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Designing optimal power system stabilizer for synchronous generator with and without damper windings

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ABSTRACT

This paper aims at effective damping of low-frequency oscillations (LFO) associated with synchronous generators (SG).
LFO are excited by system disturbances as sudden change on the load, switching events, and malfunction of the turbine controller.
Poor damping of LFO affects the stability of the generation system, in severe cases may result in instability and damage to prime-movers.
The negative effect of the automatic voltage regulator (AVR) is studied for SG without and with damper windings on the damping of oscillations.
Minimizing the LFO is achieved by incorporating the power system stabilizer (PSS), which adds an additional control signal to AVR. Effective design of PSS to maximize the damping torque while maintaining the stability of SG variables.
The problem is modelled as an optimization problem, the damping ratio of the mechanical modes is the objective function. The single-pole placement technique and the recently developed political optimizer are picked to determine the perfect PI parameters for PSS.
The satisfactory performance of the proposed PSS is appraised by testing it against mechanical power disturbances.
The obtained mathematical analytical expression makes it possible to determine easily the eigenvalues and step response for the speed and electromagnetic torque for SG in MATLAB environment.

1. INTRODUCTION

Increasing the electrical load due to overpopulation and manufacturing have created the need to operate the generated systems close to their capacity limits [1].

In addition to the appearance of unforeseen malfunctions of the control devices of the valves that control the power generated and after that the generator loses synchronism with the grid, destroy the prime-mover of the turbine or reduce the lifetime of the generation system.

This causes an unexpected change in power consumption due to switching events.

So, this leads sometimes to weak dynamic response, stability problems, make electromagnetic disturbances and oscillations on the electrical grid [2].

These reasons affect great damage on the generation power systems (SG) and reducing the stability of the electrical network and lead to decrease the life time and breakdown the generation systems [2].

Therefore, this will be considered very expensive economical. Otherwise, some designs for

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synchronous generators have damper windings that help to damp a small fraction of oscillations. Therefore, the use of excitation systems [3,4] like automatic voltage regulator (AVR) is used but it observes a voltage signal from an infinite bus and compared it with a reference signal to adjust and regulate the generated voltage of synchronous generator by controlling the field current to adjust the voltage deviation.

This led to generate additional induced current in field winding counteract the induced current of damper winding, this makes the damping process deteriorate [1].

The PSS [4] is considered that one of the most important systems in SG because it observes the electrical power and frequency of the generator and when any external fault has happened on the grid or sudden change in the loads, it leads to a swing in the power of generator [6].

The PSS generates a stabilizing signal, which produces a torque damping component on the generator rotor and the created torque component must be in phase with speed deviation, produce the required power to support the grid when a sudden change in the loads or external fault in the grid and compensate the oscillation in the system and make it more stable.

Due to the non-linear electrical grid, analysis of the small-signal eigenvalues and dynamic simulation. The Conventional PSS (CPSS) [8] system has been examined and found to be inefficient in conditions of turbulence and large-scale operation, and it cannot dampen low-frequency oscillations.

To repair this system (CPSS), many techniques have been used to contribute to the conclusion of appropriate values for the PI parameters such as particle swarm optimization [9], Fuzzy wavelet neural network [10], Single Neuron based PSS (SNPSS) [11], multi-band PSS using culture-PSO-co evolutionary (CPCE) algorithm [12], participation factor and genetic algorithm [13].

In this regard, this paper addresses the effect of the AVR system on SG is studied and the single-pole placement and the most recent optimization method (political optimizer [29,30]) are used to achieve the transient stability for SG.

The linearization process is used in park's equation [5] of SG without and with damper winding to express and simulate the problem of small-signal stability [7] at the disturbance load and analysis the dynamic response of damping.

Therefore, in the present paper:

I - modelling of the infinite bus and synchronous generator in(d-q) axis rotor reference and analysis the equations at steady-state and linearization process.

II -Analysis of the effect of AVR system with SG at the oscillations

III - designing the PSS system with the optimal controller to enhancement the dynamic performance of SG.

Iv - compartment the results of eigenvalues and step response for SG without and with damper winding at the effect of excitation systems at load disturbance.

2. Modeling of synchronous generator and finite bus

SG has been usually modeled by using the park's equations [1] to express and simulate its physical description and performance to conclude and analyze the relationship between the disturbance on the electromagnetic grid and the dynamic behavior of the generator.so, equations of SG will be analyzed in (d-q) axis rotor reference after transformed from (a-b-c) stator reference frame by using park's equations.

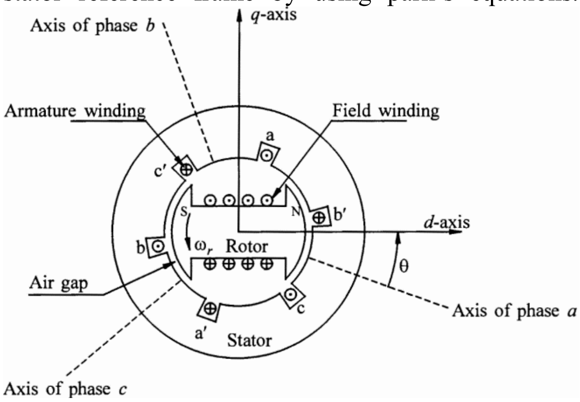


Fig 1. Schematic diagram of SG [2]

the voltage in d-q stator equations (1,2):

$$v_{ds} = -r_s\, i_{ds} + \frac{p}{\omega b}\, \psi_{ds} - \frac{\omega_r}{\omega_b}\, \psi_{qs} \quad (1)$$

