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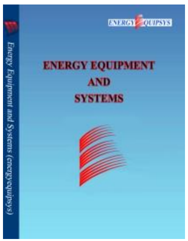

Damping analysis of sub-synchronous resonance (SSR) in a wind farm based on DFIG in a series compensated network

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ABSTRACT

The effect of wind generator on sub-synchronous resonance (SSR) is being interested by increasing penetration of wind turbine in power systems,. Purpose of this article is to analyze SSR in a wind farm based on doubly fed induction generator (DFIG) which is connected to compensating series grid. A dynamic model for analysis of induction generator effect and Torsional Interaction (TI) has been utilized and simulated. The IEEE first benchmark model, is modified to include a 100 MW DFIG-based wind farm, is employed as a case study. three phenomena including a) series compensation level, b) the rotor speed, and c) effect of internal parameters of RSC controller on SSR are evaluated and the simulation results are analyzed.

Keywords: DFIG, SSR, Torsional Interaction (TI), RSC Controller, GSC Controller.

1. Introduction

Wind generation is the fastest-growing form of renewable energy at present [1], [2]. Nowadays, most wind farms in Europe and North America use Adjustable Speed Generator Wind Turbines (ASGWT). An important class of ASGWT is the Doubly-Fed Induction Generator (DFIG), which has gained significant attention from electric power industry in the past few years [3]. Large-scale integration of DFIG wind farms in transmission or distribution level may require essential upgrades of the transmission line substructure, such as building new transmission lines, in order to accommodate the increased wind-generated power flow [4]. Series compensation is considered as a more economical solution to increase the power transfer capability of an existing transmission line compared to construction of new transmission lines [5].However, the potential risk of Sub-Synchronous Resonance (SSR) is a factor hindering the extensive use of series capacitive compensation [6].The SSR phenomenon in series compensated system with synchronous generators has been widely investigated. Totally, SSR can be evaluated by three main effects. First, by induction generator effect, second by Torsional Interaction (TI) and third by torsional amplification. The two first are related to steady state condition and the third one should be evaluated in transient mode. Specifically, IGE just covers interactions between the generator and the grid. However, TI contains the mechanical dynamic which are generated by the turbine.

By having the power profile of a wind farm, the most serious problem is: Does SSR would appear in the grid connected wind farm with series compensation or not. Generally, most of the wind farms are based on induction

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generators. VerSma et al. [3] discussed SSR phenomena of a self-excited double induction generator based on wind farm interconnected with a series-compensated network. Effects of wind speeds and compensation levels on SSR are investigated. FACTS devices, such as TCSC and SVC, are used to demonstrate how to mitigate SSR in such systems.

In another research [7], SSR phenomenon in compensated series wind farms with constant speed are investigated, in which 2 squirrel induction generators have been utilized,. SSR and TI phenomena have been simulated by PSCAD and the results are presented in this paper. It can be concluded thatthe system oscillation would decrease more whatever the wind farm output power increases more. Since the variable speed wind system with DFIG topology is more applicable and has higher efficiency, they are grounded more quickly compared to constant speed wind system.

In [8], a dynamic model for DFIG-based wind farm with series compensation has been proposed and its stability has been discussed. Its main parameters such as wind speed, compensation level, and current control parameters under sub synchronous oscillation have been studied. However, the relation among turbine parameters and turning oscillation modes has not been evaluated in this paper.

Hence, this paper has focused on SSR in series compensation systems based on DFIG. A basic analysis has been performed in [9], and a more detailed analysis has been performed in this paper to evaluate under which parametric condition, IGE and TI would appear.

The SSR damping using DFIG-based wind farms has also been studied by Fan and Miao in [10].Their goal is to design an auxiliary SSRDC for the GSC controllers using eigenvalue analysis method in order to increase the stability of both sub-synchronous and super-synchronous modes. Only average converter models are used for validation.

In chapter 2, SSR phenomenon in DFIG based systems has been presented. Then the dynamic model of DFIG with its back to back converter, series compensated grids and torsion dynamic have been demonstrated in chapter 3. Simulation results which demonstrate eigenvalues and time domain analysis have been presented in chapter 4. Finally, the simulation results have been compared to the previous works and the paper has been concluded in chapter 5.

2.SSR analysis in DFIG

Resonance frequency of series compensated grid is defined by Eq.(1). In which, f_o is synchronous frequency. Equation (2) demonstrates the speed slip, where f_n is the synchronous frequency and f_m is the mechanical frequency of rotor.

$$f_n = f_0\sqrt{X_c/\sum X}\ Hz \tag{1}$$

$$S = \frac{f_n - f_m}{f_n} \tag{2}$$

Where in $\sum X$ is the total reactance seen from infinite bus. Generally, f_n is smaller than f_m Hence, S would be negative and according to the steady state equations of a DFIG, the rotor resistance at sub-synchronous frequency would be negative.

$$R_{r\,eq} = \frac{R_r}{S} < 0 \tag{3}$$

If the amount of this resistance is larger than the armature resistance plus of the grid resistance, the system would have a negative resistance at sub-synchronous frequency. This phenomenon would lead to self-excitation and finally would cause an oscillating current in rotor and instability of the system. This phenomenon has been known as IGE.[3]

