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A Comparison between a Conventional Power System Stabilizer (PSS) and Novel PSS Based on Feedback Linearization Technique

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ABSTRACT

Relying on input-output linearization technique, a power system stabilizer (PSS) was modeled using nonlinear control method in this study. Similarly, two different synchronous generator models, a 3rd order model excluding dampers and a 6th order model including three damper windings, were employed to model the PSS. Results of the developed models on the single machine infinite bus power system upon occurrence of three phase fault in the transmission line were analyzed using MATLAB software. For the first stage, results of the simulation process demonstrated better and faster performance of the nonlinear technique based PSS which is relied on the input-output linearization method. Likewise, these results suggested superior performance of the modeled power system stabilizer based on the synchronous generator 6th order model to the 3rd order model.

KEY WORDS: feedback linearization , power system stabilizer , synchronous generator model

1. INTRODUCTION

Ascertaining the exact model of the generator before any type of modeling is highly necessary because of heavy dependency of the PSS performance on the model of the generator [1, 2].

Because of the significant role of the generator model in power systems studies, initially it has been attempted to use of the synchronous generator model in association with its dampers, i.e. a model which covers effects of the transient state during modeling of the synchronous generator [3]. Then, the input-output linearization control method, as a modeling method to the nonlinear control area, given the nonlinear behavior of the power system and particularly the synchronous generator was used to model the PSS. Subsequently, using input-output linearization technique in a single-machine infinite-bus power system the PSS was modeled in association with the generator 3rd order model, i.e. excluding dampers which it indicates transient state of the generator and then simulation results were obtained. Afterwards, the same stages were repeated considering dampers, i.e. inclusion of the transient state of the generator which is the 6th order model of the generator, and results of the simulation were compared with the precedent mode. Subsequently, results of two previous stages were compared with the results obtained from the conventional PSS.

2. Synchronous generator model

Generally, synchronous generator behaves very complicatedly, so, achieving a very detailed model is actually impossible for such generators; however, modeling of the synchronous generator is very essential for analysis of the power system. Hence, researchers have sought for various models of the synchronous generator all the time in order to use of it to either analyze or model power systems. 8th order model is a fairly complete and detailed model of the synchronous generator which has been generalized to analyze its behavior. It includes six electrical nonlinear dynamic equations and two mechanical nonlinear dynamic equations. The order of this model for salient pole synchronous generator is 7 which has a lesser damper winding at q axis to the round pole synchronous generator 8th order model [1,2,3]. Although, it is a complete and detailed model, it is hardly used for power system related modeling procedures because of its increased state variables as well as voluminous measurements, hence designers prefer to use of more low-order models for modeling purposes[4] . Two models of the round pole synchronous generators called 3rd order model and 6th order model are introduced through the next sections of this paper.

1.2. Synchronous Generator 3rd order Model

Considering the three state variables $\boldsymbol{E'_q}$, $\boldsymbol{\omega_r}$, δ, effect of the damper windings was ignored during the designing of this model. Likewise, transient EMF of d-axis $\boldsymbol{E'_d}$, has been supposed constant. If $\boldsymbol{E'_d}$ is constant in this model, then damping induced by eddy currents of the rotor body has been ignored, as well. If there is not any winding parallel to the perpendicular axis, which models the effect of rotor body, then we have $\boldsymbol{X'_q} = \boldsymbol{X_q}$, $\boldsymbol{E'_d} = 0$ [1,2].

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The predominant equations of the round-pole synchronous generator 3rd order model are summarized as follows [1]:

$$\dot{\delta} = \omega_b \omega_r \qquad (1)$$

$$\dot{\omega}_r = \frac{1}{2H}(T_m - T_e - K_D \omega_r) \qquad (2)$$

$$\dot{E}'_q = \frac{1}{T'_{d0}}[-E'_q - (X_d - X'_d)\, I_d + E_{fd}] \qquad (3)$$

1.2. Synchronous Generator 6th order Model

In this model, for the round pole synchronous generator including 6 state variables δ ،ω_r, E'_q, E'_d, E''_q and E''_d, a generator with series subtransient EMF, E''_d and E''_q, and subtransient reactance, X''_d and X''_q, which their names are modeled considering damper windings of *q* and *d* axes [1,2]. The sole difference between this model and the complete one (8th order model) is that in this model $\omega_r = \omega_s$, and also electromotive forces of the transformer are underestimated for voltage equations of armature.
The predominant equations of the round-pole synchronous generator 6th order model are summarized as follows [2]:

$$\dot{\delta} = \omega_b \omega_r \qquad (4)$$

$$\dot{\omega}_r = \frac{1}{2H}(T_m - T_e - K_D \omega_r) \qquad (5)$$

$$\dot{E}'_q = \frac{1}{T'_{d0}}[-E'_q - (X_d - X'_d)\, I_d + E_{fd}] \qquad (6)$$

$$\dot{E}'_d = \frac{1}{T'_{q0}}[-E'_d + (X_q - X'_q)\, I_q] \qquad (7)$$

$$\dot{E}''_q = \frac{1}{T''_{d0}}[-E''_q - (X'_d - X''_d)\, I_d + E'_q] \qquad (8)$$

$$\dot{E}''_d = \frac{1}{T''_{q0}}[-E''_d - (X'_q - X''_q)\, I_q + E'_d] \qquad (9)$$

3. Conventional Power System Stabilizer (CPSS)

The architecture of the conventional power system stabilizer (CPSS) is shown in the fig. 1 [2]. Block diagram of the CPSS has 3 blocks:

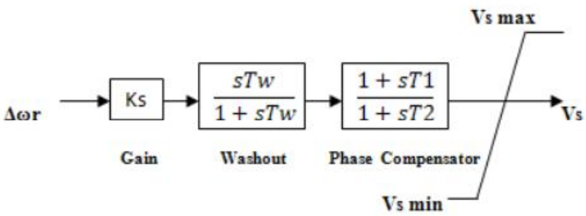


Fig 1: Block diagram of the conventional power system stabilizer (CPSS)

a) Phase compensation block which provides proper phase lead property in order to compensate the phase lag between the exciter input and electric torque of the generator.
b) The washout block which acts as a high pass filter with time constant, $T_{W,}$ which is enough to perform the task.
c) Gain block which ascertains the generated damping induced by the PSS.

