COORDINATED DESIGN OF PSS AND SERIES VECTORIAL COMPENSATOR CONTROLLERS FOR DAMPING POWER SYSTEM OSCILLATIONS

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***Abstract**: This paper details an approach for simultaneous coordinated design of conventional Power System Stabilizer (PSS) and Series Vectorial Compensator (SVeC) damping controller for damping improvement of low frequency oscillations in the multi machine power systems. To compare the damping contributed by the two devices, both frequency domain approach based on Eigen value analysis is carried out for the system matrix and time-domain approach based on non-linear model simultaneous is also performed. For optimum location of PSS, participation factor analysis has been carried out.The effectiveness of the proposed damping controllers is demonstrated on WSCC 3 machine 9 bus system. It can be concluded from the simulation results shows that use of coordinated design of PSS and SVeC can offer better damping characteristics. All the simulations are carried out in MATLAB.*

***Keywords:** Multi-machine power system, Power system stabilizer, Series Vectorial compensator, Low frequency oscillation.*

1. Introduction

The increase in utilization of power, electric power system becomes more heavily loaded and system damping is weakened. Insufficient damping of these oscillations will lead to transmission instability. There are generally two modes of oscillations are present in the power system local mode and inter area mode. Local modes are the oscillations associated with a group of generators swinging against the rest of the power system and they range in frequency between 0.8 and 2.0 Hz. Inter area modes refer to oscillations of a group of units in one area of the power system swinging against another group of units in another area of the power system, the mode frequency is in the range between 0.1 Hz to 0.7 Hz [1]. Single -machine-infinite-bus (SMIB) system investigates only local oscillations.

Synchronous generator excitation control is one of the most effective control methods to enhance the stability of the power systems and to damp low-frequency electromechanical oscillations during disturbance conditions. Nowadays application of PSSs are employed in addition with generator excitation systems to damp out low frequency oscillations and extend power transfer limits, thus ensuring secure and stable operation of the power system. This device may not produce adequate damping when a large fault occurs in the power system and its operation does not fast particularly in the multimachine power systems [1].FACTS POD damping controllers are other effective alternative in addition to PSS.Recent advances in power electronics introduce the use of Flexible Ac Transmission Systems (FACTS) controllers in power systems [2].Various types of FACTS controllers has been applied to power systems like Static synchronous compensator(STATCOM) ,Series static synchronous compensator(SSSC) ,and Unified power flow controller(UPFC),etc.These controllers are based on GTO-and IGBT-based voltage source converters [2]. Subsequently, by using the FACTS POD controllers it has been demonstrated that variable series compensation is highly effective to control active power flow in the lines and in improving the damping of power system oscillations in a very fast manner [3-5].

DC capacitors are used in the most of FACTS devices; this presents difficulties to high operating temperatures. This drawback can be overcome by using a novel FACTS device, series vectorial compensator (SVeC), means a direct AC/AC power conversion principle without large DC-link energy storage components is proposed. The SVeC has a simpler pulse width modulation (PWM) FACTS controller, with primary duty to control active power flowing in a transmission line [6-9].The secondary functions of SVeC can be provide volatge support, reducing net losses, oscillation damping [8],etc. In [8], it is demonstrated by IEEE 14-bus benchmark system and a190-bus, 46-machine model for Mexican grid that the SVeC can be very effective to damp low frequency oscillations. The overall Dynamic stability of a SVeC versus a TCSC as well as a SVeC versus a SSSC in the power system has been presented in[7] and [8],it shows that SVeC is smoother control alternative than the TCSC in a small radial power system Several applications of a SVeC such as transformer rating, capacitor, converter, power loss, and estimating power circuit cost are systematically compared with a SSSC to demonstrate the benefits of a SVeC [9].The authors discuss the use of SVeC joined with PID damping controller to damp oscillations in a SG-based SMIB system at transient conditions[10].A brief comparision and application of SVeC with SSSC using frequency domain and eigen value approach on a SMIB system is presented in [11].In the power market still the SVeC has not been physically designed; but its various benefits can be found. The Coordination of SVeC and PSS has not, however, been tested on the multi machine power systems**.** To improve the overall dynamic system performance, many researchers were made on the coordination between PSS and FACTS damping controllers [12-16].

