Analysis and Mitigation of Sub-Synchronous Resonance in Power System with SVC and Using BFO Based Optimal Controller

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Abstract: *In this paper, BFO based optimal controller has been applied for damping sub synchronous resonance and torsional modes in a series compensated power system network. The study has been carried out on IEEE first benchmark model. Static var system (SVS) has been considered to be connected at the midpoint of a long transmission line. Optimal controller uses all the system states as feedback to stabilize the outputs. Eigen value analysis using a linearized system model has been carried out on the test system for improving the system stability and damping of sub-synchronous oscillations. In this paper the effectiveness of the optimal controller and optimal plus BFOA is investigated and compared, for damping of the electromechanical torsional oscillations in a given series compensated power system. The effectiveness of the proposed damping scheme is demonstrated by using time-domain approach based on dynamic response.*

Keywords: *Static var system (SVS), Bacteria Foraging Optimization Algorithm (BFOA), Sub Synchronous Resonance (SSR).*

I. INTRODUCTION

The application of series capacitors for long distance power transmission line helps in improving power transfer and is economical compared to addition of new lines. Series capacitors are used extensively in Western USA. and Sweden. But now it is widely used in India also. Series compensated lines having capacitance C have a tendency to produce series resonance at frequencies lower than power frequencies. This is called sub-synchronous resonance. BHEL pioneered the introduction of series compensation scheme for transmission line in India by setting up 220kV series compensated station at Kozhikode on Idduki-kozhikode line of KSEB, Kerala in May 1984.The results achieved by the series capacitor installations set up by BHEL in India have been satisfactory. Then, Udhampur-Pampur line at 132kV with 60% compensation in Jammu & Kashmir in 1988, Bina-Gwalior, double circuit line (240Km) at 220kV with 36% compensation in Madhya Pradesh (1990) and Karad-Miraj Line at 220kV with 70% compensation in Maharashtra are commissioned. The need of increasing generation capacity can be reduced to some extent by well-planned transmission and distribution network. The first SSR problem was experienced in 1970 resulting in the failure of a turbine–generator shaft at the Mohave plant in Southern California. It was not until a second shaft failure occurred in 1971 that the real cause of the failure was recognized as sub-synchronous resonance [1]. Systems that experience SSR exhibit dynamic oscillations at frequencies below the normal system base frequency [2]. There are many ways in which the system and the generator may interact with sub synchronous effects. A few of these interactions are basic in concept and have been given special names [1]: Induction Generator Effect, Torsional Interaction Effect, and Transient Torque Effect. The various counter measures for SSR [3] available in the literature are as follows: New lines instead of reactive series compensation, appropriate degree of reactive series compensation, Meshed system, SSR relay bypasses series compensation or trips generator, NGH scheme – resistor across series compensation, Damping controllers, Thyristor Controlled Series Capacitor, HVDC. John W. Balance [4] presented the concept of sub-synchronous resonance in series compensated transmission lines. Contributions of synchronous generator rotor motion and induction generation to sustained sub-synchronous oscillation are discussed. Theoretical explanations have been shown to correlate very closely with actual system observations and computer simulation studies. K.R. Padiyar et.al[3] presented the general structure of a circuit model of a slip ring machine. D.N. Walker, et.al [5] was the first fundamental paper presented on SSR. A.Fouad et.al [6] used the Eigen value method in analysis of SSR of the generator connected to an infinite bus via series capacitor-compensated transmission lines. The analysis is applied to a “bench mark” model proposed by the special IEEE Power Engineering Society Task Force on Sub-synchronous Resonance. Complete detailed representation of the electromechanical system has confirmed the existence of (n-1) modes, where n is the number of lumped masses of the shaft, as well as the existence of super- and sub-synchronous components in the electrical network. S.K.Gupta et. al [7] have given an idea for damping SSR in power systems using a double-order SVS auxiliary controller in combination with continuous controlled series compensation (CCSC) and an induction machine damping unit (IMDU) coupled with the T-G shaft. A linearized dynamic, model of continuous controlled series compensation has been derived and incorporated. Adi Soeprijanto et.al [8] proposed a new optimization method for the sub-synchronous resonance problems appeared due to resonance between the turbine and the series capacitor on transmission line and is damped by installing superconducting magnetic energy storage (SMES) unit where the parameters are optimized by quantum behaved particle swarm optimization (QPSO). Damping effect has been demonstrated. Dipendra Rai et al [9] provides the series capacitive compensation concept investigated for damping sub-synchronous resonance oscillations using a static synchronous series compensator (SSSC)-based hybrid series-capacitive compensation scheme. Raman kumar & S.K. Gupta [10] applied the optimal control theory for the analysis and mitigation of sub-synchronous resonance in a series compensated network. The analysis is applied to the first benchmark model proposed by special IEEE Power Engineering Society task force on sub-synchronous resonance. Mikel De Prada et al [11] in his paper adopted the IEEE first benchmark model (IEEE-FBM) for SSR studies and modified with an aggregated Type-2 WPP model connected to the system. A damping control algorithm based on adjusting the average value of the external rotor resistance via the control its chopper’s duty cycle is presented and implemented using PSCAD/ EMTDC software.

