Online ISSN 1848-3380, Print ISSN 0005-1144
ATKAFF 55(2), 207–215(2014)

Amin Safari, Heidar Ali Shayanfar, Hossein Shayeghi, Ahad Kazemi

PWMSC Controller Design for Damping Electromechanical Oscillations

DOI 10.7305/automatika.2014.06.290
UDK 681.515.013:621.31.018
IFAC 2.2; 3.1

Original scientific paper

Pulse Width modulated based Series Compensator (PWMSC), a newly FACTS device, can modulate the impedance of a transmission line through the variation of the duty cycle of a train of pulses with fixed frequency, resulting in improvement of system performance. In this study, a current injection model of PWMSC is proposed and incorporated in the transmission system model. The purpose of the work reported in this paper is to design an oscillation damping controller for PWMSC to damp low frequency oscillations. We have used the residue method to the linearized equations of the power system for multiple operating conditions and obtained a generalized form which is suitable for different damping controller input-output channels and therefore suitable for different control devices. The case study results show that the proposed controller is very effective to mitigate the power system critical modes of oscillation.

Key words: PWMSC, Current Injection Model, Residue Method, Modal Analysis, Damping Controller.

Dizajn PWMSC regulatora za prigušenje elektromehaničkih oscilacija. Pulsno-širinski modulirani serijski kompenzator (PWMSC), novi FACTS uređaj, modulira impendanciju prijenosne linije putem promjene popunjenosti niza signala s konstantnom frekvencijom, što rezultira poboljšanim svojstvima. U ovome radu predložen je model ubrizgavanja struje u PWMSC-u koji je nadodan u model prijenosa. Cilj ovoga rada bio je dizajnirati oscilatorni regulator prigušenja za PWMSC u svrhu prigušenja niskih frekvencija oscilatora. Korištena je metoda reziduala na linearizirani model energetskog sustava za različite uvjete te je dobivena općenita forma pogodna za ulazno-izlazne kanale regulatora prigušenja pogodna za različite upravljačke ulaze. Analiza pokazuje da je regulator učinkovit kod ublažavanja kritičnih oscilacija energetskog sustava.

Ključne riječi: PWMSC, model ubrizgavanja struje, metoda reziduala, modalna analiza, regulator prigušenja

1 INTRODUCTION

As electric power demand grows rapidly and expansion in transmission and generation is restricted with the limited availability of resources and the strict environmental constraints, power systems are today much more loaded than before. This causes the power systems to be operated near their stability limits. In addition, interconnection between remotely located power systems gives rise to low frequency oscillations in the range of 0.2–2.0 Hz. If not well damped, these oscillations may keep growing in magnitude until loss of synchronism results [1-2]. The traditional solution to this problem is the use of power system stabilizers (PSSs). Flexible AC transmission systems (FACTS) devices are one of the recent propositions to alleviate such situations by controlling the power flow along the transmission lines and improving power oscillations damping [3-4]. The FACTS devices, through the modulation of bus voltage, phase shift between buses, and transmission line reactance, can cause a substantial increase in power transfer limits during steady state. Because of the extremely fast control action associated with FACTS device operations, they have been very promising candidates for utilization in power system damping enhancement [5]. It has been observed that FACTS based supplementary controller can considerably improve system damping and can also improve system voltage profile, which is advantageous over PSSs.

More recently, new FACTS controllers based on PWM based series compensator (PWMSC) with AC link convertors have been proposed [6-11], demonstrating that it is possible to attain similar control objectives in comparison with conventional FACTS devices. For many years, fixed and controlled series compensators have been used in transmission lines for compensating the line reactance in order to increasing power transfer capability and enhancing the transient stability in power networks. The conventional series FACTS devices proposed in the literature can be classified in two major groups: thyristor controlled reactance [12] and synchronous controllable voltage sources [5]. However, in recent years new devices based on AC link converters have been proposed [6-9]. These do not require a DC link, and it is possible to reach similar objectives to those obtained by means of conventional FACTS devices. The series compensator considered in this paper is of the controlled reactance type which can be viewed as a PWM controlled capacitor. One advantage of the proposed compensator is the use of a control scheme that to vary of the effective series reactance in power transmission lines. Such compensators have the advantage of being simpler in both power circuit structure and more importantly control [13].