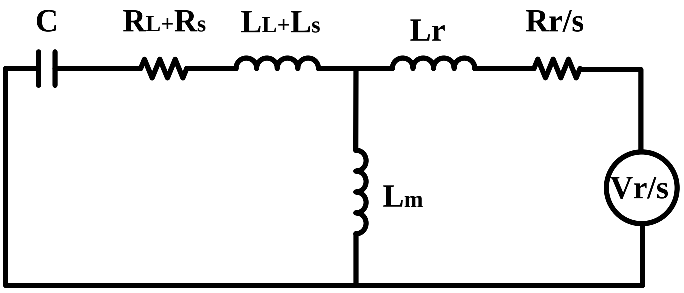

Fig.1. Sub-synchronous equivalent circuit induction generator and the grid

The relation among frequencies in a DFIG has been represented in Table1.According to series compensation, sub-synchronous components of voltage and current with frequency f_n are applied to the grid and the stator of DFIG where the complementary frequency of these components at rotor current is $f_s - f_n$. According to Table 1, the stator current has been comprised of two components named as I_{s1} and I_{s2} and similarly, the rotor current is defined by I_{r1} and I_{r2}. I_{s1} is at the nominal frequency, f_s and I_{s2} are at the resonance frequency. I_{r1} and I_{r2} are also in accordance with the equivalent rotor current components. So, I_{r1} is at the frequency of $f_s - f_n$ and I_{r2} is at the frequency of $f_n - f_m$.[3]

In Table 2, it is shown that the mentioned currents would have mutual effects on production of torque. As it can be seen in this table, T_1 is resulted from the mutual effect of I_{s1}& I_{r1}, T_2 from I_{s2}& I_{r2}, T_3 from I_{s2}& I_{r1} and T_4 from I_{s2}& I_{r2}.

Hence, the produced torque would have a component at the frequency of $f_s - f_n$ according to the series compensation of the grid. And the TI effect would be produced while the TI frequency of f_{TI} is close to the grid complementary frequency of $f_s - f_n$.

IGE phenomenon depends on slip (S). According to Eq.(2), S depends on the rotating speed of f_m and the grid resonant frequency of f_n. f_m depends on wind speed and also fn depends on the compensation level. So, any changes in the wind speed and the compensation level would affect on the slip of S. Moreover, the current control pattern which is utilized to apply the rotor voltage, would affect the amount of R_{req} at Fig. 1. The effect of changes of these parameters in SSR phenomenon, has been investigated at the next section.[4]

3.System Model

IEEE model has been first evaluated in this paper that has been shown in Fig.2; It is a wind farm based on DFIG which has been connected to a series compensated grid. In this model, the dynamic behavior of a group of turbines is considered as a single machine. This assumption has been proved in many publications with good approximation. On the other hand, dynamic simulation of a huge system by an equivalent single machine would be acceptable for most studies [14, 15].

In two recent researches, the first model of IEEE along with self-excited induction machine model has been employed to investigate the SSR phenomenon on wind farms [4, 16]. In [4], total power of wind farm is equal to 746 MW and the transmission voltage is equal to 500 kV. In [16], the wind power and the transmission voltage have been decreased down to 100 MW and 100 kV respectively. In this paper an integrated model for DFIG system has been utilized.

Basic power of the wind farm and total inertia would increase by joining the wind turbines together. Hence, the total inertia in p.u would not change. This issue would be the same for other parameters of the machine such as impedances etc. Therefore, parameters of a 2 MW DFIG can be used for an equivalent wind generator.

In the next sections, the aerodynamic model of wind turbine, the compensated series grid, induction generator, DC link of DFIG converters, TI and the control system of DFIG converters are investigated.

3.1.The aerodynamic model of wind turbine

The output dynamic torque of a wind turbine is calculated according to (4) in which, ρ is the air density (Kgm^{-3}), A is the sweep area of the

Table 1. The frequency relationship among current components of rotor and stator of DFIG

Stator current	$f_s \leftarrow I_{s1}$	$f_n \leftarrow I_{s2}$
Rotating shaft speed	f_m	f_m
Rotor current	$(f_s - f_m) \leftarrow I_{r1}$	$(f_n - f_m) \leftarrow I_{r2}$

Table 2. Torque components

Torque comp	*T1*	*T2*	*T3*	*T4*
Interaction	I_{s1} & I_{r1}	I_{s1} & I_{r2}	I_{s2} & I_{r1}	I_{s2} & I_{r2}
Frequency	*0*	$(f_s - f_n)$	$(f_s - f_n)$	*0*

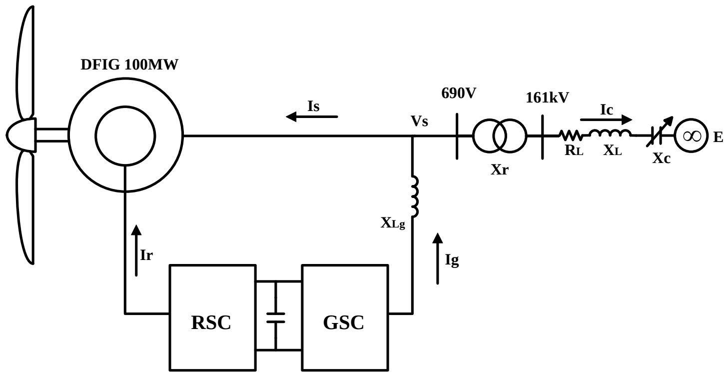

Fig.2. Study system, The nominal voltage of the wind farm terminal bus is 690V

turbine (m^2), R is the radius of wind turbine blades (m), V_w is the wind speed (m/s) and C_p is the power factor of turbine blades that is a function of the turbine pitch angle (θ) and the turbine blade tip speed (λ).[17].

