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SENSITIVITY ANALYSIS OF NONLINEAR DYNAMIC BEHAVIOR OF SELF EXITED INDUCTION GENERATOR (SEIG) IN WIND TURBINE

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Abstract- Today, in many countries wind power generation is expanding, and satisfying a steadily increasing proportion of national power demand. The necessity of using wind generators to produce energy and environmental issues, lead to increasing the importance of study between researchers in this field. In this paper, dynamic behavior of a wind power system implemented with Self-Excited Induction Generator (SEIG) is analytically investigated by using a proper nonlinear model. Nonlinear dynamical state equations of whole system are derived by aggregating the individual nonlinear models of system components. Sensitivity analysis is also performed by changing of some important system parameters. This is done by finding all system equilibrium points, determining the eigenvalues of system and investigating of system stable trajectories. By using obtained results, one can measure SEIG state trajectory sensitivity to certain parameters which can be useful in designing and operation of wind turbines for a prototype system. Differential equations of proposed analytical model have been solved using Rang-Kutta order-four method.

Keywords: Nonlinear Dynamic Modeling, Sensitivity Analysis, Wind Generator, Self-Excited Induction Generator.

I. INTRODUCTION

Nowadays, environmental pollution, shortage in fossil resources and increasing energy cost, are some important challenges, that are caused remarkable efforts have been made to expand the renewable energy resources such as wind energy [1]. With respect to the increasing rise of the importance of renewable energies, particularly wind energy, induction machines in generator state are given more attention. Therefore, conducting researches and presenting new achievements and findings in this domain is even more needed [2].

Wind turbines are one of renewable energy technologies which are rapidly developing today due to the economic and environmental issues [3-5]. Consequently, dealing with them is of great importance. The technology of wind turbines includes constant and variable speed wind turbines [4]. Due to being economic, resistant and having easier installation, most wind turbines that are installed today are chosen among constant speed ones [4-5].

Squirrel cage induction machines (SCIM) are being frequently used in industry due to having low price and easy maintenance. These advantages make this machine a proper choice to be used in constant speed wind systems [2, 4]. Since the requirement of induction generators to reactive power is varied by load changes and wind speed therefore using of variable and switchable capacitor banks can be one of the methods to generate reactive power for induction generators and to keep voltage stability [6].

One of the most important variable speed wind power technology uses doubly-fed induction generator (DFIG). Reference [7] deals with the modeling of doubly fed induction generator (DFIG) cooperating with wind turbine and wind turbine and DFIG models are presented step by step. The other type of induction machine is series connected wound rotor induction machine. In [1], dynamic behavior of a wind turbine implemented with series connected induction generator (SCIG) is studied.

In all mentioned type of induction generator, the most important characteristic is the self-excitation effect. The self-excitation effect of the induction generator has been studied in several literatures [8-27]. An exhaustive survey of the literature over the past 25 years discussing the process of self-excitation and voltage buildup, modeling, steady-state, and transient analysis, reactive power control methods, and parallel operation of SEIG are addressed in [10]. Different models have been proposed based on d-q reference model [13-18]. These models are derived on the basis of developed model of impedance, admittance-based models, models based on the equations of operational circuits and power.

By attention to the importance of steady-state behavior in design and operation of these systems, a lot of literatures exist in this era [19-26]. In [27, 28] self-excited induction generator is studied by state space model. The analysis of dynamic behavior and performance of wind generators requires proper models. The reason for that is the fluctuating nature of the input wind power to their turbines and the transient behavior resulted from it. The dynamic behavior of self-excited induction machine can be explained by differential equations.

Due to the dependence on time and speed variations of the rotor, these differential equations are so complicated. In order to decrease the calculations and to solve differential equations, variables can be transferred to the desirable reference frame which rotates at optional angular speed [2, 29]. In the present paper, the nonlinear dynamic behavior of the self-excited induction machine is studied by using a simple model. The system's modeling has been done analytically using the differential equations dominant on its behavior. The aforementioned equations have been solved using Rang-Kutta order-four method.

In section II, a suitable dynamic model is introduced for a grid connected wind power system implemented with a self-excited induction generator. Simulation results are shown in section III. The modal analysis and results of sensitivity study are presented in section IV. Finally, concluding remarks are drawn in section V.