II. SYSTEM DESCRIPTION

The system under study consists of a generating station supplying bulk power to a large power system over a long distance transmission line. The series compensation is applied at the sending end and receiving end. The IEEE type-1 excitation is used. The power transfer capability of the system is optimal for the SVS to be located at the electrical center of the transmission line. The generating station is represented by an equivalent synchronous generator and the large power system is represented as an infinite bus. The single line diagram of the study system is shown in figure 1.The SVS is assumed to be of fixed capacitor thyristor controlled reactor type configuration and is connected to transmission network through a coupling transformer.

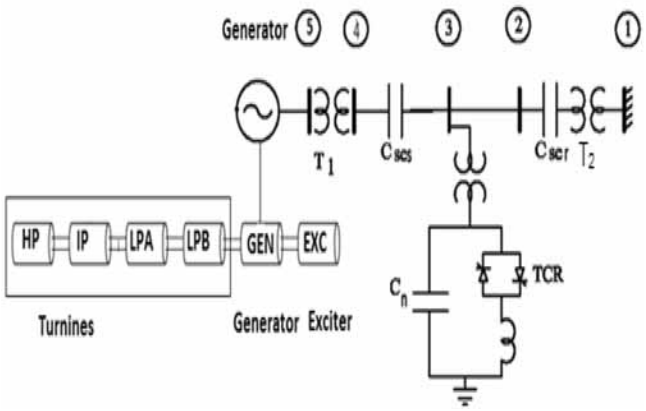

Fig. 1: Study System (IEEE first benchmark model)

With the help of the above diagram the state space model of overall system is obtained in [13], which is as follows:

The system matrix [A] is given by : .

$\Delta X=[A]X+[B]\Delta V_{ref}$

Where $X= [X_R \; X_M \; X_E \; X_N \; X_S]$

and

$B=[0\ 0\ 0\ 0\ B_{S2}]^t$

III. OPTIMAL CONTROLLER

If input vector U is the feedback of all system states U = -KX, Where K is feedback matrix. The performance Index (PI) is defined as follow:

$PI=\frac{1}{2} \int_{\downarrow} 0^{\uparrow} 00 \quad (X^{\tau' T} \; \mathbf{B} \; QX' + U'^{T} RU') \, dt$

where Q = Symmetric matrix used as performance measure. The ith entry of Q represents the weight, the designer places the constraints on the state variable. R=KI=Symmetric matrix, the ith entry of R represents the weight on the constraints on the control input. By giving sufficient weight to the control terms the amplitude of the control signals may be kept within the practical bounds. Feedback matrix (K) is obtained using reduced order Riccati matrix equation:

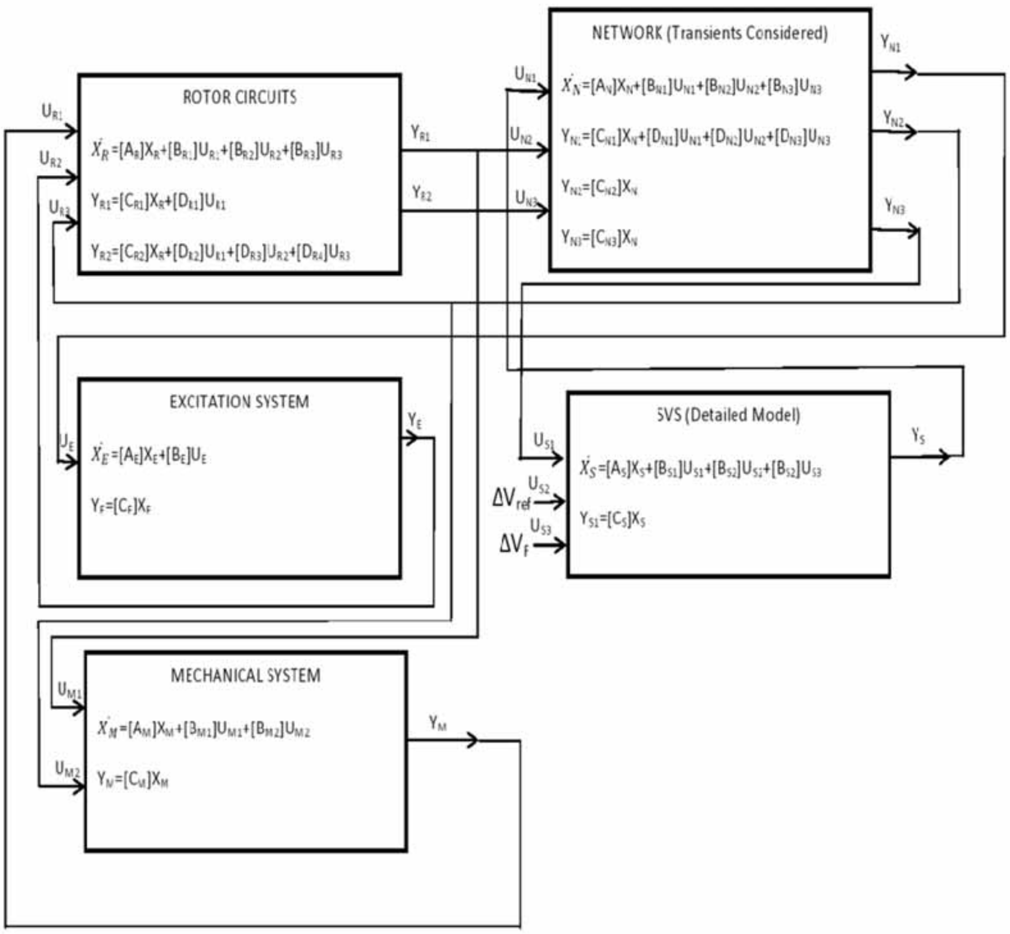

Fig. 2: Overall System Model

$$A^TS+SA-SBR^{-1}B^TS+Q=0$$

S= steady state solution of the associated algebraic Riccati equation obtained from matlab control system toolbox function called linear quadratic state feedback regulator [K,S]= lqr2 (A, B, Q, R), where k is calculated such that the control law (feedback law) U = KX minimizes the objective function or performance index.

IV. OPTIMAL PARAMETER SELECTION USING BFOA

Bacteria Foraging Optimization Algorithm (BFOA), proposed by Passino, is a new comer to the family of nature-inspired optimization algorithms. Evolutionary algorithms influenced by the law of natural selection have solved many real world optimization problems. All the evolutionary algorithms have almost three things in common: initialization, selection and reproduction. A fitness function generally used to rank the health of each population and based on which appropriate selections are made. After this selection the unhealthy population having low fitness function are eliminated and new population is formed for further evaluation and selection. It is shown in flow chart shown in Fig. 3.

V. RESULT AND DISCUSSION

Transmission line is considered with 50% series compensation and Natural damping is considered zero so as to observe the effect of the scheme present in burst case. The load flow study has been carried out for calculating the operating point. The eigen value analysis is done for the system at Pg=800MW without considering the natural damping at 50% series compensation. The actual response shall be certainly better if the natural damping is also included. A perturbance of 10% change in the electric torque and 10% change in the reference voltage is considered. The eigen values for different system modes obtained are given in Table 1.