$$T_m = \frac{1}{2}\rho A R C_p V_w^2 / \lambda \tag{4}$$

$$C_p = \frac{1}{2}\left(\frac{RC_f}{\lambda} - 0.022\theta - 2\right)e^{-0.255\frac{RC_f}{\lambda}} \tag{5}$$

λ is calculated as follows:

$$\lambda = \frac{\Omega_m R}{V_w} \tag{6}$$

In which V_w (m/s) is the wind speed and Ω_m(rad/s)is the speed of the mechanical angle The relationship among power, rotating speed and the wind speed a 2 MW wind turbine while step angle is 0, has been demonstrated in Fig. 3.

3.2. series compensated grid model

Generally the synchronous reference frame is utilized to model the induction generators.[18] The same model is considered for the grid. The series compensated system dynamic is described by the following equations in the synchronous reference frame.

$$\frac{d}{dt}\begin{bmatrix} v_{cq} \\ v_{cd} \\ i_q \\ i_d \end{bmatrix} = w_B \begin{bmatrix} 0 & -w_e X_c & 0 & \\ w_e & 0 & 0 & X_c \\ \frac{-1}{X_l} & 0 & -\frac{R_l}{X_l} & -w_e \\ 0 & \frac{-1}{X_l} & w_e & -\frac{R_l}{X_l} \end{bmatrix} \begin{bmatrix} v_{cq} \\ v_{cd} \\ i_q \\ i_d \end{bmatrix} + w_B \begin{bmatrix} 0 \\ 0 \\ \frac{v_{tq} - E_{Bq}}{X_l} \\ \frac{v_{td} - E_{Bd}}{X_l} \end{bmatrix} \tag{7}$$

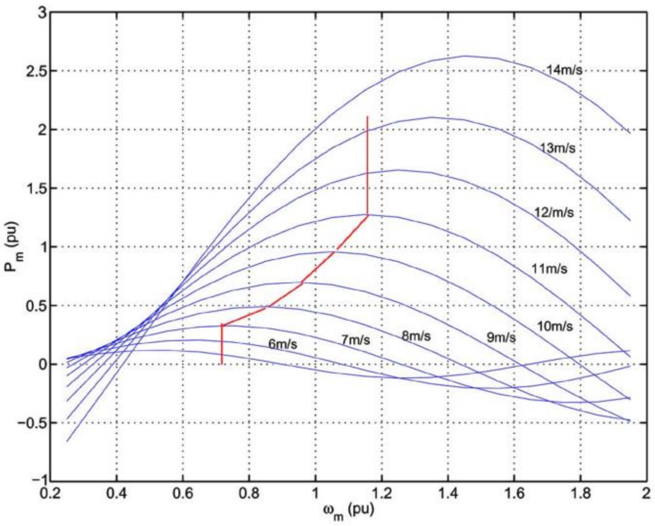

Fig. 3. The relationship among power, rotating speed and the wind speed

In which, V_{cq} and V_{cd} are the voltages of capacitors q and d axis, I_q and I_d are currents of q and d axis of the transmission line, V_{tq} and V_{td} are voltages of q and d axis of the terminal bus, and E_{bq} and E_{bd} are q and d axis of the infinite bus. w_b is the base angle speed (377 rad/s) and w_e is the synchronous reference frame speed (377 rad/s). The grid resonance in f_n is observed as a resonant mode with frequency of $f_s - f_n$. Space vector of the grid variables are defined by X_n .

$$X_n = [V_{cq}\ , V_{cd}\ , I_q\ , I_d\ ]^{\mathrm{T}} \tag{8}$$

3.3. Induction generator model

A 6 degree dynamic model with a rotor-side converter is used for DFIG, and its model has been described as follow equations:[19]

$$\dot{X}_g = AX_g + BU \tag{9}$$

where:

$$B = \begin{bmatrix} \frac{X_{ss}}{W_b} & 0 & 0 & \frac{X_M}{W_b} & 0 & 0 \\ 0 & \frac{X_{ss}}{W_b} & 0 & 0 & \frac{X_{ss}}{W_b} & 0 \\ 0 & 0 & \frac{X_{ls}}{W_b} & 0 & 0 & 0 \\ \frac{X_{ss}}{W_b} & 0 & 0 & \frac{X_{rr}^{'}}{W_b} & 0 & 0 \\ 0 & \frac{X_{ss}}{W_b} & 0 & 0 & \frac{X_{lr}^{'}}{W_b} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{X_{ss}}{W_b} \end{bmatrix}^{-1} \tag{10}$$