CPSS has the following conversion function [2]:

$$\frac{V_s(s)}{\Delta\omega_r(s)} = K_s \frac{sT_W}{1+sT_W} \frac{1+sT_1}{1+sT_2} \qquad (10)$$

Fig.2 shows the structure of the single machine infinite bus power system including PSS [4].

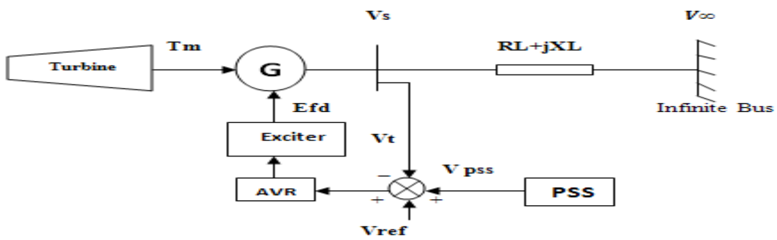


Fig 2: Single machine infinite bus power system with PSS configuration

The mentioned power system contains synchronous generator, exciter and transmission line connected to the infinite bus. PSS control signal is applied to AVR(Automatic Voltage Regulator) inputs.

4. Modeling of PSS using nonlinear control technique based on the input-output linearization method

4.1. Modeling Non Linear PSS (NLPSS) including synchronous generator 3rd order model

The modeling of the single machine infinite bus power system is developed through modeling of the synchronous generator with three dynamic equations using input-output linearization technique[8,9] . The predominant equations of the single machine infinite bus power system including synchronous generator 3rd order model are summarized as follows [2]:

$$\dot{\delta} = \omega_b \omega_r \tag{10}$$

$$\dot{\omega}_r = \frac{1}{2H}(T_m - T_e - K_D \omega_r) \tag{11}$$

$$\dot{E}'_q = \frac{1}{T'_{d0}}[-E'_q - (X_d - X'_d) I_d + E_{fd}] \tag{12}$$

$$\dot{E}_{fd} = \frac{1}{T_A}[-E_{fd} + K_A(V_{ref} + V_t - u)] \tag{13}$$

Where, electrical torque (T_e) is ($R_s + R_L$=0):

$$T_e = V_q I_q + V_d I_d = E'_q I_q + (X_q - X'_d) I_q I_d \tag{14}$$

And

$$V_t = \sqrt{V_q^2 + V_d^2} = \sqrt{(E'_q - R_s I_q - X'_d I_d)^2 + (X_q I_q - R_s I_d)^2} \tag{15}$$

Similarly, values of I_d, and I_q are measured using algebraic equations of the stator and the network:

$$\begin{cases}(R_s + R_L) I_q + (X'_d + X_L) I_d = E'_q + V_\infty \cos\delta \\ (X_q + X_L) I_q - (R_s + R_L) I_d = V_\infty \sin\delta\end{cases} \tag{16}$$

The following equations are obtained by replacing values of T_e, I_d and I_q in equations 1- 4 and ignoring resistance of the stator and transmission line and replacing the numerical values of the parameters, which are listed in the appendix :

$$\dot{\delta} = 314.16\, \omega_r \tag{17}$$

$$\dot{\omega}_r = -0.15 E'_q \sin\delta - 0.32 \sin 2\delta + 0.143\, T_m \tag{18}$$

$$\dot{E}'_q = -0.32 E'_q - 0.2 \cos\delta + 0.125\, E_{fd} \tag{19}$$

$$\dot{E}_{fd} = -20 E_{fd} + 800 V_{ref} - 800 V_t + 800\, u \tag{20}$$

$$V_t = \sqrt{(0.68 E'_q - 0.32 \cos\delta)^2 + (0.73 \sin\delta)^2} \tag{21}$$

If rotor velocity ω_r is determined as our output, then we have:

$$y = \omega_r \tag{22}$$

Regarding input-output linearization technique, y is differentiated in order to get a stage in which the input (u) is appeared at the measurement [5,6,7].

$$\dot{y} = \dot{\omega}_r = f_1 \tag{23}$$

$$\ddot{y} = \ddot{\omega}_r = f_2 \tag{24}$$

$$y^{(3)} = \omega^{(3)}{}_r = f_3 - (15 \sin\delta)\, u \tag{25}$$

Where, predominant equations of f_1, f_2, and f_3 are summarized in the appendix. According to the input-output linearization technique, the input v is selected as follows [6]:

$$v = f_3 - (15 \sin\delta)\, u \Rightarrow u = \frac{1}{15 \sin\delta}(f_3 - v) \tag{26}$$

Then, we have:

$$\omega^{(3)}{}_r = v \tag{27}$$

By selecting v as:

$$v = \omega^{(3)}{}_{rd} - K_1 e - K_2 \dot{e} - K_3 \ddot{e} \tag{28}$$

Where, error signal ,e is defined as:

$$e \triangleq \omega_r - \omega_{rd} \tag{29}$$

Where, ω_d indicates the reference speed, so we have:

$$e^{(3)} + K_3 \ddot{e} + K_2 \dot{e} + K_3 e = 0 \tag{30}$$

By selecting $x_1 = e$, $x_2 = \dot{e}$, $x_3 = \ddot{e}$ we have:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ -K_1 & -K_2 & -K_3\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix}\Rightarrow \dot{X}=AX \qquad 31$$

In the case of selecting proper k_1, k_2 and k_3, it will be possible to indicate that (31) is stable asymptotically, i.e. $(\boldsymbol{e} \to \boldsymbol{0})$and hence $(\boldsymbol{\omega_r} \to \boldsymbol{\omega_{rd}})$which is desired for the problem [5] .

