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SSSC Modeling and Damping Controller Design for Damping Low Frequency Oscillations

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ABSTRACT: This paper demonstrates the mathematical model of SMIB power system equipped with FACTS type SSSC based controller. A heuristic optimization approach is employed to determine the optimal parameters of SSSC based damping controller. Stability improvement of power system is the design objective of the system, when subjected to a severe disturbance, by damping the electromechanical mode of oscillations. PSO algorithm is used to compute the global best solution to the given different fitness functions. Eigenvalues and time-domain simulation are shown under different operating conditions, to validate the robustness and effectiveness of the proposed approach.

KEYWODS: SMIB, FACTS, SSSC,POD, PSO.

I. INTRODUCTION

One of the challenges that has arisen in recent years is getting electrical energy characterized by stability and reliability. On other hand, continuous growing of loads, sudden short circuit, in addition to unexpected faults in power system operation represent obstacles to achieve safe operation of electrical power system [1, 4]. Utilization of power electronics in electrical power system that called Flexible Alternating Current Transmission System (FACTS), were one of successful solutions, contributed in operating the power system under safe and reliable conditions, taking into account the governmental and environmental constraints [2, 3].
Gyugyi, L., Schauder, C.D and Sen, KK. led an initiative work with a proposal of the Static Synchronous Series Compensator (SSSC) or series STATCOM. SSSC is a solid-state voltage source inverter usually connected in series with the transmission lines. SSSC generates a controllable AC voltage source in quadrature with line current and simulates an inductive or capacitive line reactance, to control power flow in the transmission lines. A feature to operate the system at inductive and/or capacitive mode by controlling of transmission line reactance, through virtual compensation of line reactance, resulting in power flow control and stability enhancement of power system. Power system oscillations can be improved, by controlling the virtual compensation degree of transmission line reactance, usually by employing an auxiliary control signals. These signals can be modulated through SSSC damping controller to inject the controlled voltage (V_q) to get on the desired performance [2, 3, 5].
In recent years, heuristic techniques have been widely used to compute the optimal tuning parameters of chosen controller. These techniques featured by flexibility and ability to achieve close optimal results. SMIB is chosen as case study to investigate the capability of SSSC to achieve a robust stabilizing function, through adding supplementary controller to SSSC and, then Particle Swarm Optimization (PSO) techniques is used to determine the optimal parameters of supplementary controller. [5, 6]

II. POWER SYSTEM MODEL

Figure (1), represents the construction of Single Machine Infinite Bus (SMIB) equipped with Static Synchronous Series Compensator (SSSC). It includes series coupling transformer, Voltage Source Converter (VSC) and DC capacitor. The VSC controlled by modulation index (m) and phase angle (ψ) to provide a desired series voltage.

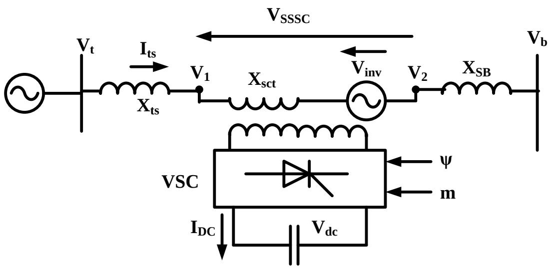

Fig.1: SMIB Power System Equipped With SSSC.

Equations (1-5) illustrates the simplified mathematical model of SMIB plus SSSC as following:

$$\dot{\delta} = \omega - \omega_s \quad (1)$$

$$\dot{\omega} = \frac{1}{2H}\left[P_m - P_e - D(\omega - \omega_b)\right] \quad (2)$$

$$\dot{\acute{E}}_q = \frac{1}{\acute{T}_{do}}\left[E_{fd} - (x_d - \acute{x}_d)I_d - \acute{E}_q\right] \quad (3)$$

$$\dot{E}_{fd} = \frac{1}{T_A}\left[-E_{fd} + K_A\left(V_{ref} - V_T + V_S\right)\right] \quad (4)$$

$$\dot{V}_{dc} = \frac{I_{DC}}{C_{dc}} = \frac{mK}{C_{dc}}\left(I_{tsd}\cos\psi + I_{tsq}\sin\psi\right) \quad (5)$$