$$v_{qs} = -r_s\, i_{qs} + \frac{p}{\omega b}\, \psi_{qs} + \frac{\omega_r}{\omega_b}\, \psi_{ds} \quad (2)$$

the voltage in d-q damper winding equations (3,4):

$$v_{dr} = 0 = r_{dr}\, i_{dr} + \frac{p}{\omega b}\, \psi_{dr} \quad (3)$$

$$v_{qr} = 0 = r_{qr}\, i_{qr} + \frac{p}{\omega b}\, \psi_{qr} \quad (4)$$

The voltage in field winding equation (5)

$$v_{fr} = r_{fr}\, i_{fr} + \frac{p}{\omega b}\, \psi_{fr} \quad (5)$$

The electromagnetic torque and motional equations (6,7):

$$T_e = \frac{3}{2}.\frac{P}{2}.\frac{1}{\omega_b}\left(\psi_{ds}\, i_{qs} - \psi_{qs}\, i_{ds} \right) \quad (6)$$

$$T_l - T_e = \frac{2\, j\ \omega_b}{P}\, p\, \left(\frac{\omega_r}{\omega_b}\right) \quad (7)$$

Assume SG is connected to the grid through line with resistance r_e , inductance l_e .Fig 2

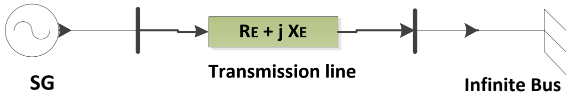


Fig 2. synchronous generator with infinite bus

So, the equations of stator voltage at the grid will be (8,9)

$$v_{ds} = v_b\, sin\theta_b + \frac{p}{\omega_b}\, x_e\, i_{ds} - \frac{\omega_r}{\omega_b}\, x_e\, i_{qs} + r_e\ i_{ds} \quad (8)$$

$$v_{qs} = v_b\, cos\theta_b + \frac{p}{\omega_b}\, x_e\, i_{qs} + \frac{\omega_r}{\omega_b}\, x_e\, i_{ds} + r_e\ i_{qs} \quad (9)$$

At steady state, the synchronous machine equations terms will be constant so the derivative terms ($p = \frac{d}{dt}$) will be zero, $\omega_{r0} = \omega_b$ synchronous speed and the current of d-q damper winding will be zero $i_{dr} = i_{qr} = 0$.

the linearization process of SG equations is very important to find the required state, input and output matrixes and analysis the state space for the transfer functions of rotor speed and electromagnetic torque and the dynamic performance of the machine to design the perfect controller so consider a small change from a balanced operating condition of park's equations in physical units.

From the linearization of the stator voltage of q-axis at SG and the linearization process of the stator voltage of q-axis at infinite bus equation. Deducing the equation (10)

$$-(r_s + r_e)\, \Delta i_{qs} - \frac{\omega_{r0}}{\omega_b}\, (x_{ds} + x_e)\Delta i_{ds}$$
$$+ \frac{\omega_{r0}}{\omega_b}\, x_{md}\, \Delta i_{dr} + \frac{\omega_{r0}}{\omega_b}\, x_{md}\, \Delta i_{fr}$$
$$+\frac{\Delta\omega_r}{\omega_b}\ (\psi_{ds0} - x_e\, i_{ds0}) - v_{b0}\sin(\delta_{b0})\, \Delta\theta_r$$
$$+ \frac{p}{\omega_b}\left(-\left(x_{qs} + x_e \right)\Delta i_{qs} + x_{mq}\, \Delta i_{qr}\right)$$
$$= -\, v_{b0}\sin(\delta_{b0})\, \Delta\delta_b + \Delta v_b\cos(\delta_{b0}) \quad (10)$$

And from the linearization of the stator voltage of d-axis at SG equation and the linearization process of the stator voltage of d-axis at infinite bus equation Deducing the equation (11)

$$-(r_s + r_e)\, \Delta i_{ds} + \frac{\omega_{r0}}{\omega_b}(x_{qs} + x_e)\Delta i_{qs} + v_{b0}\cos(\delta_{b0})\Delta\theta_r$$
$$-\frac{\omega_{r0}}{\omega_b}\, x_{mq} * \Delta i_{qr} + \frac{\Delta\omega_r}{\omega_b}(-\psi_{qs0} + x_e\, i_{qs0})$$
$$+ \frac{p}{\omega_b}\left(-\left(x_{ds} + x_e\right) \Delta i_{ds} + x_{md}\, \Delta i_{dr} + x_{md}\, \Delta i_{fr}\right)$$
$$= v_{b0}\cos(\delta_{b0})\, \Delta\delta_b + \Delta v_b\ \sin(\delta_{b0}) \quad (11)$$

Linearization for voltage of q-axis of damper winding equation (12)

$$0 = r_{qr}\ \Delta i_{qr} + \frac{p}{\omega_b}\left(x_{qr}\ \Delta i_{qr} - x_{mq}\ \Delta i_{qs}\right)$$
(12)

Linearization for voltage of d-axis of damper winding equation (13)

$$0 = r_{dr}\, \Delta i_{dr} + \frac{p}{\omega_b}\left(x_{dr}\, \Delta i_{dr} + x_{md}\left(-\Delta i_{ds} + \Delta i_{fr}\right)\right) \quad (13)$$

Linearization for voltage of field winding equation (14):

$$\Delta v_{fr} = r_{fr}\, \Delta i_{fr} + \frac{p}{\omega_b}\left(x_{fr}\, \Delta i_{fr} + x_{md}(\Delta i_{dr} - \Delta i_{ds})\right) \quad (14)$$