2.4. Modeling NLPSS Including Synchronous Generator 6th order Model

In this section, relying on the input-output linearization technique synchronous generator 6th order model including 6 dynamic equations, two mechanical and 4 electrical dynamic equations, are used to model the PSS of the single machine infinite bus power system.
The relevant equations of the power system are listed here [2]:

$$\dot{\delta} = \omega_b \omega_r \qquad 32$$

$$\dot{\omega}_r = \frac{1}{2H}(T_m - T_e - K_D\omega_r) \qquad 33$$

$$\dot{E}'_q = \frac{1}{T'_{d0}}[-E'_q - (X_d - X'_d)\, I_d + E_{fd}] \qquad 34$$

$$\dot{E}'_d = \frac{1}{T'_{q0}}[-E'_d + (X_q - X'_q)\, I_q] \qquad 35$$

$$\dot{E}''_q = \frac{1}{T''_{d0}}[-E''_q - (X'_d - X''_d)\, I_d + E'_q] \qquad 36$$

$$\dot{E}''_d = \frac{1}{T''_{q0}}[-E''_d - (X'_q - X''_q)\, I_q + E'_d] \qquad 37$$

$$\dot{E}_{fd} = \frac{1}{T_A}[-E_{fd} + K_A(V_{ref} + V_t - u)] \qquad 38$$

Where, electric torque (T_e) is $(R_s + R_L=0)$:

$$T_e = V_q I_q + V_d I_d = E''_q I_q + E''_d I_d + (X''_q - X''_d)\, I_q I_d \qquad 39$$

And

$$V_t = \sqrt{V_q^2 + V_d^2} = \sqrt{\left(E''_q - R_s I_q - X''_d I_d\right)^2 + \left(E''_d - R_s I_d + X''_q I_q\right)^2} \qquad 40$$

Similarly, values of I_d and I_q are measured using algebraic equations of the stator and the network:

$$\begin{cases}(R_s + R_L)I_q + (X''_d + X_L)I_d = E''_q + V_\infty \cos\delta\\ (X''_q + X_L)I_q - (R_s + R_L)I_d = -E''_d + V_\infty \sin\delta\end{cases} \qquad 41$$

The following equations are obtained by replacing values of T_e, I_d and I_q in equations (32-40) and ignoring resistor of the stator and transmission line and replacing the numerical values of the parameters based on the selective model:

$$\dot{\delta} = 314.16\, \omega_r \qquad 41$$

$$\dot{\omega}_r = -0.16232E''_q \sin\delta - 0.15868\, E''_d \cos\delta - 0.0018\sin 2\delta + 0.000034E''_q E''_d + 0.142857T_m \qquad 42$$

$$\dot{E}'_q = -0.125\, E'_q + 0.21442 \cos\delta + 0.21442\, E''_q + 0.125\, E_{fd} \qquad 43$$

$$\dot{E}'_d = -E'_d + 1.23321 \sin\delta - 1.23321\, E'_d \qquad 44$$

$$\dot{E}''_q = -30.68\, E''_q + 20.65 \cos\delta + 33.33\, E'_q \qquad 45$$

$$\dot{E}''_d = -20.63\, E''_d + 6.35 \sin\delta + 14.285\, E'_d \qquad 46$$

$$\dot{E}_{fd} = -20\, E_{fd} + 800\, V_{ref} - 800\, V_t + 800\, u \qquad 47$$

$$V_t = \sqrt{\left(E''_q + 0.255E''_d - 0.255\sin\delta\right)^2 + \left(E''_d + 0.284E''_q + 0.284\cos\delta\right)^2} \qquad 48$$

If rotor velocity, ω_r, is selected as our output, then we have:

$$y = \omega_r \qquad 49$$

Now with regarding input-output linearization technique was introduced in section (4-1) have

$$\dot{y} = \dot{\omega}_r = f_4 \qquad 50$$

$$\ddot{y} = \ddot{\omega}_r = f_5 \qquad 51$$

$$y^{(3)} = \omega^{(3)}{}_r = f_6 \qquad 52$$

$$y^{(4)} = \omega^{(4)}{}_r = f_7 + (0.11\, E''_d + 544 \sin\delta)\, u \qquad 53$$

Where, equations of f_4 to f_7 are summarized in the appendix. According to the input-output linearization technique the input ,v can be selected as follows:

$$v = f_7 + (0.11\, E''_d + 544 \sin\delta)\, u \Rightarrow u = \frac{1}{0.11\, E''_d + 544 \sin\delta}(v - f_7) \qquad 54$$

Then we have:

$$\omega^{(4)}{}_r = v \quad (55)$$

By selecting *v* as:

$$v = \omega^{(4)}{}_{rd} - K_1\, e - K_2\, \dot{e} - K_3\, \ddot{e} - K_4 \omega^{(3)}{}_r \quad (56)$$