Equations (6, 7) represent state space model of system.

$$[\Delta\dot{X}] = [A][\Delta X] + [B][\Delta U] \quad (6)$$

Where:

$$[\Delta X] = \left[\Delta\delta \quad \Delta\omega \quad \Delta\acute{E}_q \quad \Delta E_{fd} \quad V_{dc}\right]^T$$

$$[\Delta U] = [\Delta m \quad \Delta\psi]^T \quad (7)$$

Where

$$[A] = \begin{bmatrix} 0 & \omega_s & 0 & 0 & 0 \\ \frac{-K_1}{M} & \frac{-D}{M} & \frac{-K_2}{M} & 0 & \frac{-K_{Pdc}}{M} \\ \frac{-K_4}{\acute{T}_{do}} & 0 & \frac{-K_3}{\acute{T}_{do}} & \frac{1}{\acute{T}_{do}} & \frac{-K_{qdc}}{\acute{T}_{do}} \\ \frac{-K_A K_5}{T_A} & 0 & \frac{-K_A K_6}{T_A} & \frac{-1}{T_A} & \frac{-K_A K_{Vdc}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix}, [B] = \begin{bmatrix} 0 & 0 \\ \frac{-K_{Pm}}{M} & \frac{-K_{P\psi}}{M} \\ \frac{-K_{qm}}{\acute{T}_{do}} & \frac{-K_{q\psi}}{\acute{T}_{do}} \\ \frac{-K_A K_{Vm}}{T_A} & \frac{-K_A K_{V\psi}}{T_A} \\ K_{dm} & K_{d\psi} \end{bmatrix}$$

The K- factors computed when the system operates in normal situation.

III. SSSC SUPPLEMENTARY CONTROLLER

Lead-lag supplementary controller has been widely used for damping the power system oscillations as shown in Figure (2).

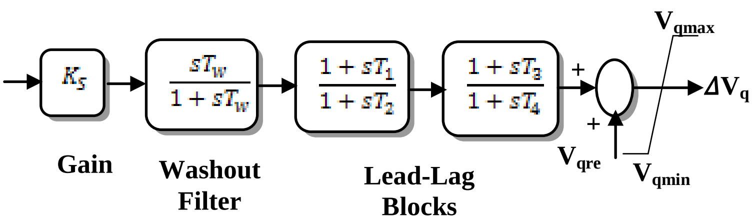

Fig.2: SSSC Based Stabilizing Controller Structure.

SSSC based stabilizing controller is chosen to modulate the injected voltage of SSSC (V_q). Simple structure, ease of parameters tuning; in addition to, lack of assurance of the stability by some variable structure and adaptive techniques, are main features made the lead-lag controller preferred choice by power system utilities. The SSSC damping controller (POD)

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constructed of sequential blocks, such as gain block with gain K_s, a washout block, in addition to two-phase compensation blocks. The washout block works as high pass filter to prevent passing the offset signal to output with time constant T_w. While the phase compensation blocks with time constants (T_1-T_4) provide the desired phase-led component to compensate the difference between input and output selected signals. In Figure (2) $V_{q\text{-}ref}$ represents the desired injected voltage which has computed at steady state flow of power system. $V_{q\text{-}ref}$ is assumed constant during the system under disturbed period and the required compensation is obtained according to change of injected voltage (ΔV_q) of SSSC. The transfer function of SSSC damping controller (POD) controller is :

$$u_{SSSC} = K_s\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)y \quad (8)$$

IV. OPTIMIZATION PROBLEM

The scope of this paper concentrates on enhancement of transient performance of power system post the disturbance, by using SSSC based stabilizing controller, through minimizing the system oscillations. To achieve this goal different objective functions (f_1, f_2) have chosen as following:

$$f_1 = maximize\left(\sigma \Big/ \sqrt{\sigma^2+\omega^2} \right) \quad (9)$$

And

$$f_2 = minimize\left(\int_{t=0}^{t=t_1} |\Delta\omega| .t\right) \quad (10)$$

Equation (9) improves the power system performance through increasing the damping ratio of electromechanical mode of oscillations while Equation (10) achieves the same aim through decreasing the speed deviation oscillations during the disturbance. Design problem can be formulated as:

Optimize f_1 and f_2 subject to:

$$K_s^{min} \le K_s \le K_s^{max}$$
$$T_1^{min} \le T_1 \le T_1^{max}$$
$$T_2^{min} \le T_2 \le T_2^{max}$$
$$T_3^{min} \le T_3 \le T_3^{max}$$
$$T_4^{min} \le T_4 \le T_4^{max}$$

PSO algorithm considers one of common heuristic techniques used to compute the optimal solutions for different engineering applications. Ability to handle with complex problems, easy coding and the time required to determine the best solutions are less than other computing techniques, reinforces the potential effectiveness of PSO in optimization problems.

The main idea of this algorithm is inspired from birds' behavior to search for food. It begins with random population represent the initial population that called particles. These particles employs in every iteration to generate new population have a feature better than last generation. Each particle is denoted by $X_i = (x_{1i}, x_{2i} \ldots x_{ni})$ and keeps track of its own coordinates in multi-dimensional space to achieve the best optimistic solution. The fittest local solution for any particle i is denoted by $P_{best}$and arranged as $P_i = (P_1, P_2 \ldots P_{in})$. The algorithm improves its performance in computing the optimal solution by tracking the global best solution (P_{gbest}) and its position or any member in population. The flow chart shown in Figure (3) shows the sequential steps of PSO to determine the best solution. Equations (11) and (12) used to update the performance of PSO algorithm [6, 7].

$$v_i^{new} = wv_i^{old} + c_1 r_1 * \left(P_i^{Local\ best} - P_i^{old}\right) + c_2 r_2 . (P_i^{global\ best} - P_i^{old}) \quad (11)$$

$$P_i^{new} = P_i^{old} + v_i^{new} \quad (12)$$

Where: c, r are learning factor and independent random uniform numbers respectively, PSO iterates many times to compute the optimal tuning of SSSC based stabilizing controller parameters. The best solution of SSSC based stabilizing controller parameters tabulated in Table (1).

Table 1: SSSC stabilizing controller parameters.

Parameters	f_1	f_2
K_s	40	100
T_1	1.5	1.4822
T_2	0.3809	0.7255
T_3	---	1.1535
T_4	---	0.9894
Fitness	0.6795	0.0032

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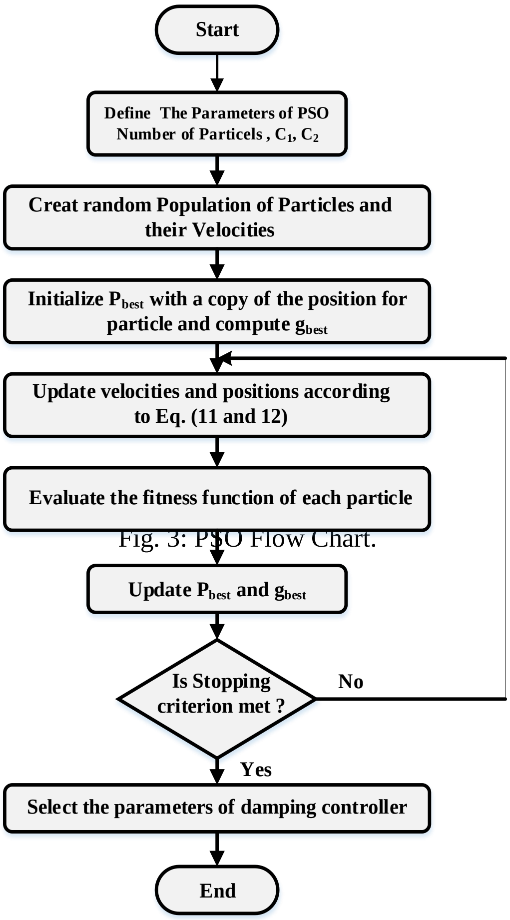

Fig. 3: PSO Flow Chart.