II. DYNAMIC MODELING OF GRID CONNECTED WIND TURBINE IMPLEMENTED WITH SELF-EXCITED INDUCTION GENERATOR

To study the dynamic behavior of the system, a grid connected wind power system implemented with self-excited induction generator (WT-SEIG), as shown in Figure 1, is selected as study system [29]. This system includes two buses, local bus and grid bus. WT-SEIG is connected to local bus and this bus is connected to grid bus (infinite bus) via a short transmission line. Infinite bus voltage and frequency is constant and does not change any of them were affected by the generator. This means that the grid voltage can be considered as the reference.

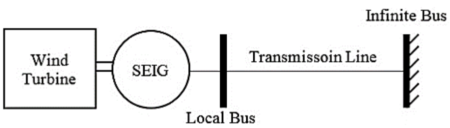

Figure 1. Self-excited wind generator connected to the infinite bus

A. Dynamic Model of Self-Excited Induction Generator

In general, the differential equations of the induction generator can be written as below [29]:

$$V_{ds} = R_s\, i_{ds} + \omega\lambda_{qs} + p\lambda_{ds} \tag{1}$$

$$V_{qs} = R_s\, i_{qs} - \omega\lambda_{ds} + p\lambda_{qs} \tag{2}$$

$$V_{dr} = R_r\, i_{dr} + (\omega - \omega_r)\lambda_{qr} + p\lambda_{dr} \tag{3}$$

$$V_{qr} = R_r\, i_{qr} - (\omega - \omega_r)\lambda_{dr} + p\lambda_{qr} \tag{4}$$

where, R_S, R_r, ω, and p are stator and rotor resistances, angular frequency and derivative operator (d/dt) respectively. All rotor variables are referred to stator winding reference frame. Linkage fluxes in the above equations are given as follow [29]:

$$\begin{cases} \lambda_{ds} = L_{1s} i_{ds} + L_m (i_{ds} + i_{dr}) \\ \lambda_{qs} = L_{1s} i_{qs} + L_m (i_{qs} + i_{qr}) \\ \lambda_{dr} = L_{1r} i_{dr} + L_m (i_{ds} + i_{dr}) \\ \lambda_{qr} = L_{1s} i_{qr} + L_m (i_{qs} + i_{qr}) \end{cases} \tag{5}$$

The torque equation of the generator is given by:

$$T_L - T_e = J\frac{d\omega_r}{dt} + B\omega_r \tag{6}$$

In general, with respect to Equation (6), the differential equations of the self-excited induction generator can be written as [29]:

$$p[i] = [L]^{-1}\left([V] - [R][i] - [G][i]\right) \tag{7}$$

$$V = \begin{bmatrix} V_{dt} & V_{qt} & 0 & 0 \end{bmatrix}^T \tag{8}$$

$$i = \begin{bmatrix} i_{ds} & i_{qs} & i_{dr} & i_{qr} \end{bmatrix}^T \tag{9}$$

$$L^{-1} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \tag{10}$$

$$G = \begin{bmatrix} 0 & \omega L_s & 0 & \omega L_m \\ -\omega L_s & 0 & -\omega L_m & 0 \\ 0 & (\omega - \omega_r) L_m & 0 & (\omega - \omega_r) L_r \\ -(\omega - \omega_r) L_m & 0 & -(\omega - \omega_r) L_m & 0 \end{bmatrix} \tag{11}$$

B. The Dynamic Model of Wind Turbine

Wind Turbine (WT) is described by its power-speed characteristic. Wind turbines restrain the kinetic energy of the wind and convert it to electric energy [30-31]. The generatable power of a wind turbine corresponds to the relating formulas coordinate to the circle area resulted from the rotation of rotor blades. Hence, with respect to the wind condition of each area and the turbine's nominal power, the rotor blades are manufactured in various sizes. Its output power can be obtained by [4, 29-31]:

$$P_m = \frac{1}{2} C_P(\lambda, \beta)\rho A V_W{}^3 \tag{12}$$

where, $C_P(\lambda,\beta)$ is called the power coefficient, which by definition refers to the percentage of wind energy that is turned into mechanical energy. $C_P(\lambda,\beta)$ is a function of the tip speed ratio (λ) and the blade pitch angle (β) for pitch regulated wind turbines that is given by [29]:

$$C_P(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \tag{13}$$

$$\lambda_i = \frac{1}{\dfrac{1}{\lambda + 0.08\beta} - \dfrac{0.035}{\beta^3 + 1}} \tag{14}$$

where, ρ (kg/m^3) is the air density, A (m^2) is the rotor disk radius, V_W (m/s) is the wind speed.