The structure of the paper is as follows: section II presents the general configuration models of the proposed PSS, SVeC applied to the multi machine power system. Section III presents the Eigen value analysis for proposed PSS and SVeC joined with designed damping controller have been discussed. Section IV describes the comparative transient stability responses of the studied system with the proposed coordinated design of PSS and SVeC joined with the designed damping controller. Finally, Specific important conclusions are summarized in section V.

2. Description of Power System model

2.1Small – perturbation analysis

In general, power systems with a two axis, IEEE type-1 exciter using a set of DAE equations as follows [17]

$$\dot{x} = f(x, y, u) \quad (1)$$

$$0= g(x, y) \quad (2)$$

Where x is a state vector of each machine, y is the set of algebric variables means voltage and current at all buses, u is a set of input vector for each machine, and g is the stator algebric and network equations. Equation 1 is the dimension of 7m and equation 2 is the dimension of 2(m+n) although, power system is non -linear and it can be linearized at a certain operating point. The linearizing equ(1) and (2) can be used to examine the effect of small - signal disturbance on the eigen values can be expressed as:

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} a' & b'_1 & b'_2 \\ c'_1 & d'_{11} & d'_{12} \\ c'_2 & d'_{21} & d'_{22} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y_c \\ \Delta y_b \end{bmatrix} \quad (3)$$

Eliminating Δy in (3), i.e.

$$\Delta\dot{x} = a' - b'_1 b'_2 \,(J_{AE}{}')^{-1} \begin{bmatrix} c'_1 \\ c'_2 \end{bmatrix} = A_{sys}\Delta x \quad (4)$$

Where as J'_{AE} is the network algebric jacobian.In general Eigen values of A_{sys} are obtained directly from the system jacobian J.

When a PSS and SVeC damping controllers are placed to the system, the extra state variable corresponding to these controllers will be added with the system matrix.

Fig.1. shows the system line diagram under study. For oscillation control to the widely used 3 machine and, 9 bus of the Western System Coordinating Council (WSCC) of single line diagram is shown in Fig.1 is considered. The base MVA is 100, and system frequency is 60Hz.Details of the system are given in [18].The system has been simulated with a classical model for the generators all presented results were obtained with the help of MATLAB.

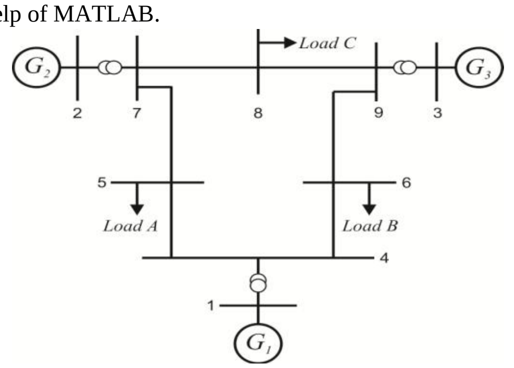


Fig.1.Single line diagram of system under study.

2.2. Generator Modeling

The synchronous generator is represented by the two-axis multi machine model is associated with a standard IEEE Type-I exciter has been consider for all 3 generators is shown in Fig.2[18].Considering all network bus dynamics is obtained by linearization of the DAEs around an operating point taken for small signal stability analysis.

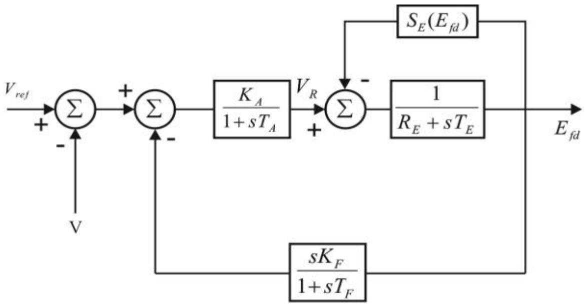


Fig 2. IEEE Type-I exciter model

Where T_E is the exciter time constant. S_E (E_{fd}) is the saturation function.R_E is the self-excited constant. K_A is the amplifier gain and T_A is the amplifier time constant.