This PWM switched capacitor for series compensation is the dual of the shunt reactor switched by a PWM AC controller that has been presented in [14]. A static phase-shifter based on the four-switch PWM AC controller has also been discussed in the literature [15]. In ref. [6], the authors proposed the use of the PWM controlled capacitor to control active power on a transmission line with a simple structure that provides a means for controlling continuously the degree of series compensation through the variation of the duty cycle control. A brief comparison of this PWMSC with thyristor controlled series capacitor (TCSC) in small power system with three buses is presented in [7] where it is shown that the PWMSC present a smoother control alternative than the TCSC. A comparative evaluation between the PWMSC and the static synchronous series compensator (SSSC) based on detailed switching models presented in [10] and show that the DC link converter requires about twice as much capacitive energy storage and about 66% additional semiconductor MVA rating rather than the AC link for the same application. It is also mentioned that the PWMSC can operate at higher temperatures due to the use of AC capacitors as opposed to DC capacitors in the SSSC which are quite vulnerable to high temperature applications. In references [16, 17], it is presented that the AC link converter topology is more compact size compared to DC link voltage source converter. The three-phase vector switching converter is proposed to develop FACTS controllers which can control the power flow in transmission system [9]. Authors have introduced a new FACTS device based on pulse width modulate AC link unified power flow controller (UPFC) named Gamma controller. In [11, 18], some studies of the effect of the AC link compensator on power system stability are presented. The formulation of power flow of the AC link compensators is analyzed at steady state performance in [11]. Some transient stability studies with fixed duty cycle are discussed in [10, 18]. In these papers, it is shown that the compensator does not provide enough damping for certain contingencies. The contribution of this work is that a novel current injection model and dynamic simulation of the PWMSC for studying the low frequency oscillations and incorporated in the transmission system model.

2 PWMSC

Fixed series capacitors have been used since a long time for increasing power transfer in long lines and allow a higher utilization level of limited transmission systems. A newly developed AC link converter based series compensation, as FACTS controller, is presented here. The PWM controlled series compensator offers a method of variable series compensation. It is known that transmission lines loading may be restricted by system dynamics stability. The PWMSC is a powerful new tool to help relieve these constraints. Furthermore, its controller can be designed to modify the line reactance and provide enough damping to system oscillation modes. Figure 1 displays a realization of schematic diagram of the PWM series compensator which it is embedded into a transmission line [19].

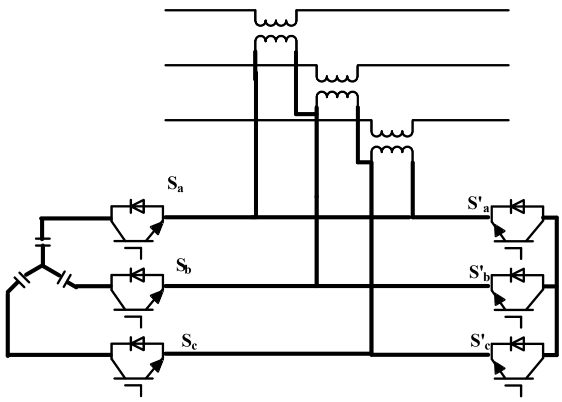

Fig. 1. PWMSC controller.

The PWM controlled series compensator consists of: (a) series injection transformers (b) compensation capacitors and (c) PWM controlled switches S_a, S_b, S_c, S'_a, S'_b and S'_c. In Fig. 1, the three switches S_a, S_b, S_c with the same switching function in a complementary way to those in S'_a, S'_b and S'_c switches. The switching period divides the circuit in two switching states. When Sa, Sb and Sc are on, the capacitors are connected to the system through a series injection transformer. When S'a, S'b and S'c are on the series injection transformer is shorted, thereby isolating the capacitors from the line. In this structure, the bank of capacitors is connected in Y to the PWM AC converter and secondary of coupling transformer is connected in Δ [6, 7]. The compensator operates as a means for controlling continuously the degree of series compensation through the variation of the duty cycle of a single asynchronous train of pulses with fixed frequency. The duty cycle (*D*) of the AC link converter is defined as the ratio of the on-period of switches S'$_a$, S'$_b$ and S'$_c$ with respect to the total switching period.

2.1 Operation of PWMSC

The PWMSC is assumed to be connected between buses *i* and *j* in a transmission line as shown in Fig. 2, where the PWMSC is operated like a continuously capacitive controllable reactance. However, for the purpose of developing a control strategy, it is useful to have a proper model representation for the PWMSC.

The main switches (S$_a$, S$_b$ and S$_c$) of the AC link converter are controlled with the train of pulses with fixed frequency and variable duty cycle (*D*). When the main switches are on, the capacitors are connected to transmission line.

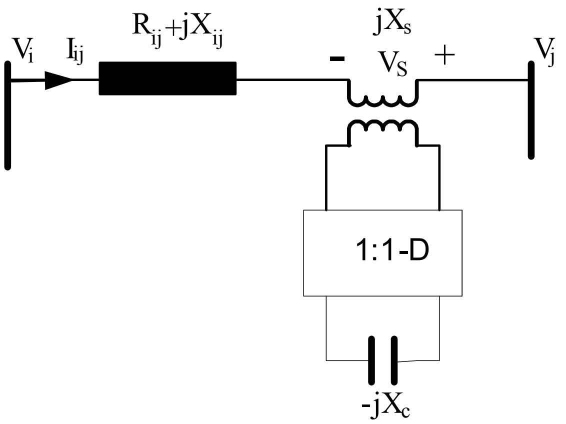

Fig. 2. Single line diagram of PWMSC.