We have:

$$e^{(4)} + K_4\, e^{(3)} + K_3\, \ddot{e} + K_2\, \dot{e} + K_1\, e = 0 \quad (57)$$

Where, by selecting $x_1 = e$, $x_2 = \dot{e}$, $x_3 = \ddot{e}$, $x_4 = e^{(3)}$ we have:

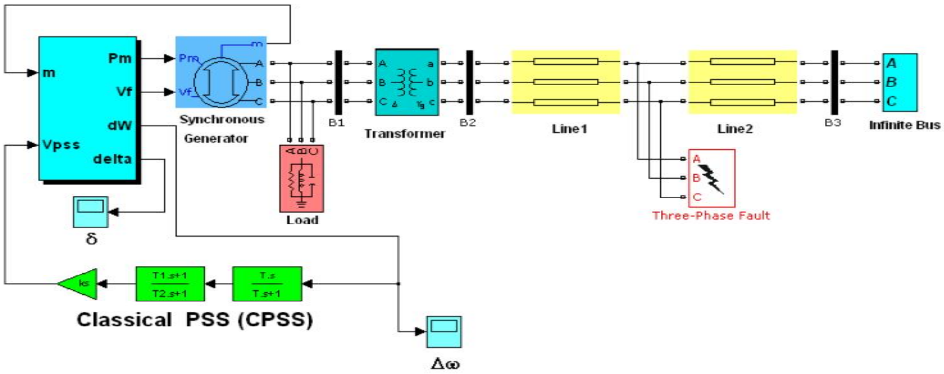
$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -K_1 & -K_2 & -K_3 & -K_4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \Rightarrow \dot{X} = AX \quad (58)$$

If proper values are selected for k_1 to k_4 as poles of the closed loop system are laid on an appropriate location in the left side of $j\omega$ axis, then error signal will move towards zero ($e \to 0$) [5].

5. Simulation and results observation

Steam turbine model, Governor, exciter, round pole synchronous generator, three phase generator, transmission line, load and the infinite bus have been considered for the simulation of the single machine infinite bus power system. MATLAB software was employed to conduct the simulation. Performance of the CPSS and NLPSS including synchronous generator 3rd and 6th order models were analyzed and compared at the presence of 3-phase fault of the transmission line.

Three phase fault in the transmission line occurs within 1.1 seconds and then is removed within 1.3 seconds.



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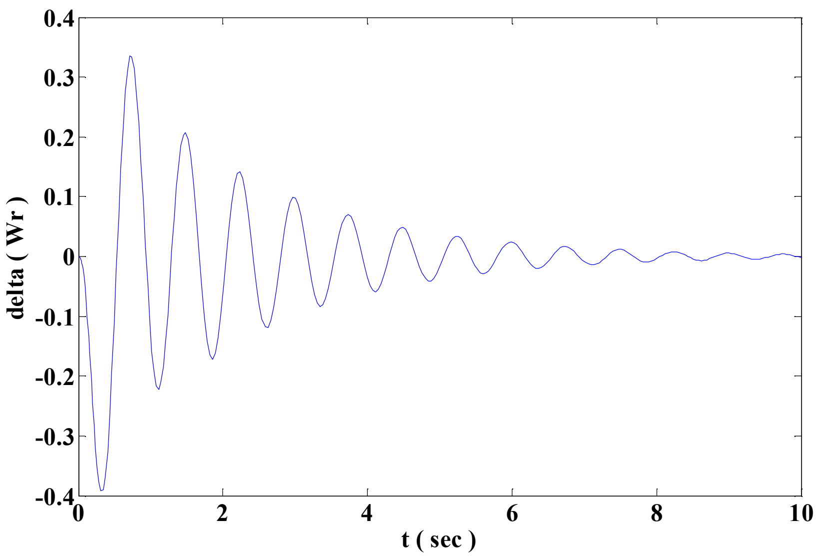

