFIG and other system components especially SVC controllers. The nonlinear modal analysis based on the modal series method can well predict these interactions. The results show that the active power controller of DFIG has important effect on the nonlinear interaction of DFIG. When this controller operates at small values of proportional and integral parameters, the nonlinear interaction of DFIG is significantly increased. Also, in this case, in addition to SVC controllers the synchronous generators so interact with the DFIG. The results of this paper show that despite of active power controller, the reactive power controller of DFIG has no important effect on the nonlinear interaction of DFIG.

APPENDIX

Synchronous generator

V_{base}=20kV, S_{base}=900MVA

$x_d = 1.8, x_q = 1.7, x'_d = 0.3, x'_q = 0.55, \tau'_{do} = 8\,s$

$\tau'_{qo} = 0.4\,s, R_a = 0.0025$

Transmission line

V_{base}=230kV, S_{base}=100MVA

$R_L = 0.0001\,pu/Km, X_L = 0.0001\,pu/Km, b_c = 0.0001\,pu/Km$

$p_{L_7} = 967\,MW, Q_{L_7} = 100\,MVAr, p_{L_9} = 1167\,MW$

$Q_{L_9} = 100\,MVAr, Q_{C_7} = 100\,MVAr, Q_{C_9} = 200\,MVAr$

DFIG

S_{base}=5MVA

$X_s = 3.55, X_r = 3.58, X_m = 3.5, R_s = 0.1015, R_r = 0.088$

$KP1 = 1, KP2 = 1, KP3 = 1, KP4 = 1$

$KI1 = 5, KI2 = 5, KI3 = 5, KI4 = 5,$

SVC

$K_{svc} = 55, T_{svc} = 0.1\,s, T_1 = 0.03, T_2 = 0.02, T_b = 0.004\,s$

$T_d = 0.001\,s, T_m = 0.004\,s, Q_{svc} = \pm 400\,MVAr$

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