Therefore, the instantaneous voltage that appears at the primary of the inserting transformer V_s is given by the voltage drop across the transformer leakage reactance plus a voltage proportional of voltage across the bank of capacitors, according to the turns ratio of the transformers. Switches S'a, S'b and S'c are controlled with the complementary signal so as to provide a freewheeling path for the currents at the secondary of the coupling transformer when the main switches are off. During this operation, the secondary of the coupling transformers are short-circuited and the voltage that appears at the primaries V_s is only the voltage drop across the transformer leakage reactance. Inserting reactance can vary from slightly inductive to capacitive, depending on the duty cycle (*D*) of the PWM AC link converter. The actual transformer is modeled by a leakage reactance (*XT*) in series with an ideal transformer, i.e. the ideal transformer do not has leakage losses. The *XC* is the reactance of the capacitors in the secondary side. The equivalent and injected impedances at transmission line may be calculated with state space averaging techniques as follows:

$$X_{eq} = X_{ij} + X_T + X_S \tag{1}$$

$$X_S = -n^2(1-D)^2 X_C \tag{2}$$

Where *n* is the turns ratio of the transformer and *Xij* is the reactance of the transmission line. Eqs. (1) and (2) show that the effective impedance depends on the duty cycle of the AC link switches; hence, this duty cycle provides a means of realizing the desired controllable reactance, power flow at line and power oscillations control. For more understanding, the variation of the PWMSC based injected reactance with duty cycle of the AC link is shown in Figure 3. In this Figure, suppose that designed PWMSC to provide a series capacitive reactance of 0.35 pu, for a line with 1 pu reactance. The leakage reactance of the series transformer is taken as 0.03 pu on the system base. From Eqs. (1) and (2) and Figure 3, it can be seen that the injected reactance can be varied continuously between two extreme values.

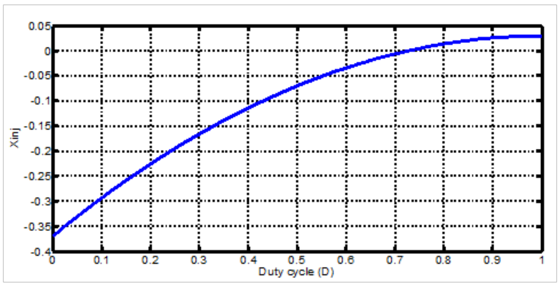

Fig. 3. Variation of the PWMSC based injected reactance with duty cycle.

2.2 PWMSC Current Injection Model

In order to investigate the impact of series compensators on power systems effectively, appropriate models of these devices are very important. In this paper, we proposed current injection model to study the effects of PWMSC on power network low frequency oscillations. The installation of PWMSC changes the system bus admittance matrix *Ybus* to an unsymmetrical matrix [20]. When the PWMSC is used for time domain simulations of multimachine power systems, the modification of Y_{bus} is required at each process iteration. This method has the disadvantage that a constant factorized Y_{bus} cannot be repeatedly used when the PWMSC variable reactance is changeable in the process of transient stability calculation. For this reason, a current injection model of PWMSC is developed to avoid using the modification of Y_{bus} at each stage. The current injection model, which can be used for small signal stability and transient stability studies, is obtained by replacing the voltage across the PWMSC with the current source. By using equivalent injected currents at terminal buses to simulate the PWMSC no modification of Y_{bus} is required at each stage. This method has the advantages of fast computational speed and low computer storage compared with that of modifying Y_{bus} technique. Also, this model is helpful for understanding the effect and performance of the PWMSC on system damping enhancement [21].

For modeling of series compensator, it has been suppose that a PWMSC connected between nodes *i* and *j* in a transmission line as shown in Fig. 4, where the PWMSC is simplified like a continuously capacitive controllable reactance and its equivalent circuit is represented in Fig. 5. In Figs. 4 and 5, $V_i\angle\theta_i$ and $V_j\angle\theta_j$ are the complex voltages at nodes *i* and *j*, and $V_S = -jX_S I_{se}$represents a voltage across the PWMSC.

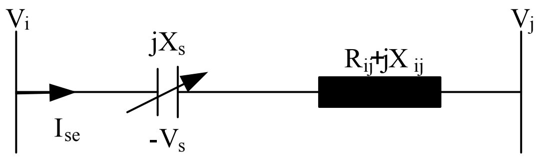

Fig. 4. PWMSC located in a transmission line.

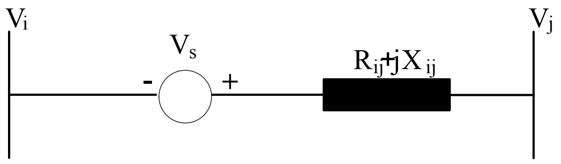

Fig. 5. PWMSC equivalent circuit.