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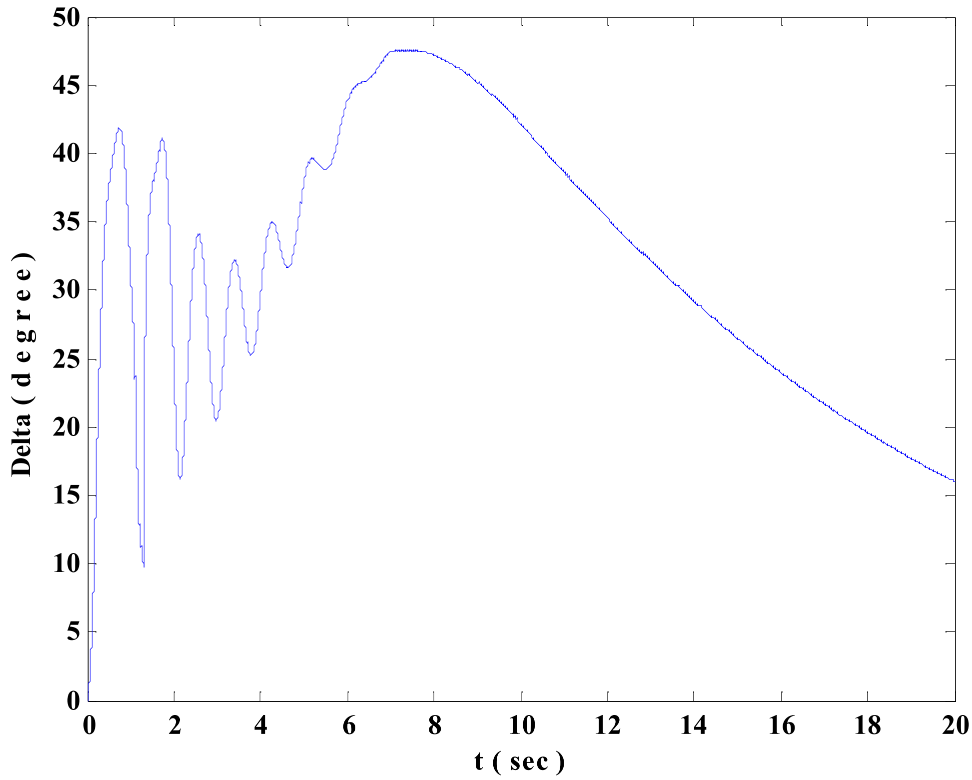
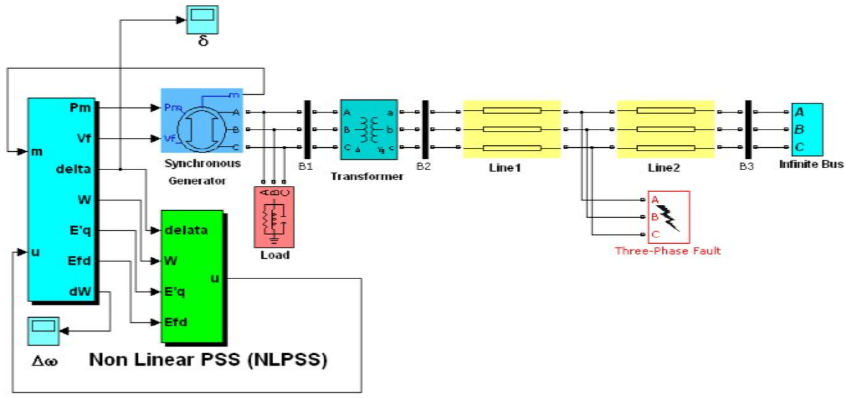


(c)

Fig 3: Results of simulation with CPSS; a) A scheme of simulation of the single machine infinite bus power system including CPSS, b) rotor speed variation diagram ($\Delta\omega_r$) before and after occurrence of three phase fault, c)torque-angle curve (δ) before and after fault occurrence



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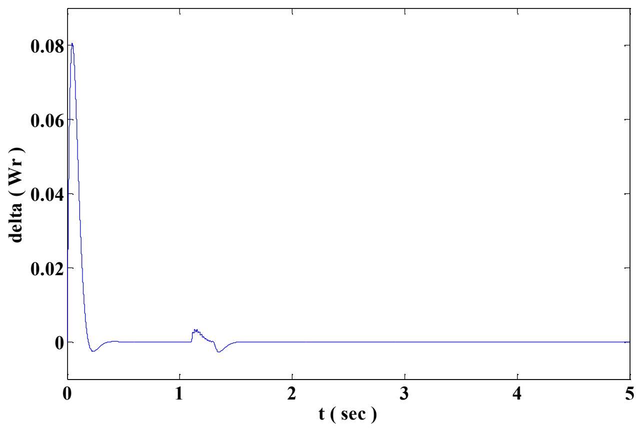

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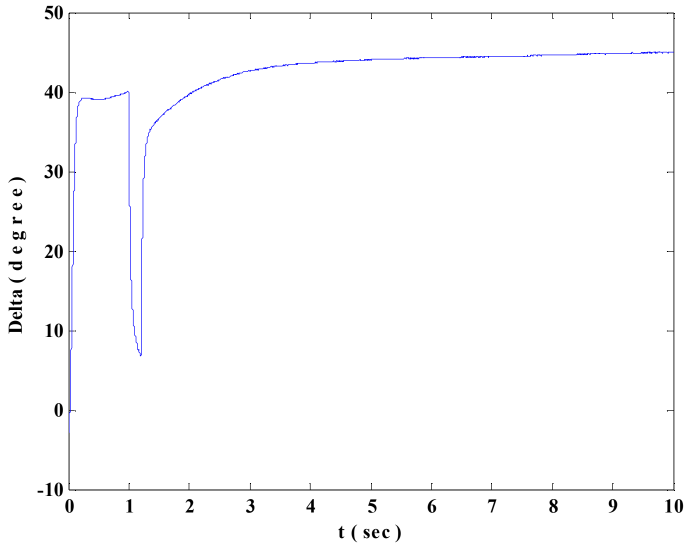
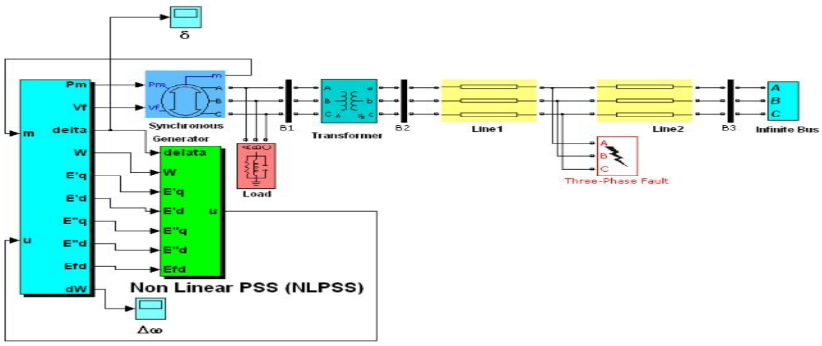


(c)