C. The Dynamic Model of the Transmission Line

The under-study transmission line has the impedance of $Z_T = R_T + jX_T$ and it injects the i_T current to infinite bus. The transmission line equations, in synchronous reference frame can be written as below [29]:

$$\begin{cases} V_{dt} = V_d^{\inf} + R_T i_{dt} + w_s L_t i_{qt} + L_T P i_{dt} \\ V_{qt} = V_q^{\inf} + R_T i_{qt} - w_s L_t i_{dt} + L_T P i_{qt} \end{cases} \tag{15}$$

where, transmission line current depends on self-excited induction generator current is as:

$$i_T = -i_s \tag{16}$$

By placing Equation (16) in Equation (15), the infinite bus voltages can be used to explain the generator's bus voltages [29]:

$$p\left[i^{sys}\right]=\left[L^{sys}\right]^{-1}\left(\left[V^{sys}\right]-\left[R^{sys}\right]\left[i^{sys}\right]-\left[G^{sys}\right]\left[i^{sys}\right]\right) \quad (17)$$

$$V^{sys}=\left[V_d^{\inf} \quad V_q^{\inf} \quad 0 \quad 0\right]^T \quad (18)$$

The system's currents are:

$$i^{sys}=\left[i_{ds} \quad i_{qs} \quad i_{dr} \quad i_{qr}\right]^T \quad (19)$$

Also, the other parameters of Equation (17) such as L^{sys} and G^{sys} are equal to:

$$L^{-1}=\begin{bmatrix} L_s+L_t & 0 & L_m & 0 \\ 0 & L_s+L_t & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \quad (20)$$

$$G=\begin{bmatrix} 0 & \omega(L_s+L_t) & 0 & \omega L_m \\ -\omega(L_s+L_t) & 0 & -\omega L_m & 0 \\ 0 & (\omega-\omega_r)L_m & 0 & (\omega-\omega_r)L_r \\ -(\omega-\omega_r)L_m & 0 & -(\omega-\omega_r)L_r & 0 \end{bmatrix} \quad (21)$$

The result obtained from this formulation is the dynamic structure, this structure can be described by differential equations with variables i_{ds}, i_{qs}, i_{qr}, i_{dr}, and ω_r. These equations can be solved using Rang-Kutta order four method.

III. SIMULATION RESULTS

Several simulations are performed on the study system (Figure 1). The parameters of study system components are given in appendix. The initial conditions of the state variables are needed for the numerical solution of the system's differential equations. The initial values of these variables determine the transient state at the beginning of the solution. In order to make the results more authentic, the primary operating speed of the machine was adjusted equal to the synchronous speed and its primary currents were set to zero.

Figure 2, indicates the induction generator speed with primary operating speed is adjusted at synchronous speed. According to the figure, after a little drop in primary speed, the generator speed rises gradually and transcends the synchronous speed.

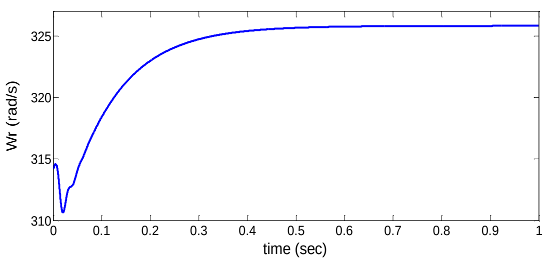

Figure 2. The speed-time characteristic curve

Figure 3, shows the torque-time characteristic curve. The value of this torque, after the primary transient state, reaches 10 N.m at about 0.1 seconds. According to the figure, the self-excited induction generator has a high transient torque variation and low settling time.

Figure 4, shows the torque-slip characteristic curve for SEIG connected to the grid. Figure 5 show the currents of the SEIG which reach their constant value after a primary transient state.