V. SIMULATION RESULTS

To determine the optimal parameters of SSSC supplementary controller, as well as evaluates its performance, the mathematical model of SMIB power system equipped with SSSC based stabilizing controller, is developed as explained previously.

Linear state-space model is represented by equations (6-7). In the present study, PSO is employed to search for optimal tuning parameters of damping controller so as, to maximize the first objective function (f_1) and minimize the second objective function (f_2). While applying the PSO algorithm first objective function is evaluated through state-space model and the second objective function assessed by simulating the power system model under study. Figures (4, 5) illustrates the graphs of optimal objective functions against number of generations.

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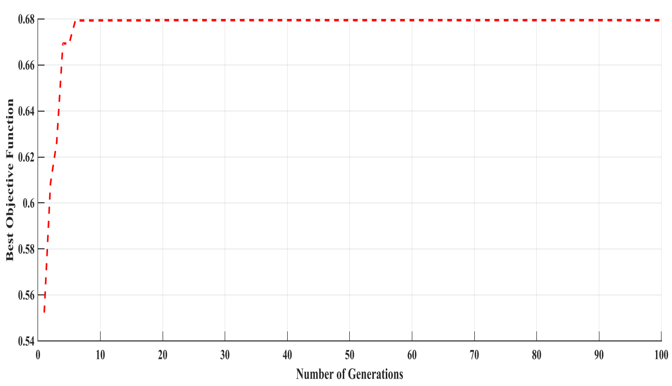

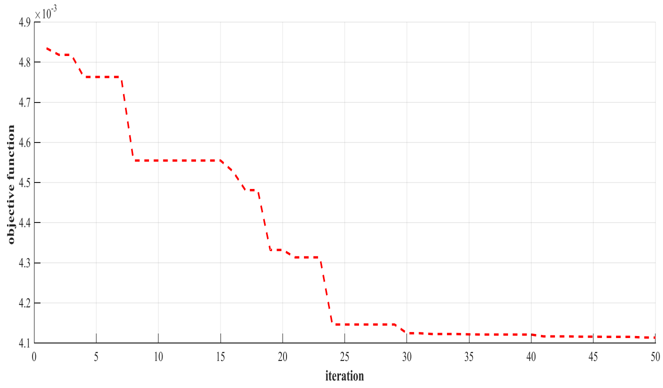

Fig. 4: Objective Function Graph (f_1).Fig. 5: Objective Function Graph (f_2).

Table 2: Eigenvalues analysis of power system at different loading condition.

Loading	***Normal Load***		***Heavy Load***		***Light Load***	
W.C	***Eigenvalues***	***D. Ratio***	***Eigenvalues***	***D. Ratio***	***Eigenvalues***	***D. Ratio***
	0.0145 ± j8.0002 -98.8055;-1.5996**;** -0.0014	-0.0018	**0.0230 ±j8.3704**; -98.8072;-1.6198; 0.0011	-0.0027	**-0.0032 ± j7.1503** -98.7700;-1.5950; -0.0011	0.0004
POD(m)	***Eigenvalues***	***D. Ratio***	***Eigenvalues***	***D. Ratio***	***Eigenvalues***	***D. Ratio***
	-8.0240 ± j11.7427 -98.7990**;** -1.6239 -3.2651 ± j2.3765 -0.1004**;** -0.0014;-10.0000	0.5642	**-7.7194 ±j12.0483** -98.7986; -1.6524; -3.5582 ± j2.2135; -0.1003; 0.0011;-10.0000	0.5395	**-8.5523 ± j10.5534** -98.7689; 1.5985; -0.1004; -0.0011; -2.7622 ± j2.6127 -10.0000;	0.6296