2.3. Participation factor analysis:

The participation factor is one of the method, to find the best location for Placement of PSS to minimize the cost. In order to study dynamic stability, it is necessary to find the relative participation of state variable in the modes [18].System matrix, and PF analysis, aids in the identification of how each state variable affects a given mode[17].The PF can be defined as,

$$PF_{ki} = w_{ki} v_{ki} \quad (5)$$

Where w_{ki} and v_{ki} are the k^{th} entries in the left and right Eigen vectors respectively and associated with the i^{th} eigen value. The generator having the highest participation factor is considered best location for placement of PSS damping controller.

2.4. Power System Stabilizer:

The function of a PSS is to increase the damping torque component to the rotor of the machine to damp the oscillations of the rotor. Damping is provided by adding an auxiliary stabilizing signal to exciter of generator. Where Vs is the stabilizing signal generated by the PSS to improve damping and stabilization in the power system [1]. Fig.3 shows the general diagram of the PSS damping controller.

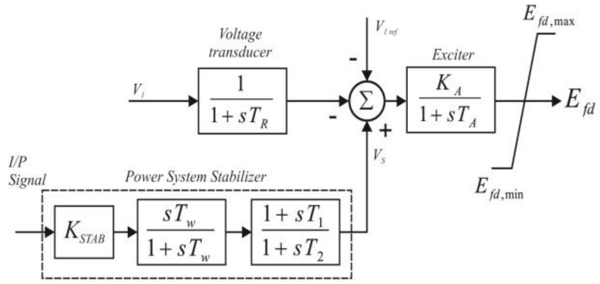


Fig 3: Control block diagram of Exciter with PSS

In the block diagram the transfer function of PSS is given by

$$\frac{V_s}{\Delta\omega_m} = K_{STAB}\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1}{1+sT_2}\right) \quad (6)$$

PSS is a Lead-lag compensator, where $\boldsymbol{\Delta\omega}_m$ is the deviation in speed from the synchronous speed it is consider as input signal to the PSS and a supplementary control signal (V_s) is the PSS output.Vs which is added to the V_{ref} and V_1 to excitation system so as to improve the damping and stabilization of power system.

This type of stabilizer consists of gain block, washout filter, and phase compensator. The gain (K_{STAB}) produces the required level of damping to the input signal. Wash out with time constant (T_W), acts as high pass filter. The system frequency changes steady state voltage offset will change; to prevent this wash out may be used. The phase compensation with time constants T_1 and T_2 should be adjusted to compensate the phase lag between excitation and the generator electrical torque[19].

2.5. SVeC Model and Controller

The main disadvanges in TCSC are, harmonics are present when the switches are gated at line frequency and open -circuit operating conditions [6] and need several milliseconds to vary the firing angle of thyristors. On the further more a synchronous type PWM is required in SSSC, this leads to very complexity in control infrastructure [8] .These drawbacks can be eliminated by replacing the ac controllers [6].In the transmission line the equivalent reactance of the transformer primary winding can be adjusted by using PWM ac controllers.

Basically SVeC consist of three components:(1)3series injection transformers T_R,T_Y,T_Z ;(2) 6 IGBT switches and 3 compensation capacitors C_R,C_Y,C_Z connected to a bus bar through a step down transformer, are shown in Fig.4.The primary application of SVeC is to control the active power flow in the transmission line by means of the duty cycle (D_S) of the switches are controlled to adjust the series reactance (X_{SVeC}) of the primary winding in the transmission line.