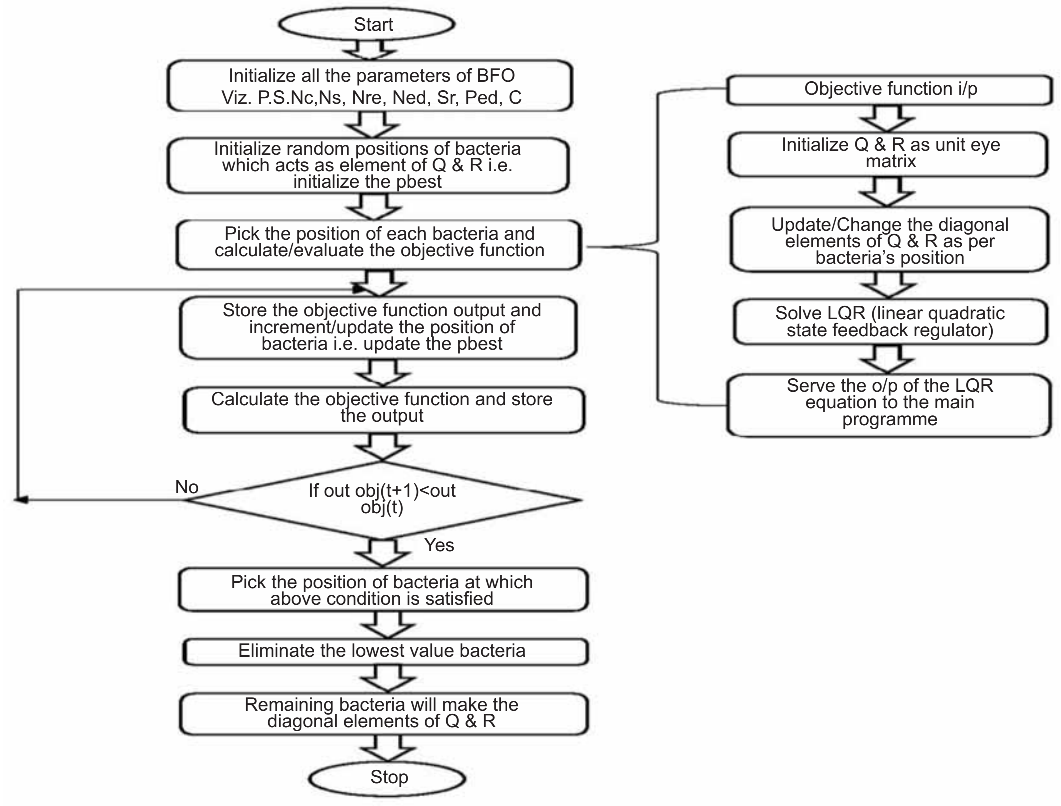

Fig. 3: Flow Chart of BFOA

Table 1: System eigen values for case-1 at 50% compensation

MODE Mech.	With SVS Only	With optimal controller	With optimal Controller & BFO
Mode 5	7.0129e-05 ± 298.18i	-0.42252 ± 298.18i	-0.42258 ± 298.18i
Mode 4	-0.11323± 203.01i	-6.5595 ± 202.91i	-6.5668 ± 202.91i
Mode 3	-0.089727 ± 160.77i	-7.9616 ± 160.76i	-7.9655 ± 160.76i
Mode 2	-0.018756 ± 127.06i	-5.8125 ± 128.31i	-5.8132 ± 128.31i
Mode 1	0.0306 ± 99.6767i	-7.4304 ± 98.8561i	-7.4306 ± 98.8562i
Mode 0	-2.0265 ± 13.6598i	-2.9213 ± 12.6086i	-2.9214 ± 12.6052i
Network	-3.2878 ± 3497.1i -3.2880 ± 2868.8i -13.911 ± 2528.9i -15.861 ± 1900.7i -12.490 ± 1120.8i -18.929 ± 493.31i	-3.2882 ± 3497.1i -3.2888 ± 2868.8i -13.913 ± 2528.9i -15.867 ± 1900.7i -18.919 ± 1121.4i -58.218 ± 498.67i	-3.3192 ± 3497.1i -3.3484 ± 2868.8i -14.029 ± 2528.9i -16.133 ± 1900.7i -50.065 ± 1125.3i -66.235 ± 493.65i

	-11.854 ± 328.38i -3.3187 ± 315.07i -11.698 ± 299.62i	-371.39 ± 366.05i -11.839 ± 328.30i -11.815 ± 299.63i	-1585.1 ± 453.73i -11.839 ± 328.30i -11.815 ± 299.64i
Generator System	-32.3668 -24.8779 -1.9448	-51.4780 -30.4181 -5.7939	-51.4780 -30.4182 -5.7939
SVC	-545.08 ±72.704i -55.4864 ±92.8421i -2.9118 ±310.64i	-625.19 -447.95 -165.53 ±351.39i -127.40 -1.7614	-804.95 -417.13 -169.20 ±333.78i -127.71 -1.7816
AVR	-26.1307 ±24.1266i -0.6407 ±1.2882i	-0.14624 ±314.16i -0.9066 ±1.2882i	-0.14624 ±314.16i -0.9066 ±1.2747i

The system response for the change in electric torque output and step input disturbance with SVS, optimal controller, and optimal controller plus BFO is shown in Fig. 4. The time domain analysis for the rotor angle (MECH-DELTA 5) curve shown in fig. 5 is given below in table 2, which shows all the time domain parameters viz. Rise time, Settling time, over shoot and peak time have been improved by the use of the optimal controller which is further improved by the application of BFO on the optimal controller.