$$A = -B \begin{bmatrix} r_s & \frac{w_e}{w_b} X_{ss} & 0 & 0 & \frac{w_e}{w_b} X_M & 0 \\ -\frac{w_e}{w_b} X_{ss} & r_s & 0 & -\frac{w_e}{w_b} X_M & 0 & 0 \\ 0 & 0 & r_s & 0 & 0 & 0 \\ 0 & \frac{w_e - w_r}{w_b} X_M & 0 & r_r^{'} & \frac{w_e - w_r}{w_b} X_{rr}^{'} & 0 \\ -\frac{w_e - w_r}{w_b} X_M & 0 & 0 & \frac{w_e - w_r}{w_b} X_{rr}^{'} & r_r^{'} & 0 \\ 0 & 0 & 0 & 0 & 0 & r_r^{'} \end{bmatrix} \tag{11}$$

$$X_g = \left[i_{qs}, i_{ds}, i_{0s}, i_{qr}, i_{dr}, i_{0r}\right]^T \tag{12}$$

$$U = \left[v_{qs}, v_{ds}, v_{0s}, v_{qr}, v_{dr}, v_{0r}\right]^T \tag{13}$$

Statements A and B are in the appendix.

3.4. DC link model

In Fig. 4 V_r و V_g are Phase voltages of RSC and GSC side, which have:
V_r =0.707($V_{qr} - jV_{dr}$) and V_g = 0.707($V_{qg} - V_{dg}$)

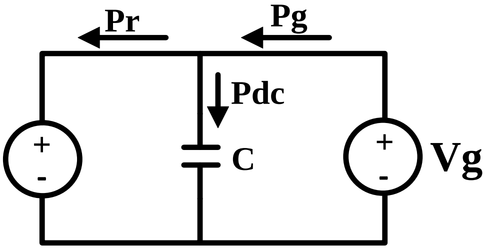

Fig.4. dc link

Capacitor dynamic between stator and rotor-side converter has been expressed by following equations:

$$Cvdc\frac{d_{vdc}}{dt} = P_r - P_g \tag{14}$$

$$P_r = \frac{1}{2}\left(v_{qr}i_{qr} + v_{dr}i_{dr}\right) \tag{15}$$

$$P_g = \frac{1}{2}\left(v_{qg}i_{qg} + v_{dg}i_{dg}\right) \tag{16}$$

Where $\mathrm{P_g}$ and $\mathrm{P_r}$ are active powers at RSC and GSC side.

3.5.Twisting dynamic model

Generally, a two-mass system is used to show twisting dynamic.[16]

$$\frac{d}{dt}\begin{bmatrix} \Delta w_t \\ \Delta w_r \\ T_g \end{bmatrix} = \begin{bmatrix} \frac{-D_t - D_{tg}}{2H_t} & \frac{D_{tg}}{2H_t} & \frac{-1}{2H_t} \\ \frac{D_{tg}}{2H_g} & \frac{-D_g - D_{tg}}{2H_g} & \frac{1}{2H_g} \\ K_{tg}w_e & -K_{tg}w_e & 0 \end{bmatrix}\begin{bmatrix} \Delta w_t \\ \Delta w_r \\ T_g \end{bmatrix} + \begin{bmatrix} \frac{T_m}{2H_t} \\ \frac{-T_e}{2H_g} \\ 0 \end{bmatrix} \tag{17}$$

Where w_t and w_r are turbine and rotor speed of generator. P_m and P_e are turbine mechanical power and generator electrical power, respectively. T_g is the Internal torque .H_t and H_g , are turbine and generator inertial constants, respectively. D_t and D_g are turbine and generator Mechanical damping coefficients respectively. D_{tg} is shaft attenuation coefficient between two mass and K_{tg} is shaft hardness. State variables related to twisting dynamic are shown with X_t

$$X_t = [\Delta w_t, \Delta \mathrm{w}_r, T_g]^T \tag{18}$$

The entire system model without considering converters' control is expressed by following relation:

$$X = f(X, U) \tag{19}$$

As X = [X_n^{T}, X_g^{T}, V_{dc}, X_t^{T}] is implemented in Matlab. Eigenvalues analysis and time domain simulation which is obtained from this model are discussed in the following.

3.6. DFIG converters controls

Both GSC and RSC controller are modeled in this Research. Control loops have been shown in Fig. 5 and 6.[20]