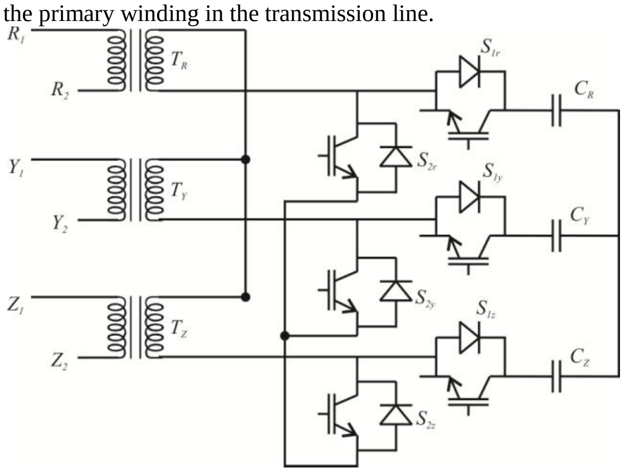


Fig 4: PWM SVeC installed in a transmission line.

In Fig 4.when the main switches S_{1R}, S_{1Y} and S_{1C} are closed the compensation capacitors C_R, C_y and C_Z are connected to the transmission line ; when the switches S_{2R}, S_{2Y} and S_{2C} are closed, the secondary terminals are short-circuited and compensation capacitors are isolated from the transmission line.

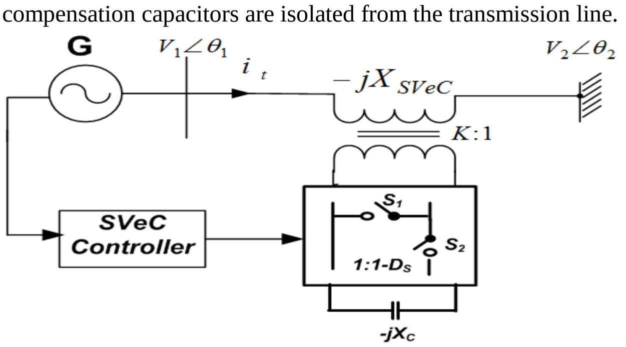


Fig 5 .Single line diagram of power system with SVeC.

In Fig.5 shows the single line diagram of Fig.4. The switches S_{1R}, S_{1Y} , S_{1Z} , S_{2R}, S_{2Y} and S_{2Z} are represented by S_1 and S_2 respectively. In stability studies where the SVeC is represented as the equivalent series rectance X_{SVeC} .The relationship between D_S and the reactance of the transmission line can be defined as [11].

$$X_{SVeC} = -k^2(1 - D_s)^2 X_C \quad (7)$$

Where X_C is the capacitor bank reactance, k is the coupling transformer turns ratio and D_s is the term duty ratio of the converter is defined as the ratio of the on-state to the total switching period.

The variable capacitive reactance within the limits defined by the limits imposed by D_S.Thus $X_{SVeC\ min} \le X_{SVeC} \le X_{SVeC\ max}$,
With $X_{SVeC\ min} = -k^2 X_C$ when $D_{s\ min} = 0$
$X_{SVeC\ max} = 0$ when $D_s \max = 1$

In the transmission line the value of volatge phasor across the primary of the coupling transformer is [8].

$$V_{SVeC} = k^2(1 - D_s)^2 X_C i_t \quad (8)$$

Where i_t is the current flowing in the transmission line.

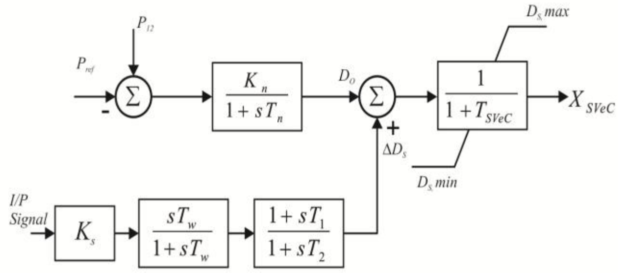


Fig6. Simplified control block diagram of SVeC Controller.

The power flow in the transmission line can be defined as

$$P_{12} = \frac{V_1.V_2}{X_{Total} - k^2(1-D_s)^2.X_c}\sin(\theta) \quad (9)$$

Where X_{Total} is the total rectance of the transmission line.