Linearization of electromagnetic torque and motional equation (15,16)

$$c_t = \frac{3}{2}.\frac{P}{2}.\frac{1}{\omega_b}$$

$$\Delta T_e = c_t\begin{pmatrix} (\psi_{ds0} + x_{qs}\, i_{ds0})\Delta i_{qs} \\ -(x_{ds}\, i_{qs0} + \psi_{qs0})\Delta i_{ds} + x_{md}\, i_{qs0}\, \Delta i_{dr} \\ + x_{md}\ \ i_{qs0}\, \Delta i_{fr} - x_{mq}\ \ i_{ds0}\, \Delta i_{qr} \end{pmatrix} \quad (15)$$

$$\Delta T_l - \Delta T_e = \frac{2\ .j.\ \omega_b}{P}\ p\left(\frac{\Delta\omega_r}{\omega_b}\right) \quad (16)$$

Deducing the small change in mechanical torque equation (17) from equations (15,16)

$$\Delta T_l = c_t\begin{pmatrix} (\psi_{ds0} + x_{qs}\, i_{ds0})\Delta i_{qs} - (x_{ds}\, i_{qs0} + \psi_{qs0})\Delta i_{ds} \\ + x_{md}\, i_{qs0}\, \Delta i_{dr} \\ + x_{md}\, i_{qs0} * \Delta i_{fr} - x_{mq}\ \ i_{ds0}\, \Delta i_{qr} \end{pmatrix} + \frac{2\ .\ j\ .\omega_b}{P}\ p\left(\frac{\Delta\omega_r}{\omega_b}\right) \quad (17)$$

Linearization of rotor and speed equation (18)

$$p\, \Delta\theta_r - \Delta\omega_r = 0$$
(18)

From equations (10-14), (17-18) respectively are equivalent to the matrix expression to analysis the state space at constant field voltage and dynamic behaviour with damper winding and without damper winding after removing equations (12,13)

3. Modeling of AVR with synchronous generator

AVR system observes a voltage signal from infinite bus and compare it with a reference signal to adjust and regulate the generated voltage of synchronous generator by controlling the field current.

this part describes and analysis the linearization of the automatic voltage regulation system and study the effect of AVR on the disturbance on mechanical load.

the AVR system (IEEE Type 1(ST1A) excitation system) as shown in Fig.3

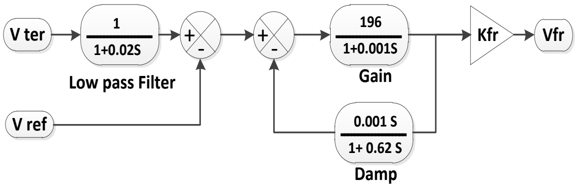


Fig 3. Block Diagram AVR system

Linearization AVR system, all constant values will be removed at small changes from steady state, rewriting the block diagram of AVR after simplifying the system at linearization process. as shown in Fig.4

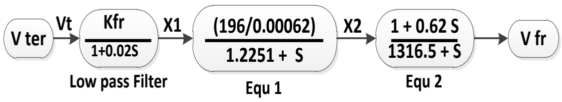


Fig 4. Block diagram after simplifying the exciter system

linearization of the generated voltage of synchronous generator ΔV_t

$$V_t = \sqrt{{v_{ds}}^2 + {v_{qs}}^2} \quad (19)$$

consider a small change from a balanced operating condition on v_t:

$$v_{t0} + \Delta V_t =$$
$$= v_{t0}\sqrt{1 + \frac{2\, v_{ds0}\Delta v_{ds}}{{v_{t0}}^2} + \frac{2\, v_{qs0}\Delta v_{qs}}{{v_{t0}}^2}}$$

(20)

From power series expansion

$$\sqrt{1+x} = 1 + \frac{x}{2!} + \frac{x^2}{4!} + \cdots \quad (21)$$

After eliminate the steady state term and ΔV_t will be divide on v_{t0} to get the value of small change as per unit, where v_{t0} is the base voltage

$$\Delta v_t = \frac{\Delta V_t}{v_{t0}}$$

$$\Delta v_t = a\_v_t\, \Delta\delta_b + b\_v_t\, \Delta v_b + c\_v_t\, \Delta\theta_r + d\_v_t\, \Delta\omega_r + e\_v_t\, \Delta i_{ds} + f\_v_t\, \Delta i_{qs} + \Delta i_{ds}\, \frac{p}{\omega_b}\, x_e \frac{v_{ds0}}{v_{t0}} \frac{1}{v_{t0}} + \Delta i_{qs}\, \frac{p}{\omega_b}\, x_e \frac{v_{qs0}}{v_{t0}} \frac{1}{v_{t0}} \quad (22)$$

Where,

$$a\_v_t = [v_{b0}\cos(\delta_{b0})\frac{v_{ds0}}{v_{t0}} - v_{b0}\sin(\delta_{b0})\frac{v_{qs0}}{v_{t0}}]\frac{1}{v_{t0}}$$

$$b\_v_t = \left[\sin(\delta_{b0})\,\frac{v_{ds0}}{v_{t0}} + \cos(\delta_{b0})\,\frac{v_{qs0}}{v_{t0}}\right]\frac{1}{v_{t0}}$$

$$c\_v_t = \left[-v_{b0}\cos(\delta_{b0})\frac{v_{ds0}}{v_{t0}} + v_{b0}\sin(\delta_{b0})\frac{v_{qs0}}{v_{t0}}\right]\frac{1}{v_{t0}}$$

$$d\_v_t = \left[\frac{-x_e\ i_{qs0}}{\omega_b}\frac{v_{ds0}}{v_{t0}} + \frac{x_e\ i_{ds0}}{\omega_b}\frac{v_{qs0}}{v_{t0}}\right]\frac{1}{v_{t0}}$$

$$e\_v_t = \left[r_e\,\frac{v_{ds0}}{v_{t0}} + x_e\,\frac{\omega_{r0}}{\omega_b}\frac{v_{qs0}}{v_{t0}}\right]\frac{1}{v_{t0}}$$

$$f\_v_t = \left[-x_e\,\frac{\omega_{r0}}{\omega_b}\frac{v_{ds0}}{v_{t0}} + r_e\,\frac{v_{qs0}}{v_{t0}}\right]\frac{1}{v_{t0}}$$

