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A Novel Current Injection Model of PWMSC for Control and Analysis of Power System Stability

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Abstract: This paper proposes a novel current injection model of Pulse width Modulation based Series Compensator (PWMSC), as new FACTS controller, for damping of low frequency oscillations. The PWMSC operates as a means of continuous control of the degree of series compensation through the variation of the duty cycle of a train of fixed frequency-pulses. The methodology is tested on the sample single machine power system including PWMSC controller by performing computer simulations for small and large distributions. MATLAB/ Simulink software package was used for the simulations.

Keywords: PWMSC, Current Injection Model, Dynamics Stability.

1 Introduction

Power system stability is defined as the ability of an electric network at initial operating condition to regain a state of operating equilibrium after being subjected to different disturbances [1]. Using dynamic controllers such as power system stabilizers, excitation systems and more recently Flexible AC transmission systems (FACTS) devices improves the system stability. To design the controllers, proper modeling of generators, the network and controller dynamics must be applied. 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 the enhancement of power system damping [2].

A problem of interest in power industry is the mitigation of power system oscillations. These oscillations are related to the dynamics of system power transfer and often exhibit poor damping. Various types of FACTS controller's first and second generations, particularly SVC, TCSC, STATCOM, SSSC, UPFC and IPFC are being used in literature in order to damp power system oscillations [3 – 8]. The main motivation of this work is to damp out the

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electromechanical oscillations using a newly developed PWM based series compensator with proposed injection model in a power system. These controllers are based on thyristors or a voltage source converter. However, more recently, new controllers based on PWM based series compensator (PWMSC) with AC link converters have been proposed [9 – 14], demonstrating that it is possible to attain similar control objectives.

The main objective of this work is to present a more detailed investigation on the AC link series compensator for stability enhancement. For modeling, the PWMSC is presented as a continuously controllable capacitive reactance. This paper describes a novel current injection model of PWMSC for low frequency oscillations analysis.

2 Mathematical Model of PWMSC

2.1 Literature review

Fixed and controlled series compensators have been used for many years in transmission lines for compensating line reactance in order to increase power transfer capability and enhance the transient stability in power networks. One advantage of the series compensators is the use of a control scheme that varies effective series reactance. Thereinafter, this scheme can provide an effective means of active and reactive power flow control in a transmission line. Conventional series FACTS devices proposed in literature can be classified in two major groups:

1) Thyristor controlled reactance, and

2) Synchronous controllable voltage sources.

The first group is usually implemented with line commutated thyristors [15] while the second is based on force-commutated voltage source converters. However, in recent years new devices based on AC link converters have been proposed [9 – 11]. 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. Such compensators have the advantage of being more simple in both power circuit structure and control.

This PWM-switched capacitor for series compensation is the dual of the shunt reactor switched by a PWM AC controller that is presented in [16]. A static phase-shifter is based on four switches.

PWM AC controller has also been discussed in literature [17]. In [9] the authors proposed the use of the PWM controlled capacitor to control active power on a transmission line with a simple structure that provides continuous control of the degree of series compensation by varying the duty cycle control.

A brief comparison of this PWMSC with the TCSC in small power system with three buses is presented in [10] where it is shown that the PWMSC is a smoother control alternative than the TCSC. A comparative evaluation between PWMSC and SSSC based on detailed switching models is presented in [16] showing 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. Since no practical PWMSC has been built and installed on a real power system so far, an estimation of composed components cost for these two controllers are also considered in [16]. The authors show that the cost of SSSC is higher than that of PWMSC for that particular application. The paper also highlight that the use of AC capacitors enables PWMSC to operate at higher temperatures, in contrast to DC capacitors used in SSSC, which are quite vulnerable to high temperatures. The three-phase vector switching converter is proposed to develop FACTS controllers which can control power flow in transmission system [12]. Authors have introduced a new FACTS device based on pulse width modulated ac link UPFC named Gamma controller. In [14, 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 [14]. Some transient stability studies with fixed duty cycle are discussed in [12] and [18]. In these papers, it is shown that the compensator does not provide enough damping for certain contingencies. Based on these preliminary studies, a better and current injection model for the PWMSC is proposed and studied in this paper.

2.2 Basic module of PWMSC

Fixed series capacitors have been used for a long time for increasing power transfer in long lines and providing a higher utilization level of limited transmission systems. They are also most economical solutions for this purpose. However, the control of series compensation using thyristor switches has been introduced for fast power flow control only 15–20 years ago. A newly developed AC link converter based series compensation, a FACTS controller, is presented. 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 line reactance and provide enough damping to system oscillation modes. Fig. 1 displays a realization of schematic diagram of the PWM series compensator which is embedded into a transmission line [19].

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 S_a, S_b and S_c are on, the capacitors are connected to the system through a series injection transformer.