In order to improve the dynamic stability of the power system by means of control the active power flow in the transmission line, the controller block diagram of SVeC device is shown in Fig 6.These blocks will do the same purpose as in PSS.The deviation in the duty ratio (ΔD_S) is the output of the proposed SVeC damping controller. By changing the duty ratio (ΔD_S) the desired value of compensation is obtained it is added to the D_0. P_{ref} is calculated by the percentage compensation level of SVeC with the active power flow in the transmission line. The percentage of compensation level for the proposed system is chosen as 50%.The duty cycle (D_S) of the IGBT determines the value of rectance (X_{SVeC}) to be included in the network in order to maintain the bus voltage magnitude, which is orthogonal to line current.

3. Eigen value analysis:

A MATLAB program has been carried out for the system matrix of the studied system to get the Eigen values, Damping Ratios and Frequencies associated with the rotor oscillation modes of the electro mechanical modes of the system are listed in Table 1.System without any control, total 21 eigen values are present at nominal operating condition. In the total 21 Eigen values, two has zero magnitude, three are real and the remain 16 are complex conjugate. In the Table 1, the results clearly indicates that the mode,$\Lambda_{3,4}$ (=-0.1906 ± 8.3666i) is stable and very close to the imaginary axis (jω) of the s- plane and has a damping ratio 0.022 is small and therefore this mode has been referred to as critical swing mode. The damping needs to be improved by adding damping controller to the system so, the critical swing mode shifted to a most desirable position in the s plane.

The participation factor (PF) analysis also suggest that G2 having highest participation factor (load angle deviation and angular velocity deviation) on mode 2 among other generators G1 and G3 so the nature of this critical swing mode has been referred to as a local mode and strongly related with the G2 from the TABLE-I.PF greater than 0.2 are listed in Table.1.

Mode	Eigen Value	Damping Ratio (ζ)	Frequency (rad/sec)	Machine variable	Mac. No	Participation Factor
$\wedge_{1,2}$	-0.179±12.745 i	0.056	12.8	δ,ω	3	1.0,1.0
				δ,ω	2	0.22,0.22
$\wedge_{3,4}$	**-0.190±8.3666 i**	**0.022**	**8.37**	**δ,ω**	**2**	**1.0,1.0**
				δ,ω	**1**	**0.419,0.419**
$\wedge_{5,6}$	-5.6804±7.965 i	0.581	9.78	E_{fd},V_R,R_F	2	0.99,1,0.28
$\wedge_{7,8}$	-5.362±7.9308 i	0.56	9.57	E_{fd},V_R,R_F	3	0.978,1.0,0.292
$\wedge_{9,10}$	-5.2280±7.825 i	0.555	9.41	E_{fd},V_R,R_F	1	0.97,1.0,0.3
$\wedge_{11}$	-5.1777	1	5.18	E_d'	2	1.0
				E_d'	3	0.921
$\wedge_{12}$	-3.3995	1	3.399	E_d'	2	0.9
				E_d'	3	1.0
$\wedge_{13,14}$	-0.451±1.2003 i	0.352	1.28	R_f, E_q'	1	0.743,1
				R_f, E_q'	2	0.434,0.61
				R_f, E_q'	3	0.272,0.369
$\wedge_{15,16}$	-0.4478±0.729 i	0.523	0.856	R_f, E_q'	1	0.78,1.0
				R_f, E'_q	2	0.62,0.82
				R_f, E_q'	3	0.22,0.28
$\wedge_{17,18}$	-0.436±0.4871 i	0.667	0.654	R_f, E_q'	2	0.37,0.48
				R_f, E_q'	3	0.84,1.0
$\wedge_{19}$	0.0	1	0	$\delta,\boldsymbol{\omega}$	2	0.26,0.26
$\wedge_{20}$	0.0	1	0	$\delta,\boldsymbol{\omega}$	1	1.0,1.0
$\wedge_{21}$	-3.1250	1	3.125	E_d'	1	1.0

Table - 1. Participation Factor Associated With The Eigen Values Of The Studied System.