From Fig.4, first the transfer function (T.F) for block diagram of $\frac{\Delta x_1}{\Delta v_t}$:

$$k_{fr}\ \Delta v_t - \frac{p}{\omega_b}(0.02\,\omega_b\ \Delta x_1) - \Delta x_1 = 0 \quad (23)$$

substitute Δv_t from equation (22) into equation (23)

$$k_{fr}\, a\_v_t\, \Delta\delta_b + k_{fr}\, b\_v_t\, \Delta v_b = -k_{fr}\, e\_v_t\, \Delta i_{ds} - k_{fr}\, c\_v_t\, \Delta\theta_r - k_{fr}\, d\_v_t\, \Delta\omega_r - k_{fr}\, f\_v_t\, \Delta i_{qs} - x_e\,\frac{v_{ds0}}{v_{t0}}\frac{1}{v_{t0}}\ k_{fr}\ \frac{p}{\omega_b}\ \Delta i_{ds} - x_e\,\frac{v_{qs0}}{v_{t0}} * \frac{1}{v_{t0}}\ k_{fr}\ \frac{p}{\omega_b}\ \Delta i_{qs} + 0.02\omega_b\,\frac{p}{\omega_b}\,\Delta x_1 + \Delta x_1 \quad (24)$$

second, analysis of the T.F for the block diagram of $\frac{\Delta x_2}{\Delta x_1}$:

$$\frac{p}{\omega_b}(\omega_b\,\Delta x_2) + 1.2251\,\Delta x_2 - \left(\frac{196}{0.00062}\right)\Delta x_1 = 0 \quad (25)$$

Third, analysis of the T.F for the block diagram of $\frac{\Delta v_{fr}}{\Delta x_2}$:

$$\frac{p}{\omega_b}(\omega_b\,\Delta v_{fr}) + 1316.517\,\Delta v_{fr} - \frac{p}{\omega_b}(0.62\,\omega_b\Delta x_2) - \Delta x_2 = 0 \quad (26)$$

From equations (10-14), (17,18), (24-26) respectively are equivalent to the matrix expression to analysis the state space at AVR and dynamic behaviour with damper winding and without damper winding after removing equations (12,13)

4. Modeling of AVR and PSS with synchronous generator

Deduction of the effect of the AVR system from (Fig.11 and Table 4) for SG without damper windings and (Fig.13 and Table 5) for SG with damper windings, AVR system weaken the damping process for SG with damper winding and make unstable dynamic behavior for SG without damper winding at sudden change in the electrical load. Therefore, there must be a system for power system stabilizer (PSS) to enhance the dynamic performance and transient stability for SG.

it is considered that effective system in synchronous generator because it observes the electromagnetic power and frequency of the generator and when any external fault is happened on the grid or sudden change in the loads ,it leads to swing the power of generator so the system (PSS) generates a stabilizing signal, which produces a torque damping component on the generator rotor and the created torque component must be in phase with speed deviation or produce the required power to support the grid when sudden change in the loads or external fault in the grid .

so, there is a lot of studies and researches about study and analysis the perfect components for PSS system and deducing the best values of PI controller.

in this part of paper discuss and analysis the effect of power system stabilizer (IEEE type PSS1A) on the dynamic performance of synchronous generator with and without damper winding.
PSS use the signal from electromagnetic power of synchronous generator as input as shown in Fig.5

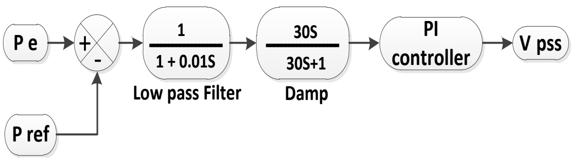


Fig 5. Block Diagram of PSS

PSS is a feedback controller which provides an additional signal to input of summing point with automatic voltage regulation (AVR) as shown in Fig.6

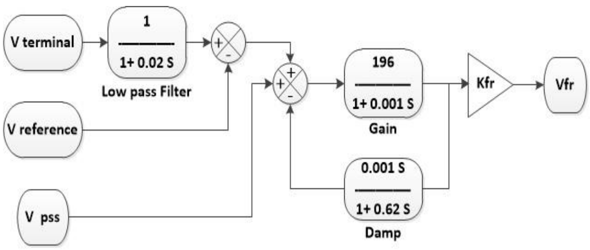


Fig 6. Block diagram of exciter system with PSS signal
In this paper, there are two methods to design PI controller for PSS by using Single Pole Placement and political optimizer method to get the perfect values for K_p , K_i to achieve the desirable dynamic performance for PSS and compensate the oscillation of system to make the behaviour of SG is more stable at the disturbance in the grid so:

The following steps describe the Single Pole Placement [28]:

1- get the T.F of $\frac{\Delta v_{pss}}{\Delta p_e}$ from the block diagram of PSS that shown in Fig (5).
2- get the T.F of $\frac{\Delta p_e}{\Delta v_{pss}}$ from the state space of synchronous generator with the signal of PSS and Δv_{pss} is selected as input, Δp_e is selected as output.
3- Equating the sides of the equation from above step1,2, Subsequently, Conclude an equation with one unknown variable (S).
4- assuming the best value of (S) that achieve the desirable dynamic performance of the rotor speed and electromagnetic torque and make sure the value of (S) is the same the eigen value of $(\Delta\omega_r , \Delta\theta_r)$.
5- deduce the pi controller parameter (K_p , K_i).