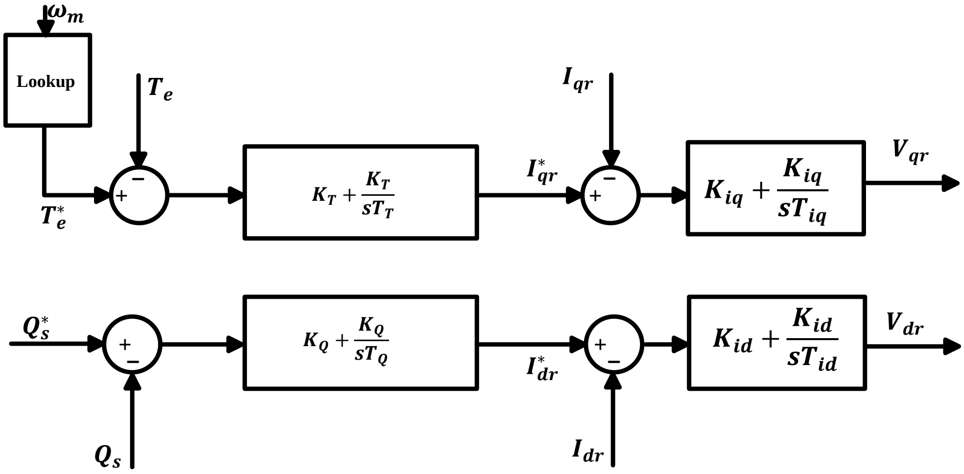

Fig.5. RSC control loops

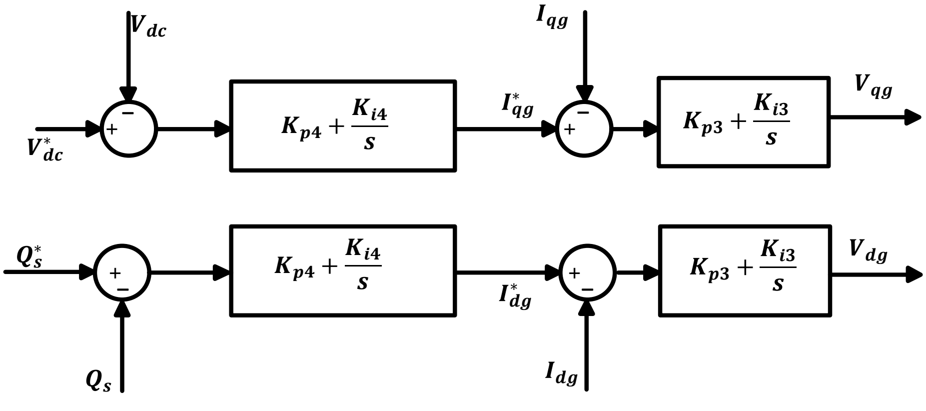

Fig.6. GSC control loops

4.SSR Phenomenon and its results

4.1.Compensation level influence on SSR

By changing system Compensation level at various rotor rotation speeds and using eigenvalues Analysis method, the following result is given.(network active resonance mode (f_o - f_n) has a Supplement frequency equal to f_n and the f_o is base frequency)

- network resonance frequency of f_n increases and fluctuations damping reduces by increasing compensation level.

The graph in Fig.7 shows the torque response in different compensation levels.

According to simulated graph of Fig.7, it is seen that damping reduces by increasing Compensation level. In the other words, the Supplements oscillation frequency decreases by increasing Compensation level. This frequency which appears in T_e and P_e is network supplement frequency (f_o – f_n). Figure 7 also confirms that increasing Compensation level increases SSR frequency and consequently reduces damping.

In a two-mass system with shaft, there are two swinging modes. One of them is total rotation of rotor against power system and the other one is twisting mode. Twisting effect appears when twisting mode frequency of f_TI becomes equal with network mode frequency supplement of f_s – f_n. In a situation when series compensation level of network is low, the amount of f_n is low too, but the amount of supplement frequency is high., supplement frequency decreases by increasing series compensation level and consequently f_n. Twisting effect becomes more tangible when twisting mode frequency is close to network supplement frequency ($f_s - f_n$).

4.2.Effect of rotor spin speed on SSR

Simulation results in the following show that damping improves by increasing rotation speed of the rotor and spin speed f_m decreases by decreasing rotation speed of the rotor, thus slip magnitude (absolute value) s1 decreases. So, s1 is related to speed rotation of the rotor and becomes negative by decreasing equivalent resistance slip of rotor and it worsens mode damping problem. Similarity, slip magnitude becomes bigger and consequently, equivalent resistance of the rotor becomes smaller by increasing spin speed of rotor, and this improves mode damping I.

- resonance mode damping of the network will increase by increasing spin speed of rotor, and consequently increasing output power.

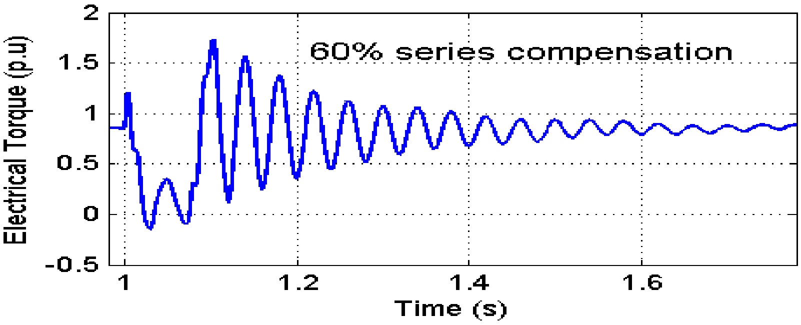

Fig.7(a). Electric torque response under 60% Compensation

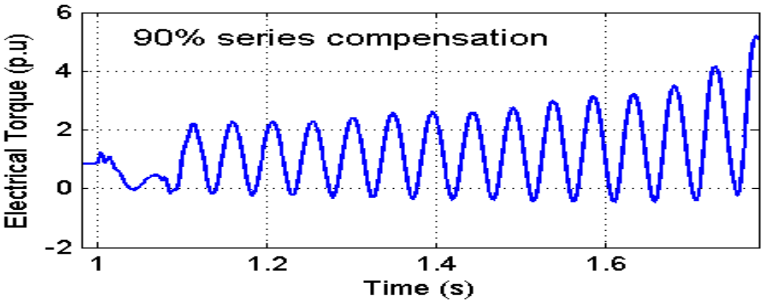

Fig.7(b). Electric torque response under 90% Compensation

$$R_{r,eq} = R_r \,/\, s_1 \qquad (20)$$

Rotor equivalent resistance as a function of rotor spin speed is shown with f_m in Fig. 8. According Fig.9 it can be seen that by increasing spin speed of rotor, damping improves, as mentioned before.