From Fig. 4 we have:

$$I_{se} = \frac{V_i - V_j}{R_{ij} + j(X_{ij} + X_S)} \tag{3}$$

$$I_{se} = \frac{V_i - V_j}{R_{ij} + j(X_{ij} + X_T - n^2(1-D)^2 X_c)} \tag{4}$$

The current injection model of the PWMSC is obtained by replacing the voltage across the PWMSC by an equivalent current source, Is, in Fig. 6. Then, we have:

$$I_s = \frac{V_S}{R_{ij} + jX_{ij}} = -\frac{jX_S I_{se}}{R_{ij} + jX_{ij}} \tag{5}$$

The current source model of the PWMSC is shown in Fig. 7. Current injections into nodes *i* and *j* are calculated

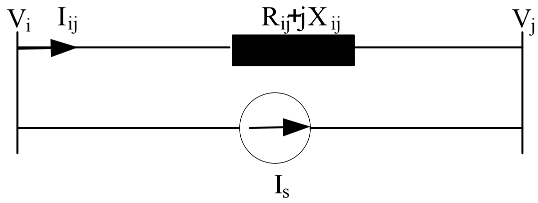

Fig. 6. Replace of a voltage across the PWMSC by a current source.

as follows:

$$I_{si} = \frac{j(X_T - n^2(1-D)^2 X_c)}{R_{ij} + j(X_{ij} + X_T - n^2(1-D)^2 X_c)} \cdot \frac{V_i - V_j}{R_{ij} + jX_{ij}} \tag{6}$$

$$I_{sj} = -I_{si} \tag{7}$$

2.3 PWMSC Damping Controller

A damping controller is provided to improve the damping of power system oscillations. It comprises gain block, signal-washout block and lead-lag compensator. The structure of PWMSC based damping controller with dynamic control model for typical oscillatory stability studies is shown in Figure 8.

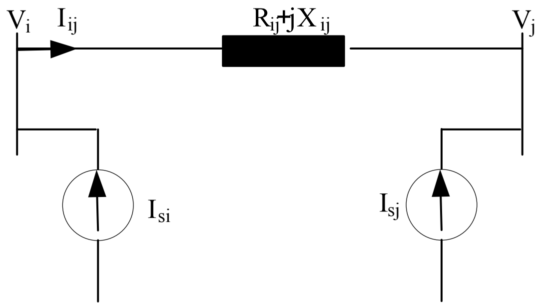

Fig. 7. Proposed current injection model for PWMSC.

It can be notice that following a similar modeling approach as in the case of the other series compensator, the line reactance is assumed to be controlled through the duty cycle *D*. The model includes an input signal and a reference signal X_{sref} which is the initial value of the series compensator. The output of the lag block X_S has windup limits associated with it. The ultimate reactance value is used to modify the line impedance of the series compensated branch during the calculation of the network solution [22-24].

3 MODAL ANALYSIS FOR POWER SYSTEM

The modal analysis is a very powerful tool for the study of the dynamic performance of linear systems. The lin-

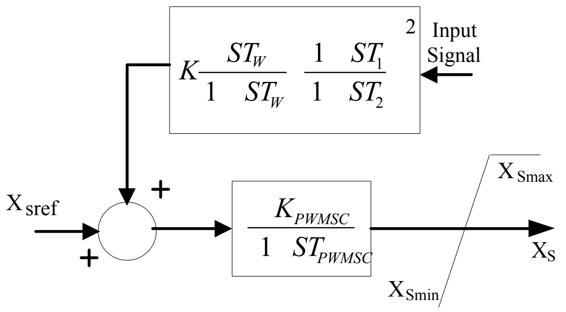

Fig. 8. PWMSC Damping Controller.

earized system can be represented by the following equation:

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{8}$$

$$\Delta y = C\Delta x + D\Delta u \tag{9}$$

Where A is an n-order state matrix, B and C are n-order vectors. Analysis of the eigenproperties of A provides valuable information regarding the stability characteristics of the system. Using the state transformation$X = VZ$, the state space of the system becomes [25]:

$$\dot{Z} = V^{-1}AVZ + V^{-1}B\Delta u = A_z Z + B_z \Delta u \tag{10}$$

$$y = C^T VZ = C_z Z \tag{11}$$

where *Az = diag(*λ_i*),*λ_i*(i =1, 2, ..., n)* is the eigenvalue of the matrix A, while we get:

$$\begin{array}{l} V = [V_1,\, V_2,\, ...,\, V_n] \\ V^{-1} = [W_1,\, W_2,\, ...,\, W_n]^T = W \end{array} \tag{12}$$

For any eigenvalue λ_i,

$$\begin{array}{l} AV_i = \lambda_i V_i \\ W_i^T A = \lambda_i W_i^T \\ W_i^T V_j = 1, \quad if\ i = j,\ 0\ otherwise \end{array} \tag{13}$$

That is, V_i and $W_i^T$are the n-order right and left eigenvectors of the state matrix A with respect to the eigenvalueλ_i. According to the conclusions from modal analysis, we know that:

$$b_{Zi} = W_i^T B, \qquad c_{Zi} = C^T V_i \tag{14}$$

The $b_{Zi}$is referred to as the modal controllability matrix, and the c_{Zi} as modal observability matrix [25]. A mode must be both controllable by the chosen input and observable in the chosen output for a feedback control to have any effect on the mode. Therefore, the determination of suitable feedback variables is an important objective in FACTS damping controller design procedure. The $b_{Zi}$and c_{Zi} measure the controllability and observability of the mode λ_i by the FACTS based controller, respectively. Their product is the residue:

$$R_i = b_{Zi} c_{Zi} \tag{15}$$

The residue R_i of a particular mode *i* give the measure of that mode's sensitivity to a feedback between the output y and the input$u$. Hence, the effectiveness of the FACTS based controller to be installed in the power system can be predicted by modal analysis.