In the second method, the political optimizer [29] (PO) method by using MATLAB is used to design the PI parameters for PSS. The PO is considered one of the best recent optimizations techniques because it has a formidable execution on solving engineering optimization problems additional to complex multimodal functions. PO is inspired by human behaviours within the multi-stage political process.

PO follows a novel position updating strategy called recent past-based position updating strategy which is the mathematical modelling of the learning behaviours of the politicians from the previous election. And design the mathematical mapping of all the main steps of politics.
PO has proven [30] its superiority when compared with Whale Optimization Algorithm (WOA), Ant Lion Optimizer (ALO), Gray Wolf Optimizer (GWO), Moth Flame Optimization (MFO), Multi-Verse Optimizer (MVO), Sine-Cosine Algorithm (SCA)), and Slap Swarm Algorithm (SSA). through experiments that PO has an excellent convergence speed with good exploration capability in early iterations.
By using the m-file of PO:

1- assuming the upper and the lower limiter (0.001-100) for the possible values of (K_p , K_i).
2- Define Objective function equation the optimum damping ratio from required eigen value of $(\Delta\omega_r , \Delta\theta_r)$.

$$\lambda_{\omega_r,\theta_r} = \sigma \pm j\, \omega \quad (27)$$

$$\zeta = \sqrt{\frac{1}{1+(\frac{\omega}{\sigma})^2}} \quad (28)$$

Objective function equation (o) = $\frac{1}{\zeta}$

3- Define the number of iterations (100) and runs (15).

4- run m-file to get the best value for pi parameters to get the desired the eigen-value $(\Delta\omega_r, \Delta\theta_r)$ and make all parameters of SG to be stable.

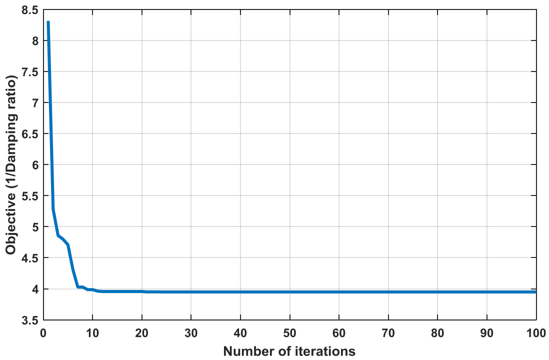


Fig 7.PO optimization for SG with damper winding

Table 1. the optimal values for PI parameters for SG with damper winding

	Single pole placement	Political optimizer
K_p	0.1095	0.1548
K_i	0.0014	0.001
$\lambda_{\omega_r,\theta_r}$	$-2.1982 \pm j11.199$	$-2.9559 \pm j11.29$
Damping ratio ζ	0.2138	0.2533

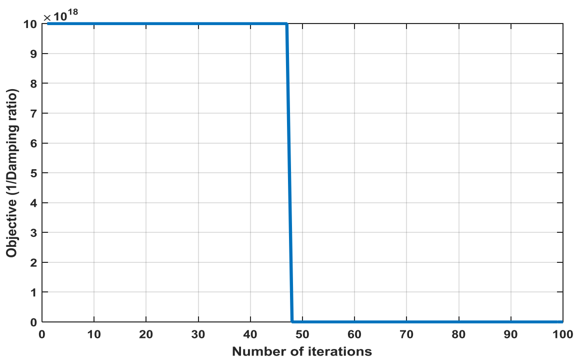


Fig 8.PO optimization for SG without damper winding

Table 2. the optimal values for PI parameters for SG without damper winding

	Single pole placement	Political optimizer
K_p	0.2459	0.2604
K_i	0.0061	0.0011
$\lambda_{\omega_r,\theta_r}$	$-2.1982 \pm j8.1425$	$-2.3484 \pm j8.373$
Damping ratio ζ	0.2527	0.27

From Table1, 2.the damping ratio is improved by using PO optimizer.

after getting the best PI parameter, Linearization PSS and AVR system at small changes from steady state, rewriting the block diagrams of PSS and AVR after simplifying the system at linearization process as shown in Fig.9.

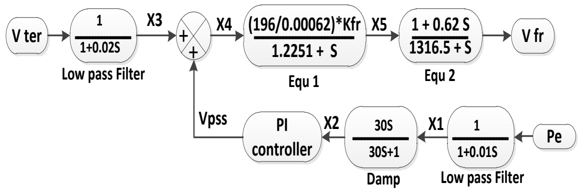


Fig 9. Block diagram after simplifying the exciter system with PSS system.

convert the equation of electromagnetic power to be per unit by dividing it to base power p_b

$$\frac{p_e}{p_b} = \frac{2}{P}\ \omega_r\ T_e\ \frac{1}{p_b} \quad (29)$$

at small changes for electromagnetic power at normal operation

$$\Delta p_e = \Delta i_{qs}\ a\_p_t + \Delta i_{ds}\ b\_p_t + \Delta i_{dr}\ c\_p_t + \Delta i_{qr}\ d\_p_t + \Delta i_{fr}\ e\_p_t + \Delta\omega_r\ f\_p_t \quad (30)$$