4.3.Effect of DFIG converter controls on SSR and TI

DFIG converter controls and its effect on SSR is investigated in this section. Rotor voltage injection which is done by current control loop in two-axle device has been shown in Fig. 5. In this research, only impact of parameters related to RSC control such as K_{id} and K_{iq} and also K_T and K_Q on SSR is investigated. Results of control Gate impact of K_{id} and K_{iq} on mode damping SSR is investigated by eigenvalues analysis method.

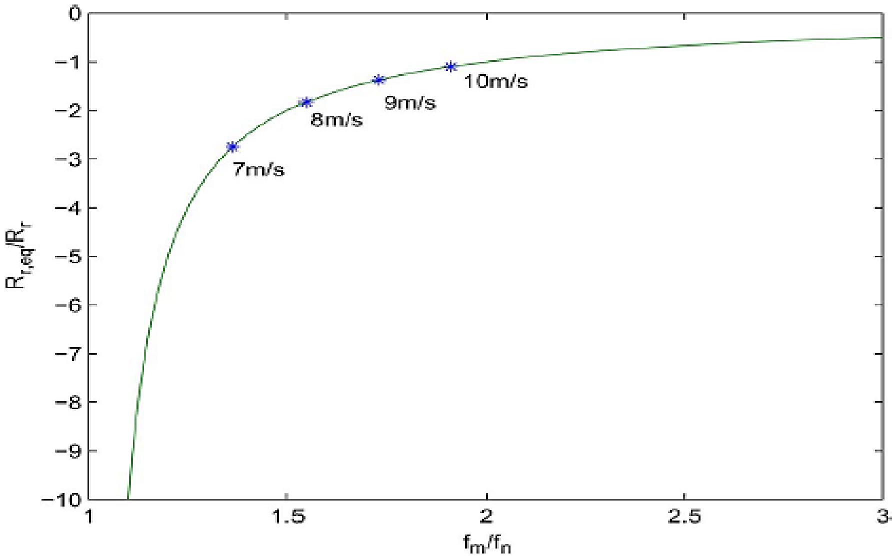

Fig.8. rotor equivalent resistance as a function of rotor spins speed under 45% Compensation

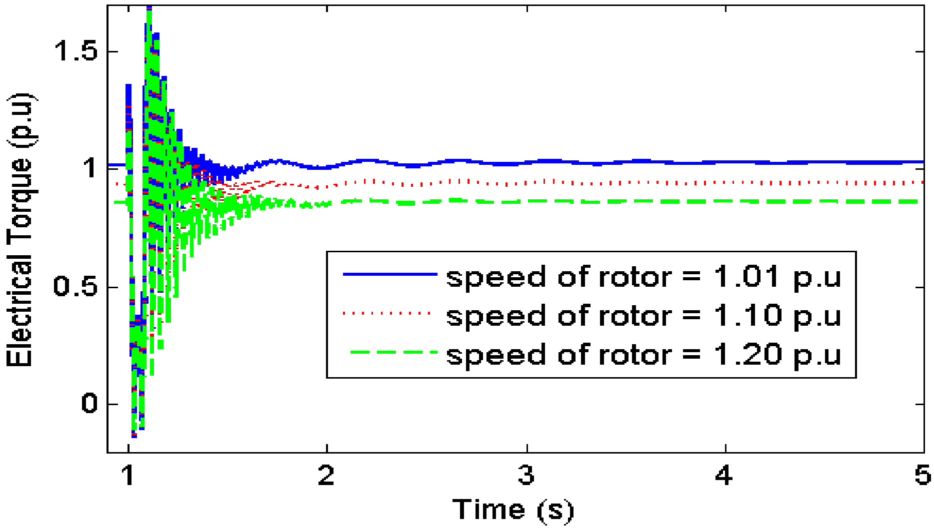

Fig.9. electrical torque response in various speeds of rotor twisting

According to the graph obtained from Fig.10, it is seen that gain increase has a destructive effect on damping which is discussed in the following. Effect of rotor voltage is equivalent to a resistor $R = -\Delta V_r/(s*\Delta I_r) = -(k/s_1)$ in the rotor circuit. A positive resistance value in rotor circuit can improve the stability of the system. Since S_1 is negative in SSR situation, k factor should be positive. Although in current control system, DFIG is a controller loop with negative feedback.

As in Fig. 5, circuit control rings have destructive effects on damping. In the following, the effect of gain K_{Te} and K_{Qs} on SSR and TI has been investigated and simulation results have been presented in Fig. 11.