Table 2: Time domain analysis for the rotor angle curve

MECH-DELTA 5 Spec.	With SVS only Time (Sec.)	With optimal Controller Time (Sec.)	With optimal Controller & BFOTime (Sec.)
Rise- Time	0.59301	0.84108	0.83252
Settling- Time	24.99	4.5629	3.3641
Over- shoot	32.563	18.83	17.968
Under- shoot	0	0	0
Peak- time	1.62	1.88	1.86

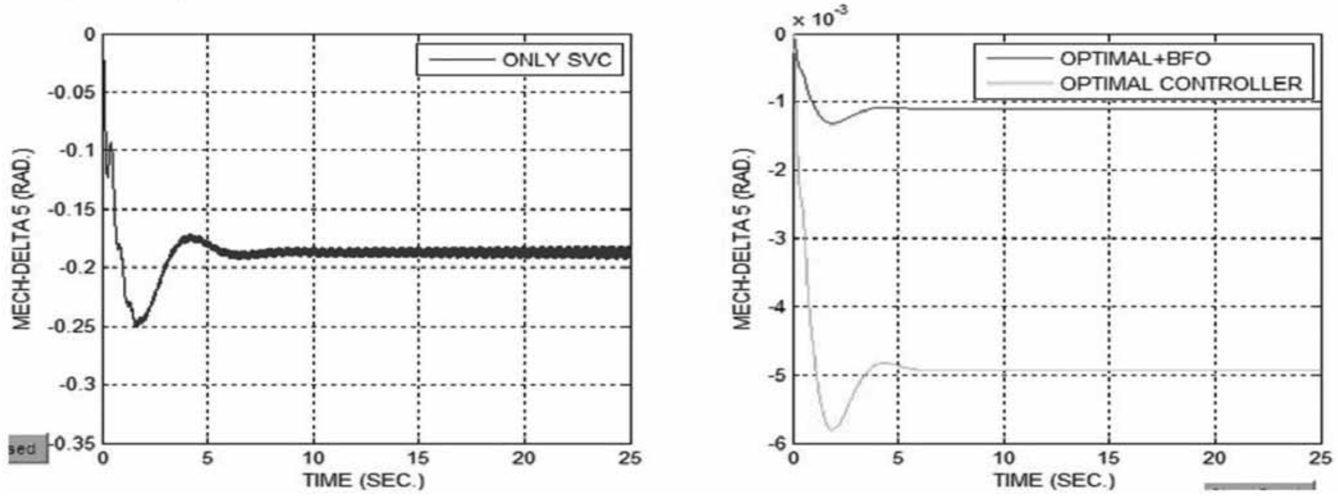

Fig. 4. Mech-Delta 5 (RAD)

The other responses are shown in Figure 5, 6, 7 respectively.

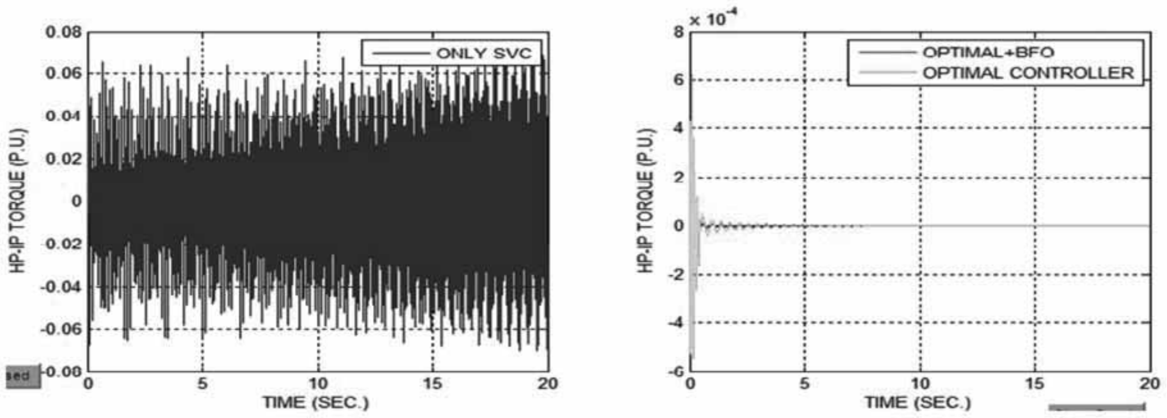

Fig. 5. HP-IP Torque (P.U.)