Fig 4: Results of simulation with NLPSS along with generator 3rd order model ; a) A scheme of simulation of the single machine infinite bus power system including NLPSS, b) rotor speed variation diagram ($\Delta\boldsymbol{\omega}_r$) before and after occurrence of three phase fault, c)torque-angle curve (δ) before and after fault occurrence



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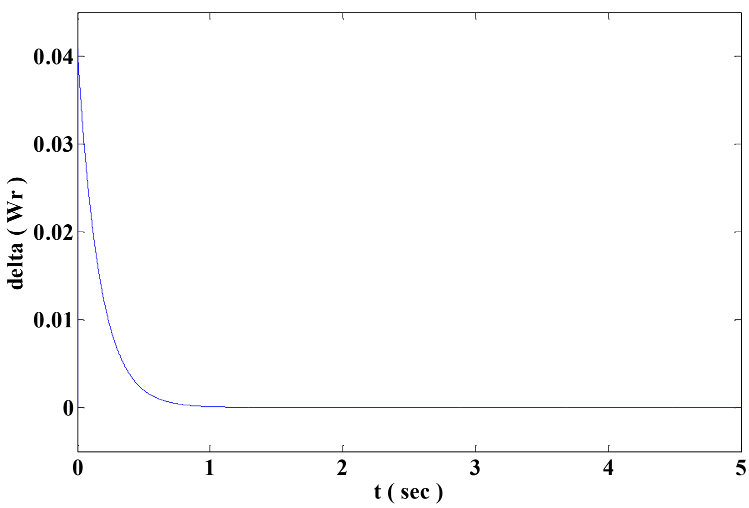

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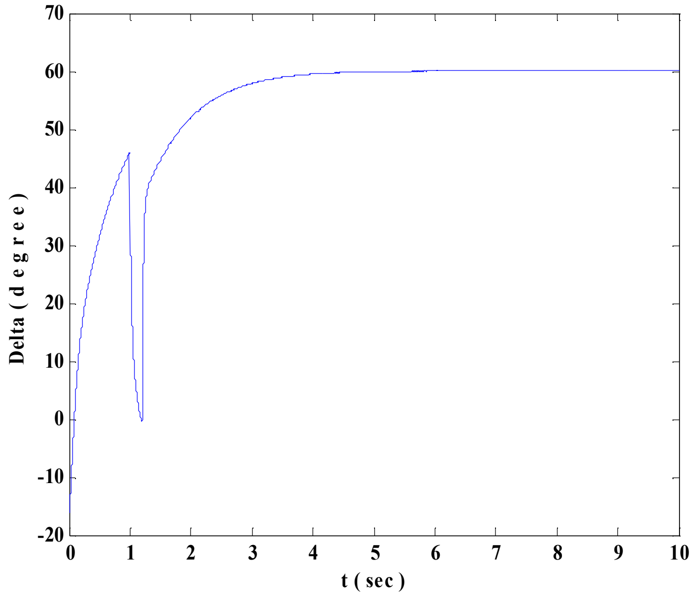
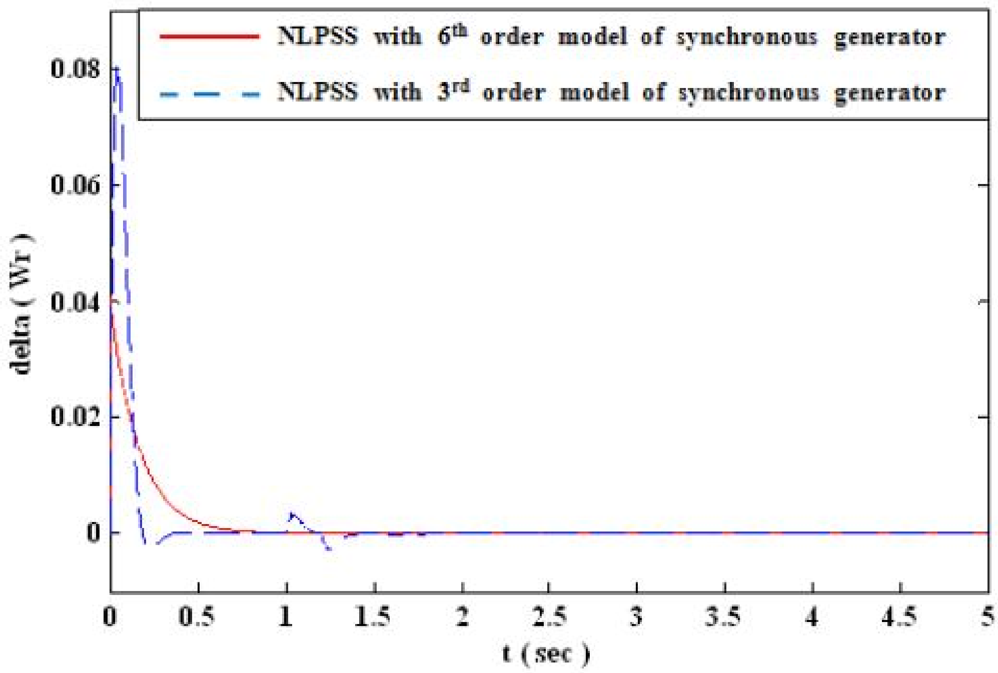


(c)

Fig 5: of simulation with NLPSS along with generator 6th order model ; a) A scheme of simulation of the single machine infinite bus power system including NLPSS, b) rotor speed variation diagram ($\Delta\omega_r$) before and after occurrence of three phase fault, c)torque-angle curve (δ) before and after fault occurrence

6. Comparison and Conclusion

They explicitly indicate superiority of nonlinear control modeling method based on input-output linearization method to the classical linear control modeling method; it is because of this fact that naturally synchronous generator acts nonlinearly, hence some key factors in description of behavior of the generator are underestimated in the case of linearization of the generator model around a given operating point.