4 PWMSC DAMPING CONTROLLER DESIGN

To damp electromechanical oscillations in power systems, supplementary control action can be applied to some FACTS devices to increase the system damping. Because PWMSC are located in transmission lines, local signals as input are always preferable. The residue method is an appropriate approach in finding the most proper local feedback signal in the controller design procedure. Moreover, it is also a simple and practical approach for designing of damping controller. Therefore, in this paper, the residue method is applied to design of the PWMSC damping controller. Figure 9 shows a system $G(s)$equipped with a feedback control $H(s)$. Assuming the PWMSC location is determined, therefore the input signal $u(s)$ is available. The output signal $y(s)$can be chosen based on the maximum residue provided by the selected outputs [23].

As illustrated in Figure 8, the transfer function of the PWMSC damping controller is:

$$H(s) = K\frac{sT_w}{1+sT_w}.\left(\frac{1+sT_1}{1+sT_2}\right)^2 = KH_1(s) \tag{16}$$

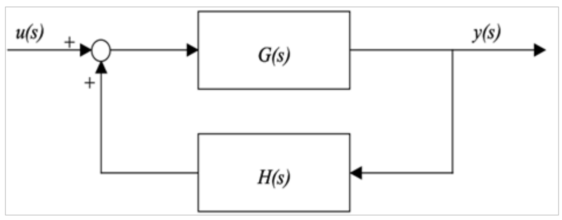

Fig. 9. Closed-loop system with damping controller.

Where K is a positive constant gain and $H_1(s)$is the transfer function for the wash-out and lead-lag blocks. It can be proven, that when the feedback control is applied, the shift of an eigenvalues can be calculated by:

$$\Delta\lambda_i = R_i \Delta K H_1(\lambda_i) \tag{17}$$

Where $\lambda_i$denotes the mode that should be influenced by the PWMSC damping controller. The objective of the series compensator is to improve the damping ratio of the selected oscillation mode *i*th. Therefore, $\Delta\lambda_i$ must be a real negative value to move the real part of the eigenvalue $\lambda_i$direct to the negative region without changing its frequency [21, 26]. After the selection of the feedback signal, in order to control the direction of the eigenvalue displacement, the lead-lag stabilizer parameters can be determined using the following equations [21]:

$$\begin{array}{l} \varphi_{com} = 180^o - \arg(R_i) \\ \alpha = \frac{T_2}{T_1} = \frac{1-\sin(\varphi_{com}/2)}{1+\sin(\varphi_{com}/2)} \\ T_1 = \frac{1}{\omega_i\sqrt{\alpha}},\ T_2 = \alpha T_1 \end{array} \tag{18}$$

Where, $\arg(R_i)$denotes phase angle of the residue R_i, ωi is the frequency of the researched mode of oscillation in rad/sec. The controller gain K is computed as a function of the desired eigenvalue location $\lambda_{i,des}$ according to Eq. (17):

$$K = \left| \frac{\lambda_{i,des} - \lambda_i}{R_i H(\lambda_i)} \right| \tag{19}$$

5 TEST SYSTEM

To investigate the proposed model of the PWMSC on the small signal and transient stability of a power system, as well as to assess its performance for power flow control in tie line and for oscillation damping, the test system with PWMSC, between nodes 2 and 3, depicted in Fig. 10 is considered for analysis. This system [27] comprises a thermal generation station consisting of four 555 MVA, 24 kV, 60 Hz units connected to an in?nite bus through a step-up transformer followed by two transmission circuits. The four generators are represented by an equivalent synchronous generator which has a 6th order model equipped with an automatic voltage regulator Type III of Simulink library. The full data of the system and the control parameters are presented in the Appendix**.** Three cases, described in Table 1, are considered. Case *a* is the nominal condition with a 120 MW real power flow from node 2 to node 3.

Under nominal conditions, P=0.75 and Q=0.24 pu, and there is no PWMSC damping controller, this system has the dominant eigenvalue λ = 0.198 $\pm$ i3.182. There is one oscillation mode, which is unstable with a damping ratio $\xi = -0.019$. In the literature, signals which carry invaluable information about the oscillation mode can be considered as input signals for example, line active power, line current, bus voltage magnitude and machine speed deviation. For this reason, here, the active power of the transmission line and machine speed deviation is selected as the input signal.

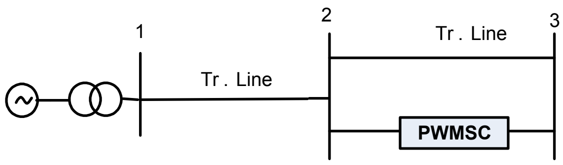

Fig. 10. Test system with PWMSC.

Table 1. Three operating conditions.