PSS is placed separately to each generator to increase the damping torque component of each machine and the PSS parameters are assumed as K_{PSS}=20, T1=0.15 and T_2=0.11. System with PSS control total 22 Eigen values are present means increased by one.

Mode	PSS at 2		
	Eigen value	Damping Ratio(ζ)	Frequency (rad/sec)
$\Lambda_{1,2}$	-0.7448 ±12.7604i	0.0583	12.8
$\Lambda_{3,4}$	**-0.3033 ± 8.3503i**	**0.0363**	**8.36**
$\Lambda_{5,6}$	-5.5571 ± 7.8937i	0.5760	9.65
$\Lambda_{7,8}$	-5.3563 ± 7.9324i	0.5600	9.57
$\Lambda_{9,10}$	-5.2283 ± 7.8241i	0.5560	9.41
Λ_{11}	-5.1855	1	5.1855
Λ_{12}	-3.3974	1	3.3974
$\Lambda_{13,14}$	-0.4361 ± 1.2119i	0.3390	1.29
$\Lambda_{15,16}$	-0.4327 ± 0.7340i	0.5080	0.852
$\Lambda_{17,18}$	-0.4258 ± 0.4865i	0.6590	0.646
Λ_{19}	-0.018	1	0.018
Λ_{20}	0	1	0
Λ_{21}	-3.125	1	3.125
Λ_{22}	-9.1292	1	9.13

Table-2: Eigenvalues with the application of PSS at Gen2

The value of Damping Ratio (ζ) for the critical swing mode by placing of PSS in machines 1, 2 and 3 is 0.0230, 0.0363, and 0.0255 respectively. The highest degree in the improvement of damping ratio for the critical swing mode is 0.0363, by placing the PSS at machine 2. PSS placed to the machine 2 and the corresponding Eigen Values, Damping Ratios are listed in Table 2.So the critical swing mode $\wedge$3,4 moves to (-0.3033 ± 8.3503i)on the imaginary axis of the s plane and simultaneously oscillations are decreases.

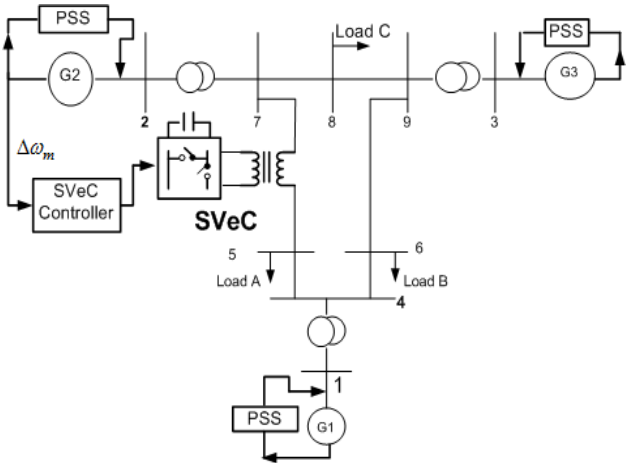


Fig.7.Coordinated design of PSS and SVeC in a studied system

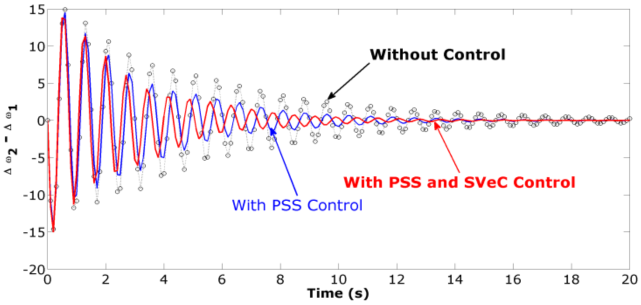
The SVeC has been inserted in the branch 5-7 associated with the highest load bus 5, and for each generator, PSS is installed in each machine separately a speed-input PSS has been equipped mandatorily is shown in Fig.7.The SVeC parameters are assumed as K_S=20, K_n=1,T_n=0.1s and X_C=0.5 p.u. The gain parameters for the both PSS and SVeC are kept identical for each step. The Eigenvalues of the system matrix for the coordinated design of PSS and SVeC controllers are computed in MATLAB and are listed in Table 3.In the presence of PSS and SVeC controllers in this system results in 26 eigen values, among which 16 are complex conjugate, 9 are real and 1 is at zero magnitude. It has been observed that the critical swing mode (**$\Lambda_{3,4}$**)has been moved to (-0.35±8.72i) on the imaginary axis of the complex s plane and has the damping ratio of 0.0407 respectively. Additional improvement of damping in the Coordinated design of PSS and SVeC is around 0.0187. It is clear that by applying SVeC in addition to PSS, can simultaneously increase the damping of the studied system compared to the application of PSS and no control and influences the power system stability.