Effectiveness of the proposed optimized SSSC damping controller performance and the design approach verified through: (I) eigenvalues analysis. (II) Time domain simulation, assuming a three-phase short circuit at bus 1, at t=1 sec. Table (2) shows the eigenvalues and damping ratio of power system pre, and after implementing the proposed controller under different operating conditions. The power system at normal and heavy load was unstable, since their eigenvalues have positive real parts, and poorly damped at light load. Once the proposed optimized controller inserted, the system became more stable, and damping ratios increased to 0.5642, 0.5395 and 0.6296. Proposed controller tested at severe disturbance, when the system subjected to a sudden three-phase short circuit at bus (1). Figures (6-9), shows rotor angle, rotor speed, electrical power and control signal at normal loading, without, with proposed damping controller based J_1 and damping controller based J_2. It is obvious, the system without controller is unstable, but when the optimized controller implemented, the system performance greatly improved which reflected on system fluctuation that diminished to a single swing cycle after removing the fault.

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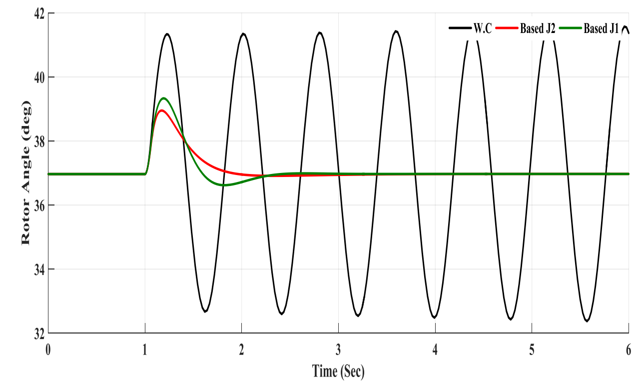

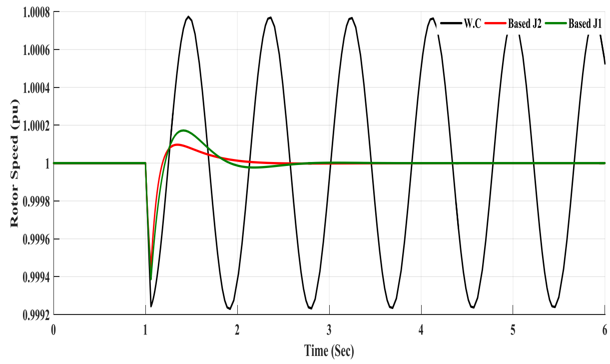

Fig. 6: Rotor Angle at Normal Condition. Fig. 7: Rotor Speed at Normal Condition.

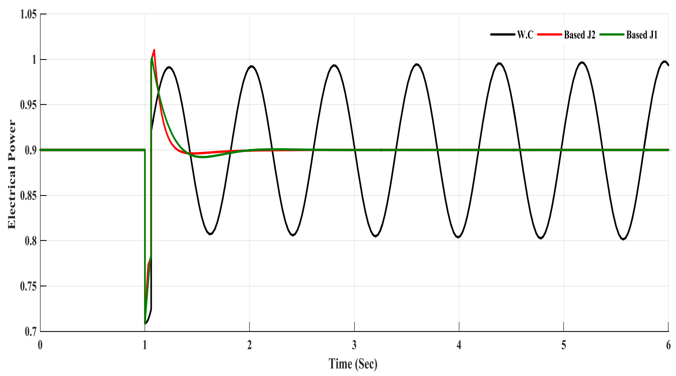

Fig. 8: Electrical Power at Normal Condition.

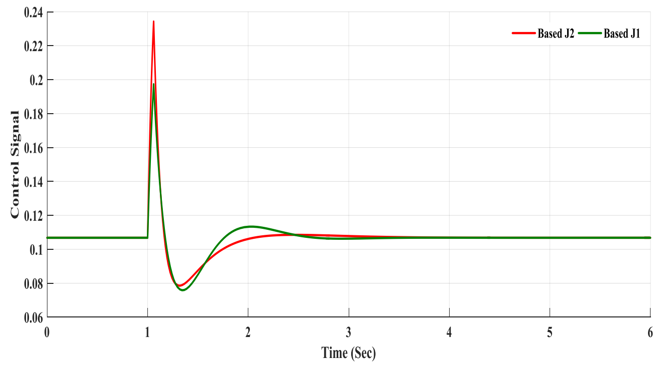

Fig. 9: Control Signal at Normal Condition.