Case	P	Q	Real power flow
a	0.75	0.24	120 MW
b	0.85	0.2	190 MW
c	0.55	0.15	50 MW

5.1 PWMSC damping controller design

Using the method presented above, damping controller parameters are calculated in order to shift the real part of the oscillatory mode, to the left half complex plane. The PWMSC damping controller is designed using the value of the speed deviation. It will be compared with a design performed in [24] using the active power flow signal. The residues of the inter-area mode are shown in Table 2.

Based on Table 2, the desired compensation phase is selected to be 90^o. Two stages of lead-lag controller are used with each providing 45^o phase compensation. With these a dynamic compensator, the oscillation mode will move in the left half plane, thus the control will damp the mode. The designed parameters for PWMSC controller are given in Table 3.

5.2 Nonlinear Simulation

To investigate the performance of the designed controller using proposed model under transient conditions, a 6-cycle three phase fault at $t = 0.1$sec is simulated at the middle of one of the line connecting Bus-2 and Bus-3. The simulation results at case *a*, *b* and *c* loading conditions due

Table 2. Residues magnitudes and angles of the oscillation mode.

Case	Input w		Input P	
	Magnitude	Angle	Magnitude	Angle
a	0.0655	95.31	0.0176	95.28
b	0.0388	88.05	0.0084	84.85
c	0.0298	87.72	0.0443	93.42

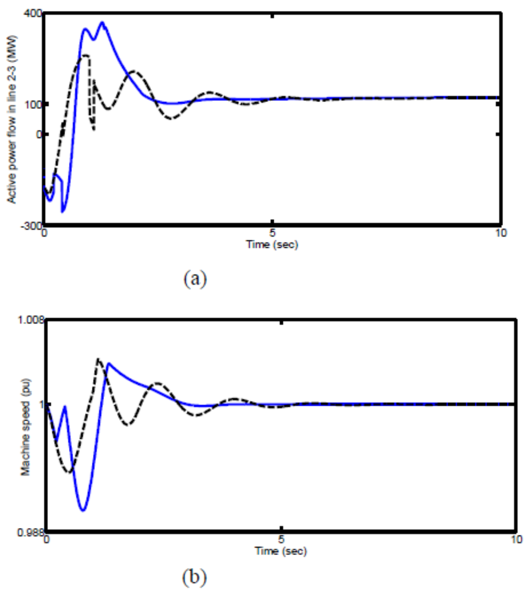

Fig. 11. Dynamic responses in case a for a) active power flow b) machine speed; Solid (PWMSC with input $\Delta\omega$) and Dashed (PWMSC with input P).

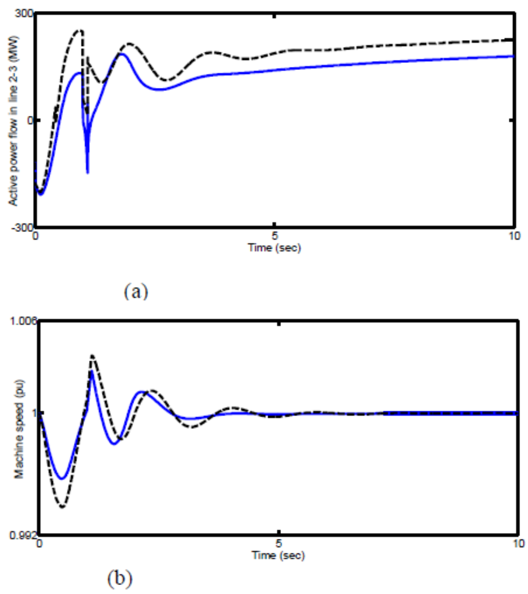

Fig. 12. Dynamic responses in case b for a) active power flow b) machine speed; Solid (PWMSC with input $\Delta\omega$) and Dashed (PWMSC with input P).

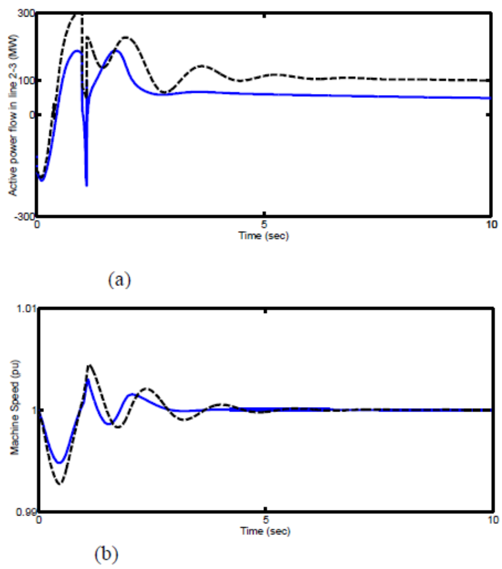

Fig. 13. Dynamic responses in case c for a) active power flow b) machine speed; Solid (PWMSC with input $\Delta\omega$) and Dashed (PWMSC with input P).

Table 3. The parameters of PWMSC damping controller

Damping controller parameters	Input speed deviation	Input active power flow
K	60	25
T1	0.72	0.069
T2	0.95	0.87

to PWMSC based designed damping controller are shown in Figs. 11-13 respectively, when machine speed deviation and active power flow are used as control signal. It can be seen that the PWMSC with proposed damping controller achieves good performance and enhance greatly the dynamic stability of the power system. Therefore, the newly proposed controller is more flexible to change in operating condition of the system.