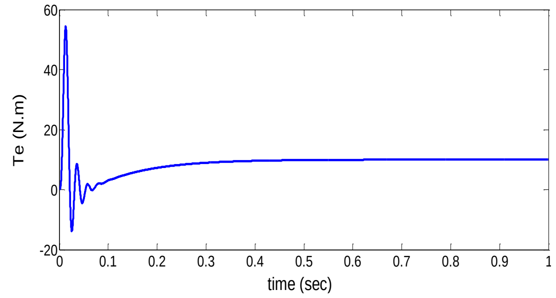

Figure 3. The torque-time characteristic curve

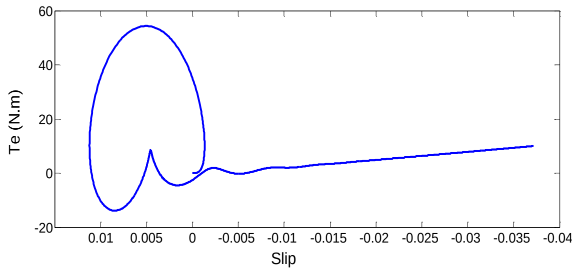

Figure 4. The torque-slip characteristic curve

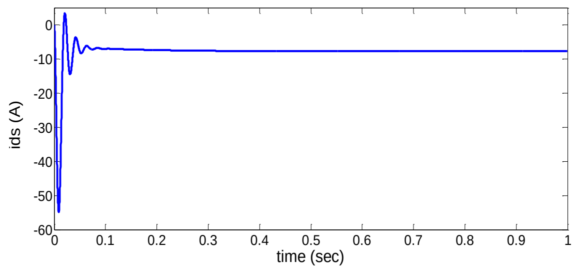

Figure 5. Stator d-axis current of the SEIG

A. Variation in Primary Operating Speed

In this section, the transient behavior of the SEIG connected to the grid is studied by exerting variation in primary operating speed and the results are compared. The primary operating speeds that are considered for this purpose, are 5% higher and 5% lower than synchronous speed. Figure 9 compares the speed-time characteristic curve at different primary operating speeds. As could be observed from the figure, as the primary operating speed increases, the speed-time diagram reaches to the steady state more quickly.

Figure 10 shows the torque-time characteristic curve. As the primary speed increases, the torque transient state increases. Also Figure 10 shows, that SEIG has a unique high transient torque at first swing for all different primary operating speeds. Figures 11 to 14 shows variation of SEIG currents with respect to variation of primary operating speed. As could be observed, the primary speed increases the value of the currents transient state as well. Of course the impact of these changes in d-axis currents is minimum in other words, the primary operating speed has low effect on d-axis SEIG currents.

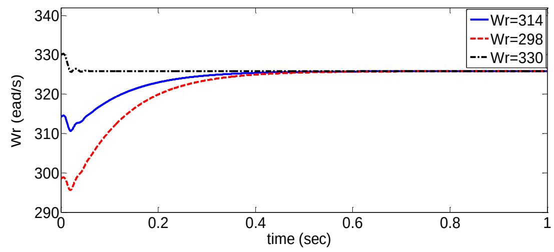

Figure 9. The speed-time characteristic curve at different primary operating speeds

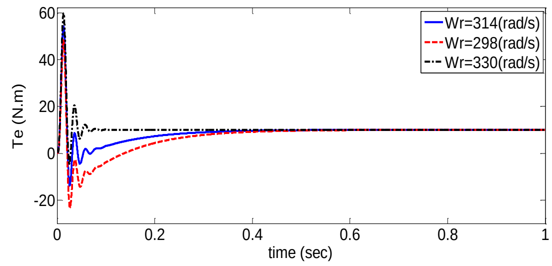

Figure 10. The torque-time characteristic curve at different primary operating speeds

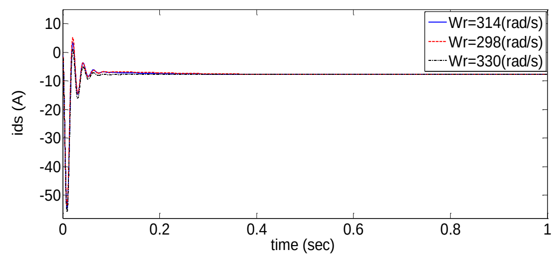

Figure 11. Stator d-axis current of the SEIG at different primary operating speed

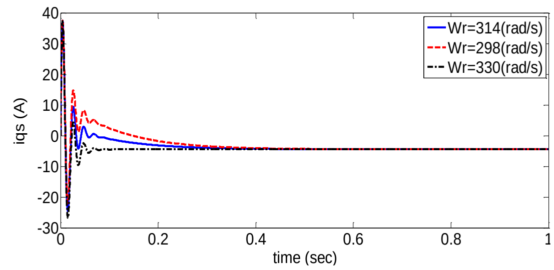

Figure 12. Stator q-axis current of the SEIG at different primary operating speed