Where,

$$a\_p_t = \frac{2}{P}\ \frac{1}{p_b}\ c_t[\psi_{ds0} + x_{qs}\ i_{ds0}]\omega_{r0}$$

$$a\_p_t = \frac{2}{P}\ \frac{1}{p_b}\ c_t[\psi_{ds0} + x_{qs}\ i_{ds0}]\ \omega_{r0}$$

$$b\_p_t = \frac{-2}{P}\ \frac{1}{p_b}\ c_t[x_{ds}\ i_{qs0} + \psi_{qs0}]\ \omega_{r0}$$

$$c\_p_t = \frac{2}{P}\ \frac{1}{p_b}\ c_t\ x_{md}\ i_{qs0}\ \ \omega_{r0}$$

$$d\_p_t = \frac{-2}{P}\ \frac{1}{p_b}\ c_t\ x_{mq}\ i_{ds0}\ \omega_{r0}$$

$$e\_p_t = \frac{2}{P}\ \frac{1}{p_b}\ c_t\ x_{md}\ i_{qs0}\ \ \omega_{r0}$$

$$f\_p_t = \frac{2}{P}\ \frac{1}{p_b}\ T_{e0}$$

from Fig (9). first, analysis of the T.F for the block diagram of $\frac{\Delta x_1}{\Delta p_e}$ and substitute Δp_e from equation (30)

So, equation (31) will be:

$$-\frac{p}{\omega_b}(0.01\ \omega_b\ \Delta x_1) - \Delta x_1 + \Delta i_{qs}\ a\_p_t + \Delta i_{ds}\ b\_p_t + \Delta i_{dr}\ c\_p_t + \Delta i_{qr}\ d\_p_t + \Delta i_{fr}\ e\_p_t + \Delta\omega_r\ f\_p_t = 0 \quad (31)$$

second, analysis of the T.F for the block diagram of $\frac{\Delta v_{pss}}{\Delta x_1}$, the equation (32) will be:

$$\frac{p}{\omega_b}\left(30\ k_p\ \omega_b\ \Delta x_1\right) + 30\ k_i\ \Delta x_1 - \frac{p}{\omega_b}\left(30\ \omega_b\ \Delta v_{pss}\right) - \Delta v_{pss} = 0 \quad (32)$$

Third, analysis of the T.F for the block diagram of $\frac{\Delta x_5}{\Delta x_4}$, the equation (33) will be:

$$\frac{p}{\omega_b}(\omega_b \Delta x_5) + 1.2251\Delta x_5 - \left(\frac{196}{0.00062}\right) k_{fr}\Delta v_{pss} - \left(\frac{196}{0.00062}\right)k_{fr}\Delta x_3 = 0 \quad (33)$$

Fourth, analysis of the T.F for the block diagram of $\frac{\Delta v_{fr}}{\Delta x_5}$, the equation (34) will be:

$$\frac{p}{\omega_b}(\omega_b\ \Delta v_{fr}) + 1316.517\ \Delta v_{fr} - \frac{p}{\omega_b}(\ 0.62\ \omega_b\ \Delta x_5) - \Delta x_5 = 0 \quad (34)$$

fifth, analysis of the T.F for the block diagram of $\frac{\Delta x_3}{\Delta v_t}$ and substitute Δv_t from equation (22), the equation (35) will be:

$$a\_v_t\ \Delta\delta_b + b\_v_t\ \Delta v_b = -c\_v_t\ \Delta\theta_r - d\_v_t\ \Delta\omega_r - e\_v_t\ \Delta i_{ds} - f\_v_t\ \Delta i_{qs} - \frac{v_{ds0}}{v_{t0}}\frac{x_e}{v_{t0}}\frac{p}{\omega_b}\ \Delta i_{ds} - \frac{v_{qs0}}{v_{t0}}\frac{x_e}{v_{t0}}\frac{p}{\omega_b}\Delta i_{qs} + \frac{p}{\omega_b}\ 0.02\ \omega_b\Delta x_3 + \Delta x_3 = 0 \quad (35)$$

From previous equations (10-14), (17-18), (31-35) respectively are equivalent to the matrix expression to analysis the dynamic behaviour for SG with damper winding and without damper winding after removing equations (12,13) and conclude the eigen values of deviation of rotor angle, rotating speed and the step response for T.F $\frac{\Delta\omega_r}{\Delta T_l}$ and $\frac{\Delta T_e}{\Delta T_l}$ at disturbance of electromagnetic load in the electric grid.

1- Get the state space of synchronous machine with exciter system (AVR and PSS) to get state and input matrices so Δv_b , $\Delta\delta_b$, ΔT_l are selected as input

$$\Delta\dot{x} = A * \Delta x + B * \Delta u$$

Δx : $(state\ vector)$, Δu : $(control\ vector)$

2- it is necessary to identify the desired output by forming the measurement equation:

$$y = C\ \Delta x + D\ \Delta u$$

$D = 0$, C: output matrix

let the change in rotor speed $\Delta\omega_r$, the change in electromagnetic torque ΔT_e are selected as output

5. Results and Effect of Disturbance Load on SG

In this part, discuss the results of eigen values and state space for T.F $\frac{\Delta\omega_r}{\Delta T_l}$ and $\frac{\Delta T_e}{\Delta T_l}$ of SG without and with damper winding at disturbance of electromagnetic power at sudden change in load of generated power 100 MW in the electric grid using a parameter of SG (555 MVA) [2] as shown in Table.3.