Mode	PSS and SVeC		
	Eigen value	Damping Ratio	Frequency (rad/sec)
$\Lambda_{1,2}$	-0.8443 ±12.8470i	0.0656	12.9
$\Lambda_{3,4}$	**-0.3553 ± 8.7223i**	**0.0407**	**8.73**
$\Lambda_{5,6}$	-5.5534 ±7.8673i	0.577	9.63
$\Lambda_{7,8}$	-5.2584 ± 7.7544i	0.561	9.37
$\Lambda_{9,10}$	-5.2410 ± 7.8507i	0.555	9.44
Λ_{11}	-5.1544	1	5.1544
Λ_{12}	-3.4049	1	3.4049
$\Lambda_{13,14}$	-0.3935 ± 1.2149i	0.308	1.28
$\Lambda_{15,16}$	-0.4188 ± 0.7466i	0.489	0.856
$\Lambda_{17,18}$	-0.4064 ± 0.6092i	0.555	0.732
Λ_{19}	-0.1	1	0.1
Λ_{20}	-9.0909	1	9.09
Λ_{21}	0	1	0
Λ_{22}	-9.1318	1	9.1318
Λ_{23}	-9.0919	1	9.0919
Λ_{24}	-9.1607	1	9.1607
Λ_{25}	-0.0766	1	0.0766
Λ_{26}	-3.125	1	3.125

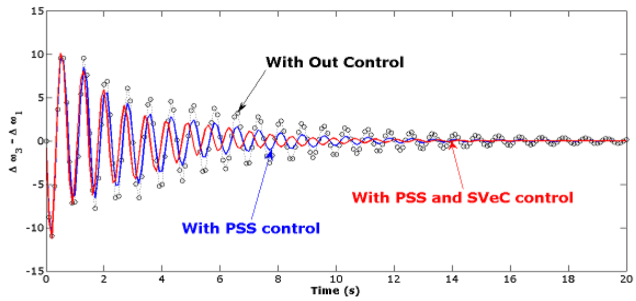
Table -3: Eigenvalues with the application of PSS and SVeC

4. Nonlinear time-domain simulation: (Simulation Results)

The non-linear time domain simulations, with constant impedance of the network, are carried out by considering the WSCC 3 machine, 9 bus System. The performance of the system under nominal loading conditions has been verified by with the coordinated design of PSS and SVeC with the response of PSS and without damping controller. Therefore, analysis of angular speed deviation response of generator 2 is particularly important in this study .The angular speed deviation response and rotor angle response has been plotted in Figures 8 and 9 for a simulation time of 20 sec. Where ω_1, ω_2, and ω_3 are the rotor speed of machine 1, 2 and 3, respectively and t is the time range of simulation. Similarly δ_1, δ_2 and δ_3 are the rotor angle of machine 1, 2 and 3 respectively.