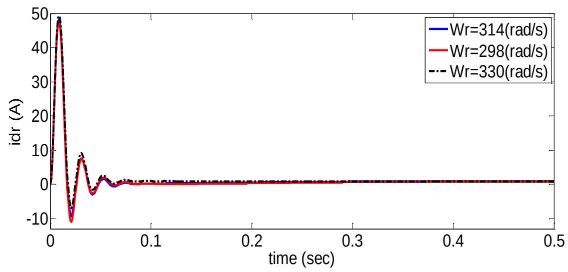

Figure 13. Rotor d-axis current of the SEIG at different primary operating speed

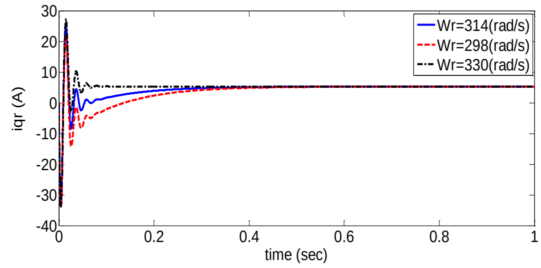

Figure 14. Rotor q-axis current of the SEIG at different primary operating speed

B. Variation in *X*/*R* Ratio of Transmission Line

The transmission line is one of the most important parts of the power system [32]. The short transmission line model includes a resistance and a reactance. In this section, as the line inductance experiences a sudden increase and the line resistance is kept constant, its impact on different system variables is studied.

Figure 15 shows speed-time characteristic curve with variation in *X*/*R* ratio of the transmission line. As this ratio increases, the generator speed increases as well. Figure 16 shows torque variations when *X*/*R* ratio is changed. According to this figure electrical torque of SEIG becomes constant after a rather high fluctuation. Yet, variation in *X*/*R* ratio of the line has no impact on the value of electrical torque at steady state.

Figures 17 and 18 show the q-axis current of SEIG when *X*/*R* ratio changes from its initial value. Initial value of *X*/*R* ratio is assumed 10 and variation is applied at t = 0.8 sec. According to the Figure 17, when the *X*/*R* ratio of the line increases, the stator q-axis current obtains its initial value after passing the transient state. But, by increasing *X*/*R* ratio the rotor q-axis current value at steady state is increased (Figure 18). Figures 19 and 20 show the d-axis current variations with variation in *X*/*R* ratio of the transmission line.

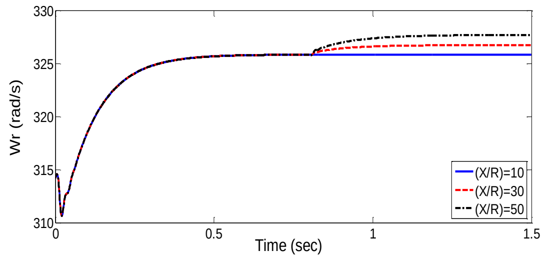

Figure 15. The speed-time characteristic curve at different *X*/*R* ratio (variation is applied at t = 0.8 sec)

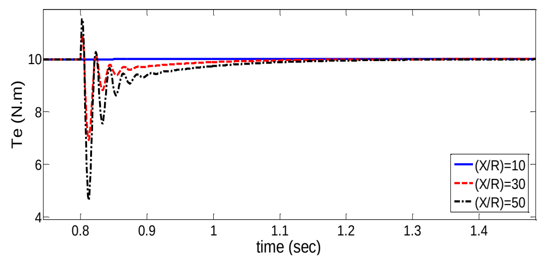

Figure 16. The torque-time characteristic curve at different *X*/*R* ratio (variation is applied at t = 0.8 sec)

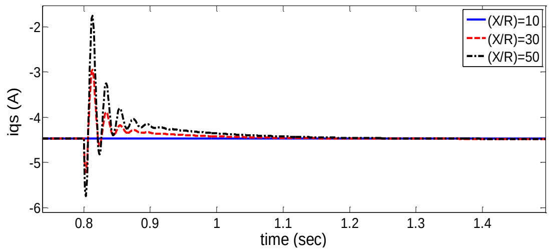

Figure 17. Stator q-axis current of the SEIG at different X/R ratio (variation is applied at t = 0.8 sec)