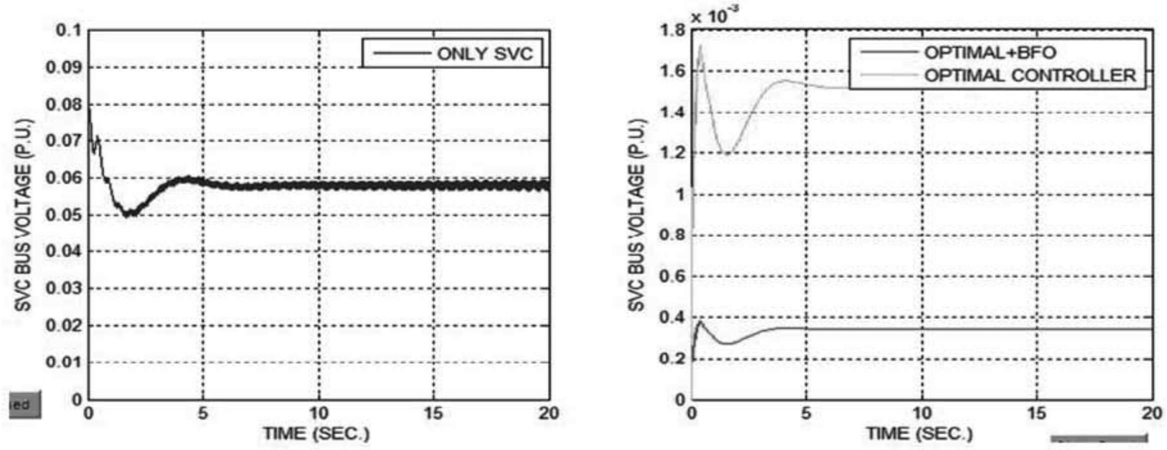

Fig. 6. SVC Bus Voltage (P.U.)

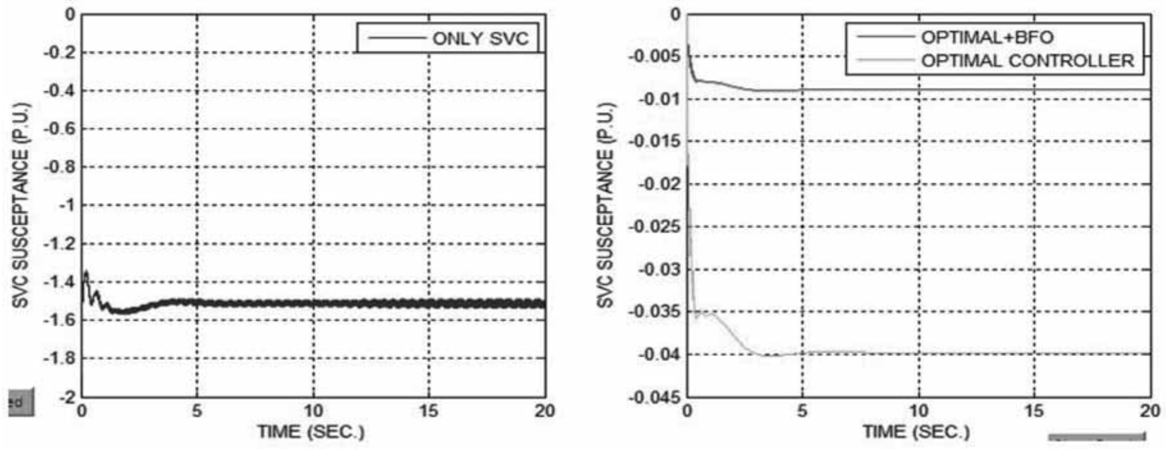

Fig. 7: SVC Susceptance (P.U.)

Time domain analysis is also made for the response curve of the rotor angle (MECH-DELTA 5) with svc, with the application of the optimal controller and optimal plus BFOA. The effectiveness of the proposed BFOA over optimal controller is clear from the results of the eigen values of the system states. The results of the time domain analysis is also seen from the response curve of the rotor angle (MECH-DELTA 5) which shows the effectiveness of the proposed BFOA over the optimal controller. All the time domain parameters viz. Rise time, settling time, Over-shoot and peak time is improved by the application of BFOA over optimal controller.

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