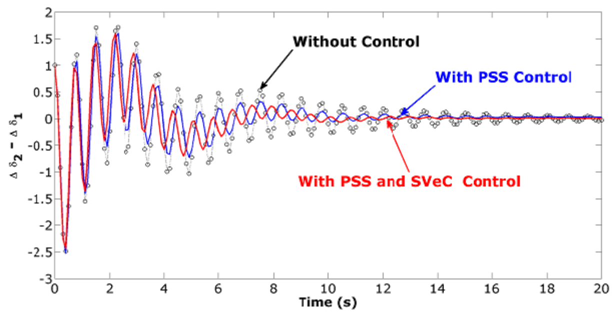


(a)

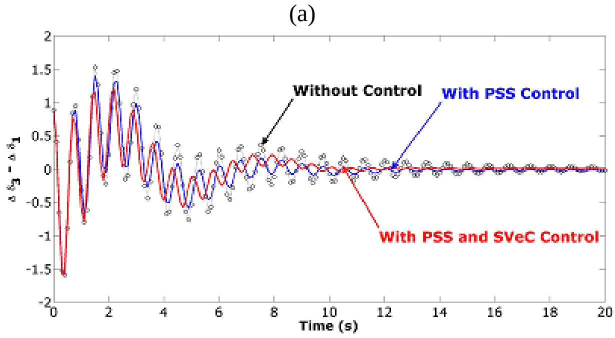


(b)

Fig 8.Comparision of the Angular velocity deviation of the original system model and the system model with PSS, PSS and SVeC controllers (a) Generator 2 and 1,(b) Generator 3 and 1.



(a)



(b)

Fig 9.Comparision of the Rotor angle response deviation of the original system model and the system model with PSS, PSS and SVeC controllers (a) Generator 2 and 1, (b) Generator 3 and 1.

Fig.8 shows the response of relative speed deviation of machines 2 and 3 with respect to machine 1.Compared to without control by placing of PSS to the generator produces better damping in rotor speed deviation response. Again, plots of Fig.8 conforms that the damping contributed by the SVeC along with PSS is very effective in damping of rotor speed deviation and not only reduces Peak overshoot but also introduces better settling time. Thus, in this study, compare the characteristics of the SVeC in addition to PSS is very effective compared to the PSS in this multi machine system.

Name of the controller	% of peak overshoot			
	ω_2-ω_1	ω_3-ω_1	$\delta_2-\delta_1$	δ_3-δ_1
Without any controller	3.95%	2.67%	0.951%	0.84%
PSS at Gen 2	3.84%	2.53%	0.9%	0.78%
PSS and SVeC	3.67%	2.51%	0.88%	0.66%

Table - 4:% of Peak Overshoot for different controllers

Name of the controller	Settling time			
	ω_2- ω_1	ω_3- ω_1	$\delta_2-\delta_1$	δ_3-δ_1
Without any controller	19.7846 Sec	19.7574 Sec	18.8143 Sec	18.8268 sec
PSS at Gen 2	13.0484 Sec	15.4770 Sec	14.3971 Sec	15.4770 Sec
PSS and SVeC	11.0130 Sec	11.0004 sec	10.5569 Sec	11.2109 Sec

Table-5: The settling time for different controllers

Fig 9.Shows the results of power angle response. Even though without controller, all the Eigen values are having negative real parts and the system is stable, but the power system oscillations are poorly damped. Coordinated design of PSS and SVeC controller significantly suppress the first swing in the power angle and provides good damping to low-frequency electro mechanical oscillations by stabilizing the system much faster. The performance of the PSS and SVeC is better compared to PSS and no control i.e. improved damping and lower settling time.Figs.8 and 9.clearly shows that, compare the damping characteristics contributed by the coordinated design of PSS and SVeC controller provides better results compared to PSS and no control interms of settling time, peak over shoot and power oscillation damping.

5. Conclusion: This paper has presented an approach to simultaneous coordinated design of PSS and SVeC damping controller's to damp out power system electro mechanical oscillations. Eigen values of the system without and with PSS and SVeC have been first examined.Time-domain simulations of the studied system at nominal loading condition have been performed to compare the damping ability of the proposed coordinated design of PSS and SVeC to suppress the low frequency oscillations of the studied system. It can be concluded from the simulation results that the proposed coordinated design of PSS and SVeC has better damping characteristics to improve the performance of the WSCC 3 machine, 9 bus system than the PSS.

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