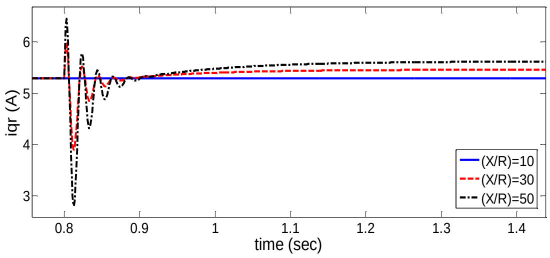

Figure 18. Rotor q-axis current of the SEIG at different X/R ratio (variation is applied at t = 0.8 sec)

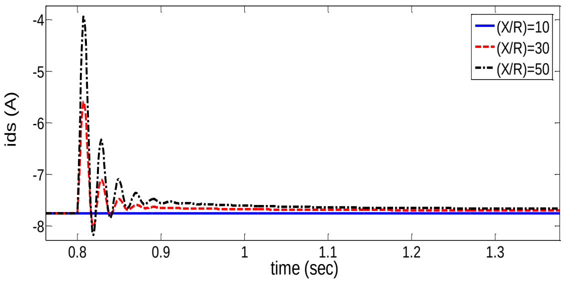

Figure 19. Stator d-axis current of the SEIG at different X/R ratio (variation is applied at t = 0.8 sec)

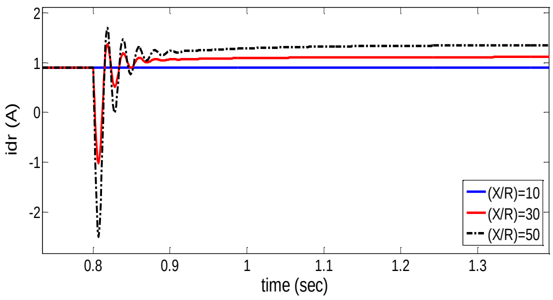

Figure 20. Rotor d-axis current of the SEIG at different X/R ratio (variation is applied at t = 0.8 sec)

IV. MODAL AND SENSITIVITY ANALYSIS

A power system can be described by a set of nonlinear differential equations that its general form is given by:

$$\frac{dX}{dt} = f(X,U,P) \quad (22)$$

where, X, U, and P are state vector, control vector and parameter vector respectively. This nonlinear DA has some equilibrium points, (X_0, P_0, U_0), which can be obtained by solving the following equations:

$$0 = f(X_0, P_0, U_0) \quad (23)$$

Linear system representation around equilibrium point is:

$$\frac{dX}{dt} = AX + BU \quad (24)$$

Stability of an equilibrium point for a certain value of P depends on the eigenvalues of system matrix A [33-35]. Table 1 shows eigenvalues of the system.

Table 1. Eigenvalues of the system

λ_1	-69.09 + 292i
λ_2	-69.09 - 292i
λ_3	-7.422
λ_4	-108.02 + 1.05i
λ_5	-108.02 - 1.05i

A. Sensitivity of System Stability to Changing of SEIG Windings Resistances

The loci of eigenvalues are shown in Figures 21 and 22, when the resistances of SEIG windings are changed.

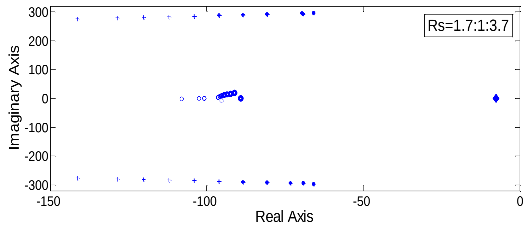

Figure 21. Effect of stator winding resistance on eigenvalues loci

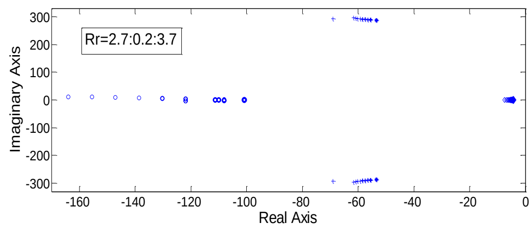

Figure 22. Effect of rotor winding resistance on eigenvalues loci

B. The Sensitivity of System Stability with Respect to X/R Ratio

For studying the effect of X/R ratio on system trajectory, the reactance of transmission line is changed and its resistance is kept constant. The eigenvalues locus for this case is shown in Figure 23. As the results shown the system stability is kept when this ratio is changed.