Table 3. synchronous generator parameter (555 MVA)

parameter	value
r_s	0.0031 Ω
r_{fr}	0.0715 Ω
r_{dr}	0.02947Ω
r_{qr}	0.006424Ω
l_{ls}	0.4129 *10^{-3} H
l_{ldr}	0.4716 *10^{-3} H
l_{lqr}	1.9964 *10^{-3} H
l_{md}	4.5696 *10^{-3} H
l_{mq}	4.432 *10^{-3} H
p_b	499.5 *10^{6} $watt$
P	2 pole
J	27547.8 N.m^2
v_{ll}	24000 volt
F	50 HZ

5.1. Eigen values and step responses for SG without damper winding

It is necessary to get the eigen values of $(\Delta\omega_r, \Delta\theta_r)$ to study the dynamic performance of (damping ratio ζ and frequency of damping ω_d) of SG at constant field voltage, AVR system and AVR & PSS system from state matrix of previous equations of SG without equation (12,13) of damper winding and by using MATLAB

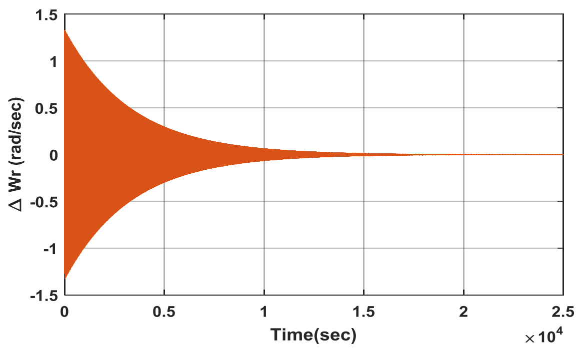
Table 4. Eigen value of rotor angle and speed of SG without damper winding

System of Field voltage	Eigen value of $\Delta\omega_r$, $\Delta\theta_r$	Status
Constant field voltage	$-0.0003 \pm j8.6441$ $\omega_d = 1.3758\ HZ$ $\zeta = 3.4706 * 10^{-5}$	stable
AVR system	$+0.189 \pm j8.632$	unstable
AVR & PSS system	$-2.3484 \pm j8.373$ $\omega_d = 1.332\ HZ$ $\zeta = \ 0.27$	Stable

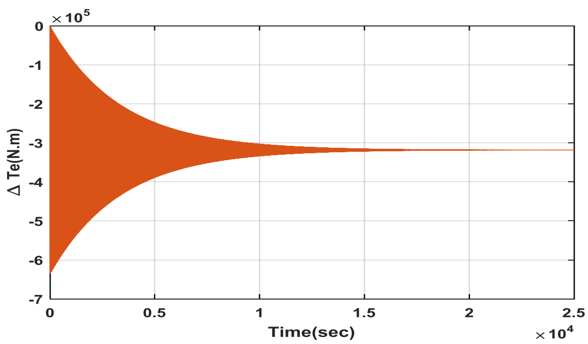
From Table.4 At SG without damper winding, the damping ratio is increased from $3.4706 * 10^{-5}$ at constant field voltage to 0.27 at PSS system and it got worse at AVR.

So, the great effect of adding PSS system to AVR because it reinforces the damping and make transient stability in the generated electromagnetic power.

As show in Fig.10, the rotor speed and electromagnetic torque of SG is stable after 20000 second but this time is too long to make the dynamic behaviours of electric grid to be critical stable



(a)



(b)

Fig 10. the analysis of rotor speed and electromagnetic torque at disturbance on the generator without damper at constant field voltage

After adding AVR system, SG became unstable as shown in fig (*11*)

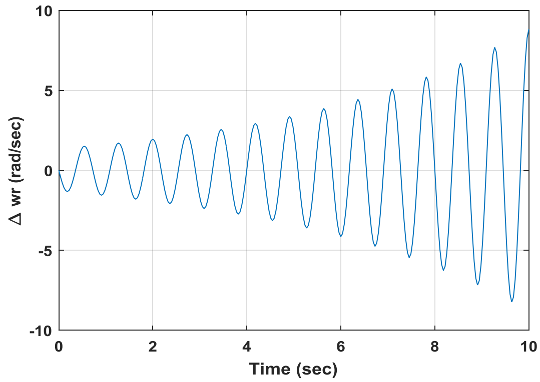
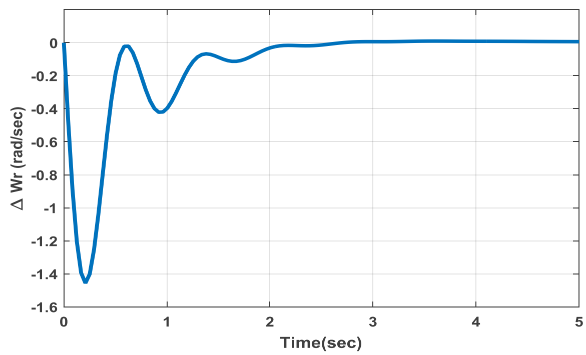
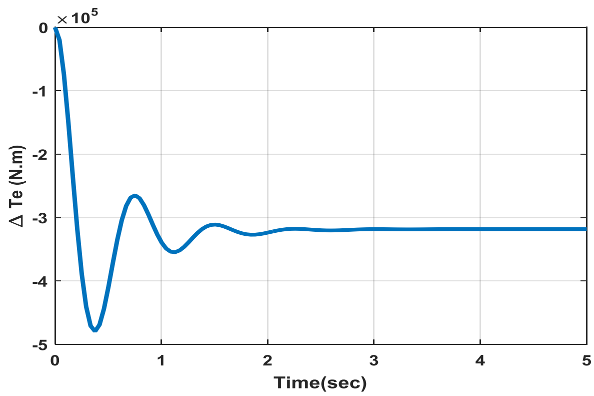


Fig 11. the analysis of rotor speed at disturbance on the generator without damper at AVR system

with PSS system and the new parameters of pi controller, SG became more stable after 2 second as shown in Fig.12.