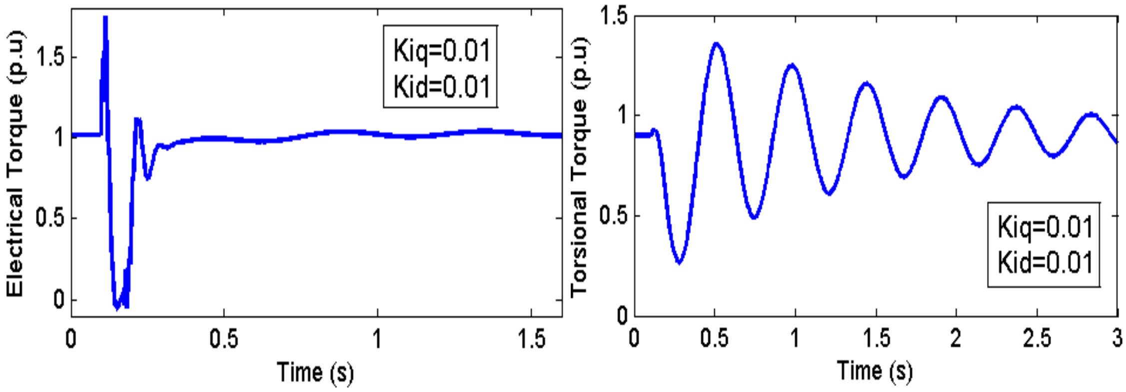

Fig.10(a). Twisting torque and electric torque response in K_{id} = 0.01and K_{iq} = 0.01

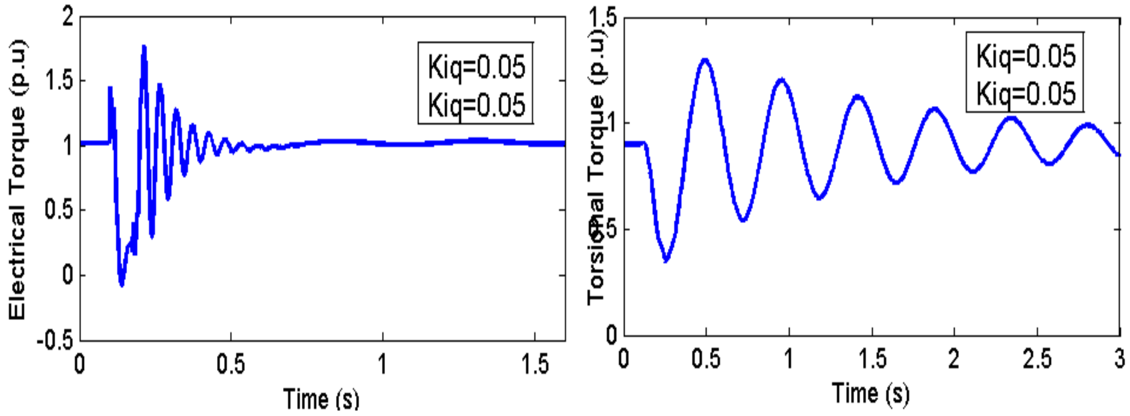

Fig.10(b). Twisting torque and electric torque response in K_{id} = 0.05 and K_{iq} = 0.05

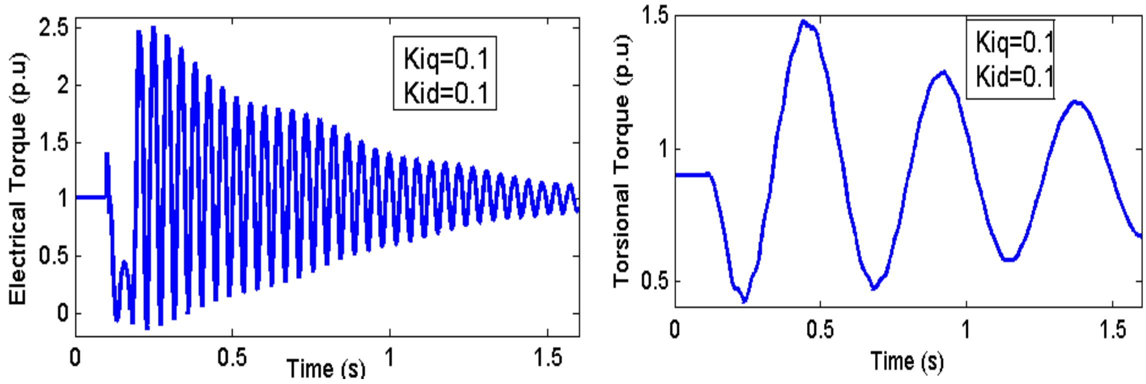

Fig.10(c). Twisting torque and electric torque response in K_{id} = 0. 1and K_{iq} = 0. 1

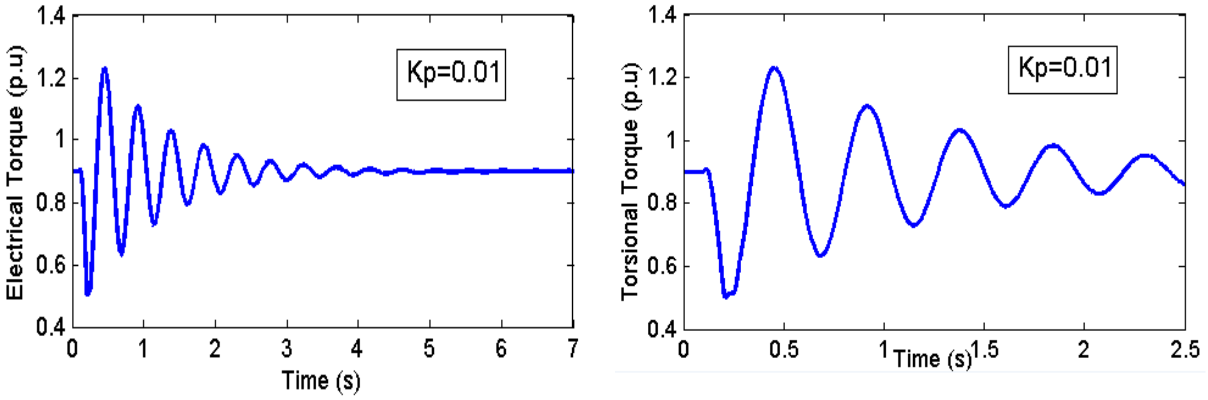

Fig.11(a). Twisting torque and electric torque response in K_{Te} and K_{Qs}= 0.01