Also, under heavy load the system is unstable. Figures (10-13) shows rotor angle, rotor speed, electrical power and control signal, respectively. However, once the optimized controller has implemented, the system performance greatly improved.

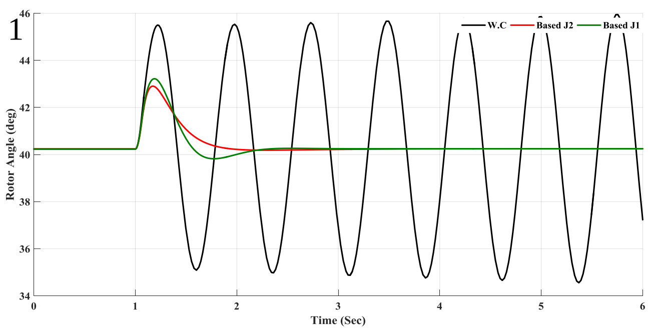

Fig. 10: Rotor Angle at Heavy Condition.

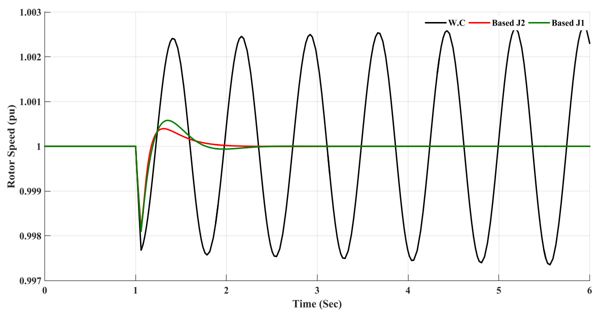

Fig. 11: Rotor Speed at Heavy Condition.

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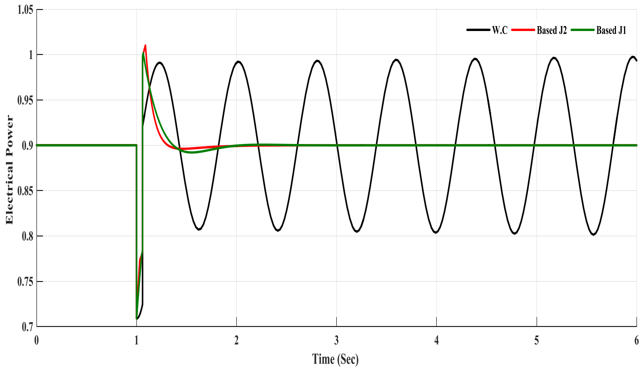


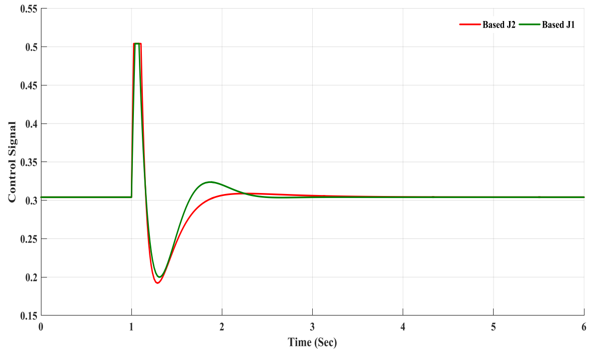
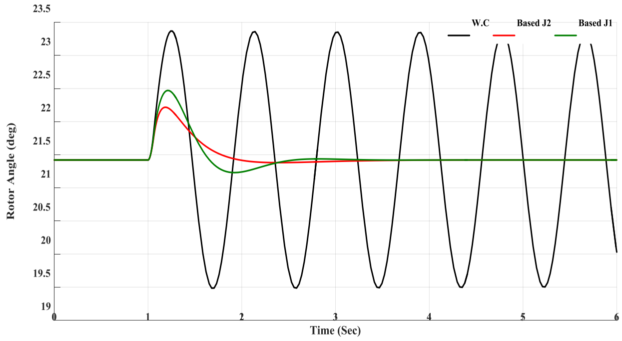


Fig. 12: Electrical Power at Heavy Condition. Fig. 13: Control Signal at Heavy Condition.