(a)



(b)

Fig 12. the analysis of rotor speed and electromagnetic torque at disturbance on the generator without damper at PSS system.

5.2. Eigen values and step responses for SG with damper winding

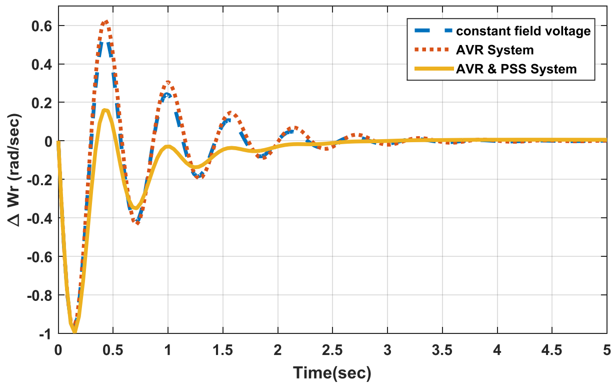
In this part, discuss the important of damper winding because it help SG to damp a small fraction of oscillations with using PSS system in SG

Table 5. Eigen value of rotor angle and speed of SG with damper winding

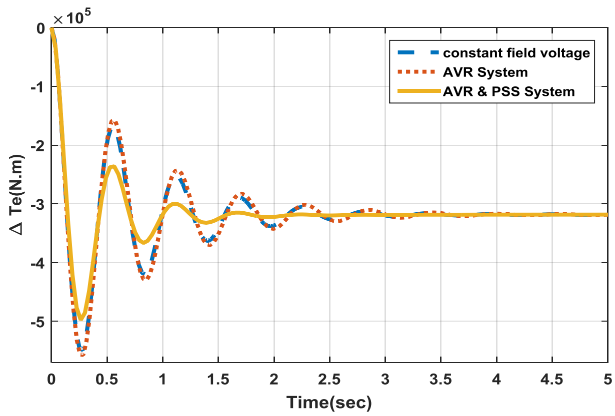
System of Field voltage	Eigen value of $\Delta\omega_r$, $\Delta\theta_r$	Status
Constant field voltage	$-1.4491 \pm j11.092$ $\omega_d = 1.7654\ HZ$ $\zeta = 0.1295$	stable
AVR system	$-1.328\ \pm j10.962$ $\omega_d = 1.7446HZ$ $\zeta =\ 0.1203$	stable
AVR & PSS system	$-2.9559 \pm j11.29$ $\omega_d = 1.797\ HZ$ $\zeta =\ 0.2533$	Stable

From Table.5. At SG with damper windings, the damping ratio is decreased from 0.1295 at constant field voltage to 0.1203 at AVR system and increased to 0.2533 at PSS system

So, the damper winding and PSS system play an important role to damp the oscillations in the electrical grid. As shown in Fig .13.



(a)



(b)

Fig 13. the analysis of rotor speed and electromagnetic torque at disturbance on the generator with damper winding at constant field voltage ,AVR and AVR&PSS.

From Fig.13. the damping weakened by AVR and improved after using PSS and SG became more stable.

6. Conclusions

Based on the points described previously ,the analysis the effect of exciter system and the step response results and eigen values it is possible to conclude that:

- The damper winding in SG helps PSS system to damp the oscillations (12.03%-25.33%) and enhance the dynamic performance.
- The excitation system (AVR) decreases the damping ratio and make the synchronous generator without damper winding to be unstable.
- The electromagnetic of the generated power from SG is used as the best input signal to PSS to supply affirmative influence for the damping and control the passive damping of AVR.
- From the simulation results, PSS can treatment the instability problem during oscillations for SG without damper winding and This will be economical in terms of raw materials used in the manufacture of synchronous generators.

7. List of symbols

f	frequency (50 HZ)
l_{ls}	portion of the leakage inductance which in stator
l_{ldr}	portion of the leakage inductance which in rotor of d-axis
l_{lqr}	portion of the leakage inductance which in rotor of q-axis
l_{lfr}	portion of the leakage inductance which in field of the rotor
l_{md}	portion of the mutual inductance in d-axis
l_{mq}	portion of the mutual inductance in q-axis
r_s	stator resistance
r_{fr}	field resistance
r_{dr}	rotor resistance of d-axis
r_{qr}	rotor resistance of q-axis
P	number of poles
ω_r	rotating speed
θ_r	rotor angle

ω_b	base electromagnetic angular velocity
p	differentiation for time $\frac{d}{dt}$
T_e	electromagnetic torque
T_l	mechanical torque
J	moment of inertia
r_e	resistance of line
l_e	inductance of line
v_b	infinite bus voltage amplitude
θ_b	Infinite bus phase
i_{ds}	d-axis stator current
i_{qs}	q-axis stator current
i_{dr}	d-axis rotor current of damper winding
i_{qr}	q-axis rotor current of damper winding
i_{fr}	current of field winding
v_{ds}	d-axis stator voltage
v_{qs}	q-axis stator voltage
v_{dr}	d-axis rotor voltage of damper winding
v_{qr}	q-axis rotor voltage of damper winding
v_{fr}	voltage of field winding
v_t	terminal voltage (peak – phase)
I_t	terminal current (peak – phase)
ϕ	Power factor angle
δ	Load angle
p_b	base power
p_e	electromagnetic power
PSS	Power system stabilizer
AVR	automatic voltage regulation
k_p	Proportional coefficient, PI controller
k_i	Integral coefficient, PI controller
ω_d	Frequency of damping
λ	Eigen Value

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