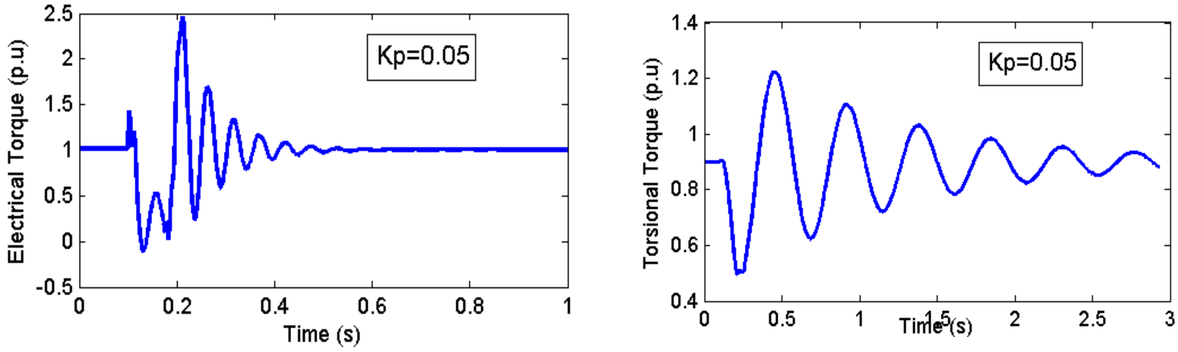

Fig.11(b). Twisting torque and electric torque response in K_{Te} and K_{Qs}= 0.05

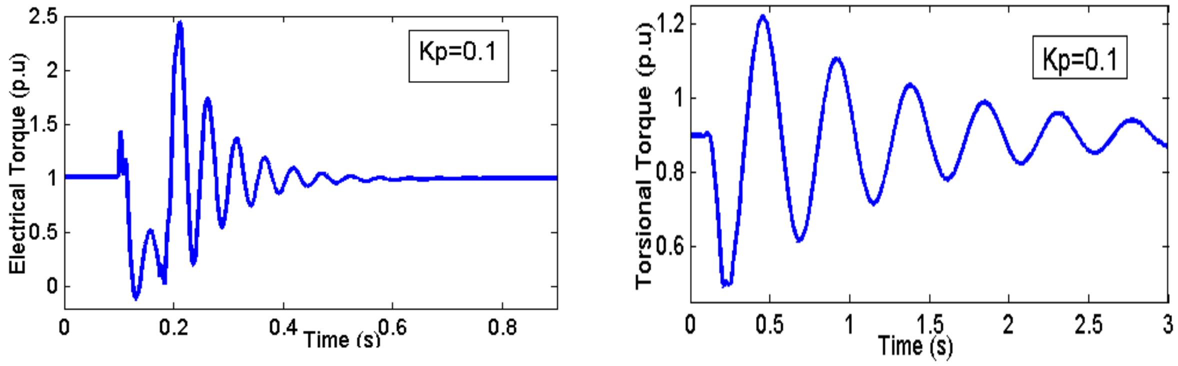

Fig.11(c). Twisting torque and electric torque response in K_{Te} و K_{Qs} = 0.1

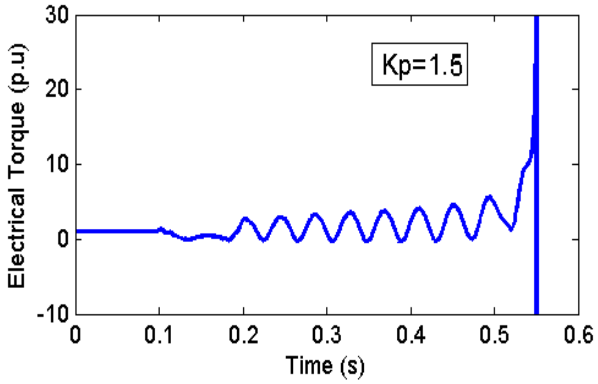

Fig.11(d). Twisting torque and electric torque response in K_{Te} و K_{Qs} = 1.5

According to Fig. 10 and Fig. 11, it can be seen that PI controller's gains, must not exceed a certain limit in order to reach system stability.

5.Conclusion

In this research, SSR phenomenon for a DFIG system with Series Compensation is analyzed. The effect of three phenomena such as 1) Series Compensation level, 2) Speed rotation of the rotor, and 3) Controller internal parameters of RSC are investigated on DFIG phenomena. We found that network resonance frequency will increase but fluctuations damping will decrease by increasing compensation level. damping mode of the network resonance will increase by increasing the speed of the rotor rotation. Moreover, increasing gain has a destructive effect on damping of RSC controller. PI controller's gain must not exceed a certain margt to stabilize the system

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