At light load the system became oscillatory. Figures (14-17), shows rotor angle, rotor speed, electrical power and control signal responses, at light loading. System without controller is oscillatory, when proposed controller inserted the system became more stable.



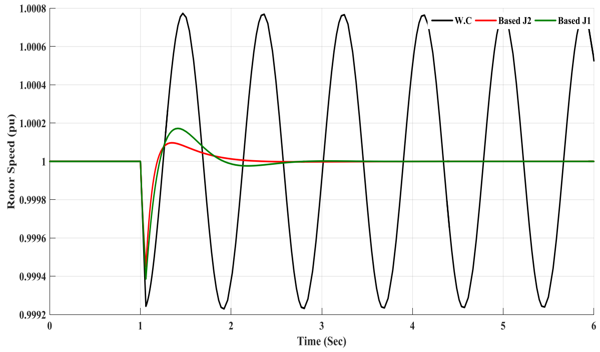
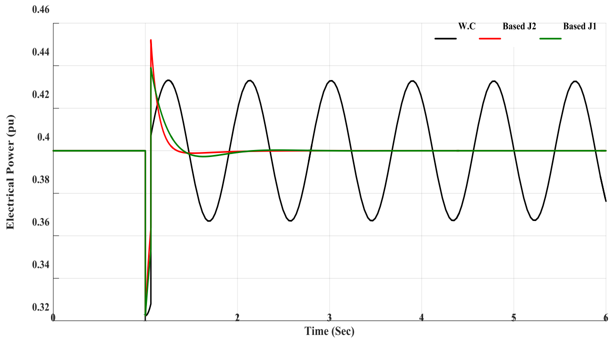


Fig. 14: Rotor Angle at Light Condition. Fig. 15: Rotor Speed at Light Condition.



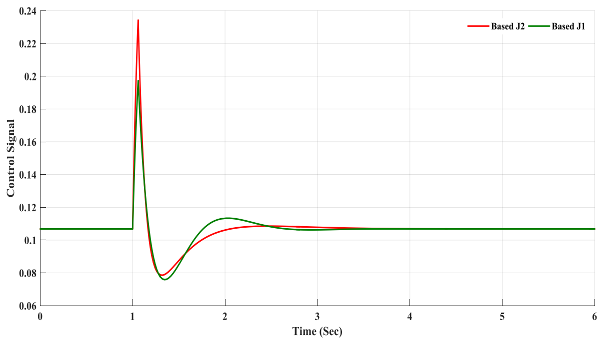


Fig. 16: Electrical Power at Light Condition. Fig. 17: Control Signal at Light Condition.

IV.CONCLUSION

This paper, developed optimistic solutions to design a SSSC based stabilizing controller. The design objective formula is a minimization of system oscillations through two objective functions: maximization of damping ratio and minimization the speed deviation oscillations. The design problem formulated taking into account constraints of parameters, time-domain based and single optimization problem. PSO based solution technique is successfully used to determine optimal tuning of parameters. Eigenvalues of system at different load conditions and time-domain simulation of system when subjected to sudden short circuit, is then, carried out. The proposed controller design based on the optimization problem (f_1) consider a preferred solution due to the lowest design cost.

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APPENDIX

SMIB Power System Parameters are:
Machine: x_d=1.0, x_q=0.6, x_d'=0.3, H=3.0 s, f=50Hz, T'_{do}=5.044 s, V_t=1.0, E_b=1.0, P_e=0.9, Q_e=0.1958.
Transmission line: x_{sb}=0.25, x_{ts}=0.15, R_e=0.0.
SSSC: x_{sct}=0.1. C_{dc}=1.0, V_{dc}=0.5, K=3/4, T_c=0.05 s,
Exciter: K_A=10, T_A=0.05s

AUTHOR'S BIOGRAPHY

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