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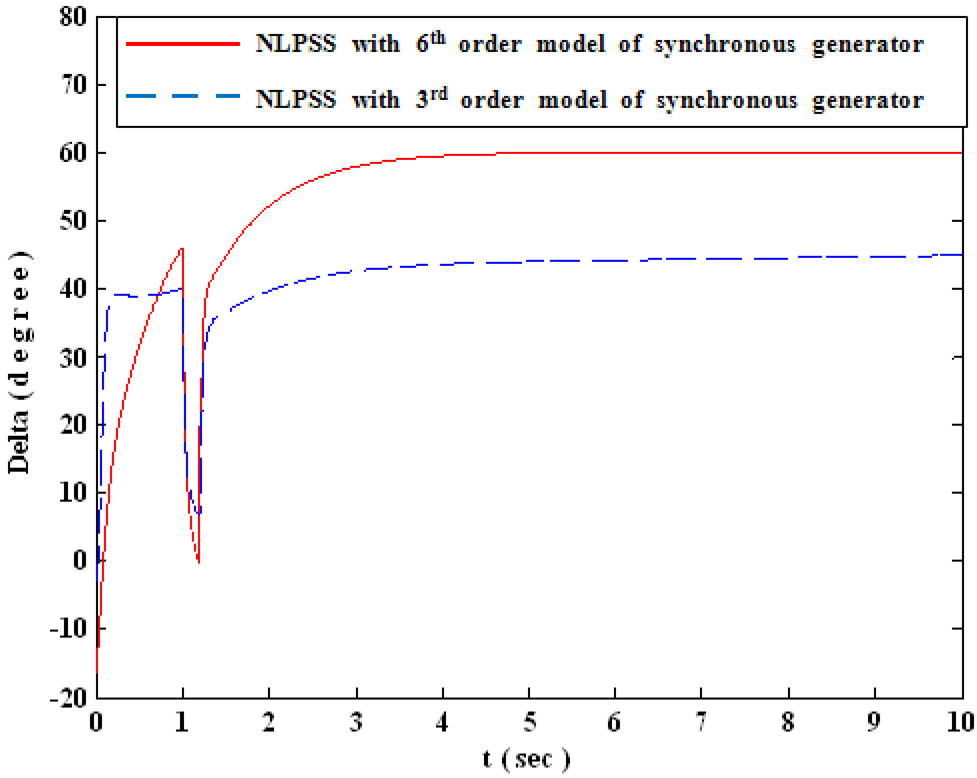

(b)

Fig 6: comparison between two nonlinear method : (a) comparison between $\Delta\boldsymbol{\omega}_r$ results, (b) comparison between $\boldsymbol{\delta}$ results

By comparing the figures obtained from the carried out simulations, it is observed when input-output linearization controlling method is used and 6^{th} order model of synchronous generator is taken into account damping velocity $\Delta\boldsymbol{\omega}_r$ has been decreased severely with respect to the other two modes. In addition, the over shoot has been decreased in this mode. Comparing two modeling methods, which are similar in terms of the application of input-output linearization method based nonlinear control method and are different based on selection of the model of the generator, indicates superiority of considering the higher order model for the generator during the PSS. By comparing the three figures that shown in figure 6, obtained from the results for the angle of torque (δ) , when CPSS is used, it is observed that the amount of reaches $\mathbf{15}^{\circ}$which results in falling of transmission power of the generator. When NLPSS is used and the 3^{rd} order of generator is taken into account, δ reaches$\mathbf{45}^{\circ}$, which indicates that the design method based on input-output linearization is superior to the classical design method. Taking the 6^{th} order model for synchronous generator into account, the obtained results are improved once again, as the amount of δ reaches $\mathbf{60}^{\circ}$. It indicates that by taking higher order model for generator in the power system stabilizer design increases the efficiency of power system stabilizer and consequently, it improves the performance of synchronous generator.

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8. Appendix

8. A Synchronous Generator Parameters

$\mathbf{S_B}$= 500 MVA , $\mathbf{V_B}$= 22 Kv , $\mathbf{f_s}$= 50 Hz

H= 3.5 $\frac{MWsec}{MVA}$, $\mathbf{K_D}$= 0

Stator Resistance (pu) :
R_s= 0.003
Reactances (pu) :
X_d= 1.81, **X'_d**= 0.3 , **X''_d**= 0.23 , **X_q**= 1.76 , **X'_q**=0.65 , **X''_q**= 0.25
Time Constants (sec) :
T'_{d0}= 8, **T''_{d0}**= 0.03 , **T'_{q0}**= 1 , **T''_{q0}**= 0.07