6 CONCLUSIONS

Improvement of power system damping using PWMSC has been investigated in a single-machine infinite-bus power system by linear analysis and nonlinear time domain simulations. The basic module, steady state operation, mathematical analysis and current injection modeling of the PWMSC were also presented. The PWMSC damping controller using proposed model is explained mathematically and it can be implemented in MATLAB/SIMULINK environment. The residue approach for tuning of damping controller with the active power of the transmission line and machine speed deviation as the input signal is applied. Hence, it may be concluded that the PWMSC is certainly a competitive, considering that the direct AC link converter principle of the PWMSC leads to an overall more compact, simpler and durable controller, with no large DC link energy storage components and a simpler PWM based controller. Nonlinear simulation demonstrates the effectiveness of the proposed methodology.

APPENDIX A

Generator:

$$R_a = 0.003 \quad X_L = 0.15 \quad X_d = 1.81 \quad X'_d = 0.30$$
$$X''_d = 0.23 \quad T'_{do} = 8.0\,s \quad T''_{do} = 0.03\,s \quad X_q = 1.76$$
$$X'_q = 0.65 \quad X''_q = 0.25 \quad T'_{qo} = 1.0\,s$$
$$T''_{qo} = 0.07\,s \quad H = 3.5 \quad D = 0.0$$

Automatic voltage regulator:

$$K_a = 200 \quad T_1 = 1.0\,s \quad T_2 = 1.0\,s$$
$$T_r = 0.015\,s \quad V_{r\max} = 7.0 \quad V_{r\min} = 6.4$$

Transformer and transmission lines:

$$X_{Tr} = 0.15 \quad X_{12} = 0.015 \quad X_{23} = 0.3$$

PWMSC:

$$X_L = 116 \quad X_c = 100 \quad X_{s\max} = 0.1 \quad X_{s\min} = -0.1$$

REFERENCES

[1] K. Prasertwong, N. Mithulananthan and D. Thakur, Understanding low frequency oscillation in power systems, *Int. J. Elect. Enging. Educ.,* Vol. 47, pp. 248-262, 2010.

[2] P. M. Anderson and A. A. Fouad, *Power System Control and Stability,* Ames, IA: Iowa State Univ. Press, 1977.

[3] N.G. Hingorani, L. Gyugyi, *Understanding FACTS: concepts and technology of flexible AC transmission systems*, Wiley-IEEE Press; 1999.

[4] M. Ishimaru, R. Yokoyama, G. Shirai, T. Niimura, Robust thyristor controlled series capacitor design based on linear matrix inequality for a multimachine power system, *Elect Power Energy Syst.,* Vol. 24, pp. 621-629, 2002.

[5] H. Shayeghi, H.A. Shayanfar, S. Jalilzadeh, A. Safari, A PSO based unified power flow controller for damping of power system oscillations*, Energy Conversion and Management*, vol. 50, pp. 2583-2592, 2009.

[6] L. A. C. Lopes and G. Joos, Pulse width modulated capacitor for series compensation, *IEEE Trans. Power Electron.*, vol. 16, no. 2, pp.167–174, Mar. 2001.

[7] G. Venkataramanan and B. K. Johnson, Pulse width modulated series compensator, *IEE Proc. Gen., Trans. and Dist.,* vol. 149, no. 1, pp.71–75, Jan. 2002.

[8] G. Venkataramanan, "Three-phase vector switching converters for power ?ow control, *IEE Proc. Elect. Power Appl.,* vol. 151, no. 3, pp. 321–333, May 2004.

[9] F. Mancilla-David and G. Venkataramanan, A pulse width modulated AC link uni?ed power ?ow controller, in IEEE Power Engineering Society General Meeting, San Francisco, CA, Jul. 2005, vol. 2, pp.1314–1321.

[10] F. Mancilla-David, S. Bhattacharya, and G. Venkataramanan, A comparative evaluation of series power-?ow controllers using DC- and AC-link converters, *IEEE Trans. Power Del.,* vol. 23, no. 2, pp.985–996, Apr. 2008.

[11] J.M. Ramirez, J.M. Gonzalez, and M. L. Crow, Steady state formulation of FACTS devices based on ac/ac converters, *IEE Proc. Electric Power Appl.,* vol. 1, no. 4, pp. 619–631, Jul. 2007.

[12] S. G. Helbing and G. G. Karady, Investigations of an advanced form of series compensation, *IEEE Trans. Power Deliv*, vol. 9, pp. 939–947, Apr. 1994

[13] V. Venkataraman and C. W. Taylor, Improving Paci?c Intertie stability using Slatt thyristor controlled series compensation, in Proc. PES Winter Meeting, Jan. 2000, pp. 1468-1470.

[14] H. Jin, G. Joós, and L. A. Lopes, An efficient switched-reactor/capacitor-based static var compensator, *IEEE Trans. Ind. Applicat.,* vol. 30, pp. 998–1005, Jul./Aug. 1994.