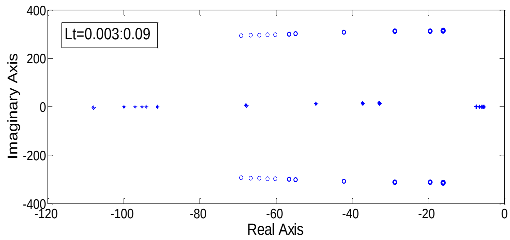

Figure 23. Effect of X/R ratio (or transmission line inductance) on eigenvalues loci

C. The Sensitivity of System Stability with Respect to SEIG Inductances Variation

Influence of the rotor and stator inductances on eigenvalues loci are shown in Figure 24 and Figure 25, respectively. By increasing the generator reactance, the poles are moving toward the origin of coordinates. In the case of rotor reactance changing, some of the poles transfer to the right hand side and system instability occurs (saddle node bifurcation).

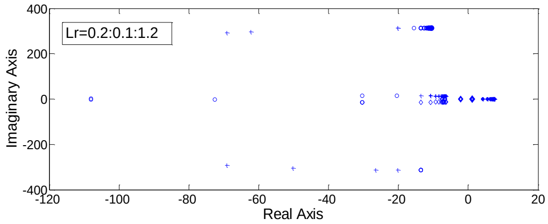

Figure 24. Effect of rotor winding inductance on eigenvalues loci

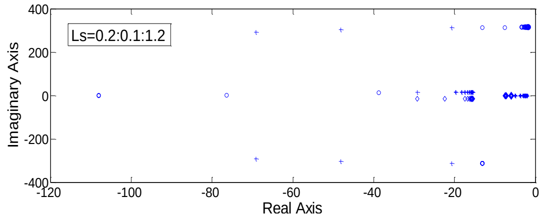

Figure 25. Effect of stator winding inductance on eigenvalues loci

V. CONCLUSIONS

In this paper, dynamic behavior of a wind turbine implemented with self-excited induction generator is investigated. WT-SEIG is modeled by a set of nonlinear differential equations. In this regards, a simple study system is selected that is a sample grid connected WT-SEIG. The system's modeling has been done analytically using the differential equations based on analyzing its behavior. The aforementioned equations have been solved using Rang-Kutta order-four method.

According to the results of simulation, changes in the initial conditions, does not affect the steady state behavior of SEIG. By operating of prime over close to the synchronous speed (steady-state speed), the electrical torque and currents quickly reach stable values and the transient period reduces. When transmission line X/R ratio increases, electrical torque of SEIG becomes constant after a rather high fluctuation, stator q-axis current obtains its initial value after passing the transient state and rotor q-axis current value at steady state increases.

But, it has no impact on the value of electrical torque at steady state. By using linearization of system differential equation around an equilibrium point and calculation of system eigenvalues, we can talk about the system stability. By using the proposed model, sensitivity analysis is also performed and the parameters affected system instability are determined. In this context, the influence of various parameters such as resistance and inductance of the stator and rotor, X/R ratio of the transmission line and the results are presented analytically.

One of the interesting results of this study is occurrence of saddle node bifurcation in the case of rotor reactance changing, that of the poles transfer to the right hand side and one of them cross the origin.

APPENDIX

The self-excited induction machine parameters are [29]:
- Machine's nominal power: 3 hp
- Frequency: 50 Hz
- Nominal values: 415 V, 3.6 kW, 7.8 A
- SEIG winding parameters:

$L_{1S} = L_{1r} = 11.4$ mH, $R_S = 1.7\ \Omega$, $R_r = 2.7\ \Omega$
- Applied parameters for short transmission line:

$R_t = 0.1\ \Omega$, $X_t = 1\ \Omega$

NOMENCLATURES

R_r , R_s : Rotor and stator resistances, respectively

I_{qs} , I_{qr} : Stator and rotor transferred currents to q-axis

I_{ds} , I_{dr} : Stator and rotor transferred currents to d-axis

V_d , V_q : Transferred voltages to q-axis and d-axis

V_d^{inf} , V_q^{inf} : Infinite bus voltages transferred to dq-axes

L_s , L_r : Stator and rotor inductances, respectively

L_m : Magnetizing inductance

P : Number of the poles

p : Derivative operator

ω_r : Rotor mechanical speed

ω_s : Angular frequency of reference voltage

T_L : Mechanical torque of load, N_m

T_e : Electromagnetic developed torque, N_m

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