8.B. Evaluation of the employed function in the text using the parameters given in appendix A, the functions f_1 to f_7 are obtained as follows :

$$f_1 = -0.15E'_q \sin\delta - 0.32\sin 2\delta + 0.143T_m$$

$$f_2 = 0.048E'_q \sin\delta - 0.01875E_{fd}\sin\delta - 47.127E'_q\omega Cos\delta - 201.06\omega Cos 2\delta + 0.015\sin 2\delta$$

$$f_3 = (30.16\omega Cos\delta - 0.01536\sin\delta + 15.08 Cos Sin 2\delta + 30.16\text{SinCos}\delta)E'_q + 9.43(\text{Cos}^2\delta + \text{Cos}2\delta)\omega$$
$$+3.53E'^2_q\text{Sin}2\delta - 0.0048\text{Sin}2\delta + 32.17\text{Sin}4\delta + (126330.02\text{Sin}2\delta + 14804.48E'_q\text{Sin}\delta)\omega^2$$
$$-(6.74E'_q\text{Cos}\delta + 28.75\text{Cos}2\delta)T_m - (15\text{Sin}\delta)V_{ref} + (0.381\text{Sin}\delta - 11.8\omega\text{Cos}\delta)E_{fd} - (15\text{Sin}\delta)V_t$$

$$f_4 = -0.16232E''q\sin\delta - 0.15868E''d\cos\delta - 0.0018\sin 2\delta + 0.000034E''qE''d + 0.142857Tm$$

$$f_5 = 4.9802E''q\sin\delta - 0.715\sin 2\delta + 3.2709E''dCos\delta$$
$$-5.41E'q\sin\delta - 2.27E'dCos\delta - 0.0017E''qE''d - 51E''q\omega\cos\delta$$
$$+49.85E''_d\,\omega\sin\delta + 0.0011E'qE''d + 0.00048E'dE''q - 1.13\omega\cos 2\delta$$

$$f_6 = -152.12E''q\sin\delta - 64.69E''d\ Cos\delta + 0.139E''qE''d$$
$$+166.68E'q\sin\delta + 48.98E'd\cos\delta + 3129.26E''q\omega\cos\delta - 1028.41E''_d\,\omega\sin\delta$$
$$+00000038E''qE''d\cos 2\delta - 16022.16E''q\omega 2\sin\delta$$
$$+15660.88E''d\omega^2\cos\delta - 0.0017E''q^2E''d\cos\delta + 0.0017E''qE''d^2\sin\delta$$
$$+8.092E''qE''d\cos 2\delta + (0.1\sin 2\delta\cos\delta\cos 2\delta + 0.18\sin\delta\cos 2\delta)E''q$$
$$+(0.18\cos\delta\cos 2\delta - 0.09\sin\delta\sin 2\delta)E''d + 15\sin 2\delta + 0.001\sin 4\delta + (451.7\sin^2\delta - 449.25Cos2\delta - 135.15)w - 710\omega^2\sin 2\delta$$
$$+(7.12E''d\sin\delta - 7.28E''q\cos\delta - 0.16\cos 2\delta)T_m + (0.0001375E''d + 0.68\sin\delta)E_{yd}$$

$$f_7 = 4725.55E''_q\sin\delta - 1295.8E''_d\cos\delta - 5091.83E'_q\sin\delta$$
$$-973.179\cos\delta - 503.72E''qE''d - 3.3057E'qE'd + 7.417E'qE''d$$
$$+3.277E'dE''q - 144524.63E''q\omega Cos\delta + 41049.01E''_d\,\omega\sin\delta$$
$$+157087.37E'q\omega\cos\delta - 30073.26E'd\omega\sin\delta - 521.745E''q^2\sin 2\delta$$
$$+244.802E''d^2\sin 2\delta - 491529.32E''q\omega^2\sin\delta - 645169.23E''_d\,\omega^2\cos\delta$$
$$+(0.0615E'd\sin\delta - 0.23E_q\cos\delta)E'qE''d + (663.5\sin^2\delta - 415.21\cos 2\delta + 0.0216\sin 2\delta)$$
$$E''qE''d - 5083.9E''_q\,E''_d\,\omega + (9.45E'q + 14.432E''q - 0.0001E''d - 423.082E''d\omega)$$
$$Cos\delta\sin 2\delta + (5201.43E''q^2\omega - 73.32E''q\sin\delta - 71.67E''d\cos\delta$$
$$-1.545w\sin^2\delta - 64.51E'dE''q - 6042.87)\sin 2\delta + (539.42E'qE''d$$
$$-4970E''d^2\omega)\cos^2\delta + (2.006E'd - 46.52E''d - 298.53E''q\omega)$$
$$\sin\delta\sin 2\delta + (96.95E''d + 2.57E'd + 119.38Eq''\omega)\cos\delta\cos 2\delta$$
$$+(136.82E''q - 113.1E''_d\,\omega)sns\delta\cos 2\delta + (566.8Eq'E''q - 144.48E'dE''d$$
$$+452672.77\omega^2 - 358.64)\sin 2\delta + 1.26\cos 4\delta + 1.02Sin4\delta$$
$$+(2697E'qE''d + 115.59E'dE''q + 9424.8\omega + 445724.75\omega^3 + 2742E''q^2\omega - 2485E''^2_d\,\omega)\cos 2\delta$$
$$-(1067868.07E'q\omega^2 - 4920022E''d\omega^3 - 1.1E''qE''d^2 - 0.566E''q^2E''d\omega - 534018.6E'q\omega^2 - 397.41\omega)\sin\delta$$
$$+(0.239E''q^2E''d - 0.024E'dE''q^2 + 223637.37E'd\omega^2 + 1.604Eq''E''d^2\omega$$
$$-5033521E''q\omega^3 + 124850.32E'd\omega^2)\cos\delta + (670.39E''q\cos\delta$$
$$-293.8E''d\sin\delta + 158E'd\sin\delta - 728.34E'q\cos\delta - 2290.67E''q\omega\sin\delta$$
$$+6711.35\omega\cos\delta + 129.342\sin^2\delta + 303.39\sin^2\delta - 71.32\cos 2\delta$$
$$-20.31)T_m + (0.006E'd - 0.0228E''d + 7.2408Sin\delta - 216.3\omega\cos\delta)Efd + (0.11E''d + 544Sin\delta)(Vref - Vt)$$