[15] L. A. C. Lopes, G. Joós, and B. T. Ooi, A PWM quadrature-booster phase shifter for AC power transmission, *IEEE Trans. Power Electron*., vol. 12, pp. 138–144, Jan. 1997.

[16] O. Simon, J. Mahlein, M. N. Muenzer, and M. Bruckmann, Modern solutions for industrial matrix-converter applications, *IEEE Trans. Ind. Electron.,* vol. 49, no. 2, pp. 401–406, Apr. 2002.

[17] P. Wheeler, J. Clare, L. Empringham, M. Apap, and M. Bland, Matrix converters, *Power Eng. J.*, vol. 16, no. 6, pp. 273–282, Dec. 2002.

[18] J. M. Gonzalez and J. M. Ramirez, AC/AC series converter in transient stability, in Proc. NAPS, Las Cruces, NM, Sep. 2007, pp. 205–211.

[19] J. C. R. Caro, Simple Topologies for power conditioners and FACTS controllers, *Ph.D. Thesis, Electrical Engineering department, Guadalajara University,* March 2009.

[20] P. L. So, Y. C. Chu, and T. Yu, Coordinated Control of TCSC and SVC for System Damping, *International Journal of Control, Automation, and Systems,* vol. 3, no. 2 (special edition), pp. 322-333, June 2005.

[21] R. Sadikovic, Damping controller design for power system oscillations, Internal Report, Zurich, 2004

[22] B. Pal and B. Chaudhuri, *Robust Control in Power Systems,* New York, Springer Science, 2005.

[23] S. Morkos and H. Kamal, Optimal Tuning of PID Controller using Adaptive Hybrid Particle Swarm Optimization Algorithm, *Int. J. of Computers, Communications & Control*, Vol. 7, No. 1, pp. 101-114, 2012.

[24] L. Fan, A. Feliachi, K. Schoder, Selection and design of a TCSC control signal in damping power system inter-area oscillations for multiple operating conditions, Electric Power Systems Research 62 (2002) 127-137.

[25] H. F. Wang, F. J. Swift, M. Li, Selection of installing locations and feedback signals of FACTS-based stabilisers in multimachine power systems by reduced-order modal analysis, IEE Proc.-Gener. Transm. Distrib., Vol. 144, No. 3, May 1997, pp. 263-269.

[26] M.W. Mustafa, N. Magaji, and Z. bint Muda, TCSC Control of Power System oscillation and Analysis using Eigenvalue Techniques, International Journal of Engineering & Technology IJET Vol: 9 No: 10, pp. 47-53.

[27] P. Kundur, *Power system stability and control*, New York: McGrew Hill, 1994.

Amin Safari received the B.Sc. and M.Sc. degrees in Electrical Engineering in 2007 and 2009, respectively. He received his Ph.D. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 2013. His areas of interest in research are Application of artificial intelligence to power system control design, FACTS device and fuzzy sets and systems. He has published more than 60 papers in international journals and conference proceedings.

Heidar Ali Shayanfar received the B.Sc. and M.S.E. degrees in Electrical Engineering in 1973 and 1979, respectively. He received his Ph.D. degree in Electrical Engineering from Michigan State University, U.S.A., in 1981. Currently, he is a Full Professor in Electrical Engineering Department of Iran University of Science and Technology, Tehran, Iran. His research interests are in the area of application of artificial intelligence to power system control design, dynamic load modeling, power system observability studies, voltage collapse, congestion management in a restructured power system, reliability improvement in distribution systems and reactive pricing in deregulated power systems. He has published more than 140 papers in international journals and 220 papers in conference proceedings. He is a member of the Iranian Association of Electrical and Electronic Engineers and IEEE.

Hossein Shayeghi received the B.Sc. and M.S.E. degrees in Electrical and Control Engineering in 1996 and 1998, respectively. He received his Ph.D. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 2006. Currently, he is an Associate Professor in Technical Engineering Department of University of Mohaghegh Ardabili, Ardabil, Iran. His research interests are in the application of robust control, artificial intelligence and heuristic optimization methods to power system control design, operation and planning and power system restructuring. He is author and co-author of six books in electrical engineering area all in Farsi, two book chapters in international publishers and more than 188 papers in international journals and conference proceedings.

Ahad Kazemi was born in Tehran, Iran, 1952. He received his M.Sc. degree in Electrical Engineering from Oklahoma State University, USA in 1979. He is currently an Associate Professor in Electrical Engineering Department of Iran University of Science and Technology, Tehran, Iran. His research interests are reactive power control, power system dynamics, stability and control and FACTS devices. He has published more than 250 papers in international journals and conference proceedings.

AUTHORS' ADDRESSES

Amin Safari
Heidar Ali Shayanfar
Ahad Kazemi
Center of Excellence for Power Automation and Operation, Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran.
email: asafari@iust.ac.ir; hashayanfar@gmail.com; kazemi@iust.ac.ir

Hossein Shayeghi
Technical Engineering Department, University of Mohaghegh Ardabili, Ardabil, Iran.
email: hshayeghi@gmail.com

Received: 2012-06-08
Accepted: 2013-03-15