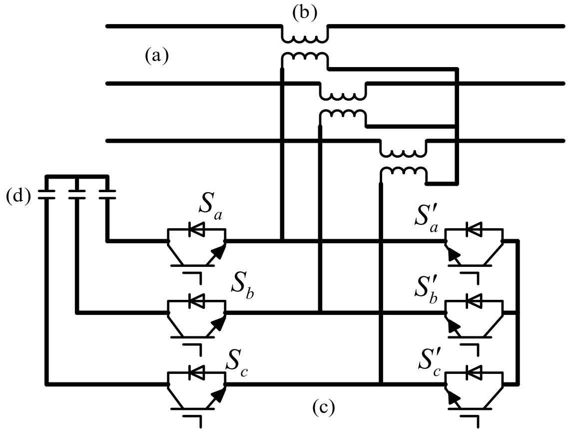

Fig. 1 – PWMSC *controller* (a) *Transmission line*; (b) *Series injection transformer*; (c) PWM *switches*; (d) *Compensating capacitors.*

When S'_a, S'_b and S'_c are on, the series injection transformer is shorted, thereby isolating the capacitors from the line. When impdendance is low at the primary winding, the primary behaves as a conductor. A little impedance is added by the transformer, but it can be neglected. In this structure, the bank of capacitors is connected in Y to the PWM AC converter [9, 10]. The compensator serves for continuous control of the degree of series compensation by varying the duty cycle of a single asynchronous train of fixed frequency pulses. 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. The differences between the PWMSC and TCSC controllers are the following:

- *Number of switches*: For minimal three-phase configuration, the TCSC requires six thyristors, while the PWMSC needs six IGBTs/GTOs, for an optimized PWMSC configuration based on two switches per phase as shown in Fig. 1.
- *Operating zone*: It is noticed that PWMSC, unlike the TCSC, presents no forbidden operating zone due to resonance.
- *Harmonics*: In the TCSC, switches are gated at line frequency. This results in generation of low frequency line current harmonics. This drawback can be mitigated by using the AC link controllers that switch at the line frequency with PWM AC controllers capable of switching at

frequencies significantly higher than line frequency with application of the GTOs or IGBTs [10].

2.3 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 main switches are on, the capacitors are connected to transmission line. Therefore, 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 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. Therefore, characteristic of the PWMSC at the primary transformer is essentially that of a controllable reactance. Inserting reactance can vary from slightly inductive to capacitive, depending on the duty cycle (*D*) of the PWM AC link converter. Mathematical expressions in the next section that describe reactance characteristics of the PWMSC and the injected reactance into the system are derived in the following section.

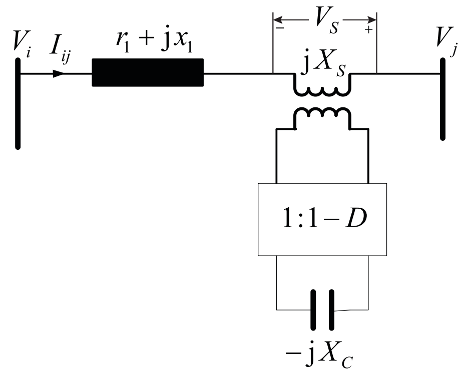

Fig. 2 – *Single line diagram of* PWMSC.

2.4 Mathematical analysis of PWMSC

For analyzing the PWMSC, a single phase equivalent model, shown in Fig. 2, is used. The primary series transformer is represented by a leakage reactance (X_T) in series with an ideal transformer at transmission line. In the secondary, there is a PWM AC link converter and a bank of capacitors with reactance X_C. The equivalent and injected impedances at transmission line may be calculated with state space averaging techniques as follows:

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

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

The n is the turns ratio of the transformer and X_{ij} is the reactance of the transmission line. Equations (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 impedance, 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 Fig. 3. In this figure, it is assumed that the designed PWMSC provides a series capacitive reactance of 0.35 p.u., for a line with 1 p.u. reactance. The leakage reactance of the series transformer is taken as 0.03 p.u. on the system base.

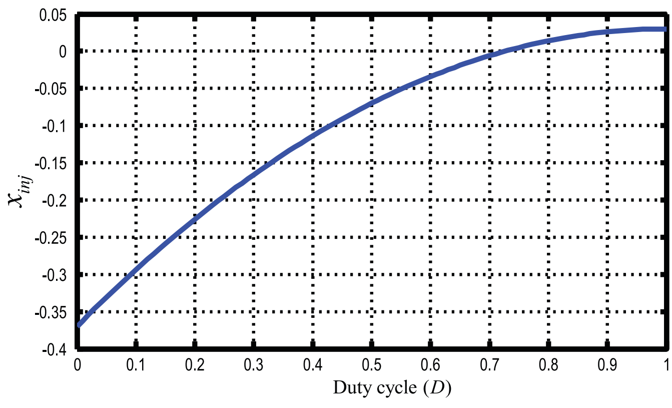

Fig. 3 – *Variation of the* PWMSC *based injected reactance with duty cycle.*

Equations (1) and (2) and Fig. 3 imply that the injected reactance using PWMSC can be varied continuously between two extreme values.

2.5 PWMSC current injection model

In order to effectively investigate the impact of series compensators on power systems effectively, appropriate models of these devices are very important. In this paper, we are proposing current injection model of PWMSC to study the effects of PWMSC on power network low frequency oscillations.

The installation of PWMSC changes the system bus admittance matrix Y_{bus} to an unsymmetrical matrix [20]. When the PWMSC is used for time domain simulations of multi-machine power systems, the modification of Y_{bus} is required at each stage. 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 a 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].

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 complex voltages at nodes *i* and *j*, and $V_S = -\mathrm{j}X_S I_{se}$ represents voltage across the PWMSC.

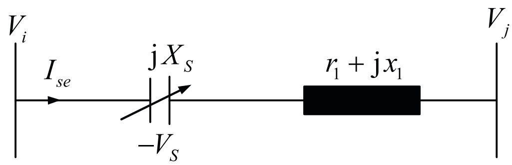

Fig. 4 – PWMSC *located in a transmission line.*

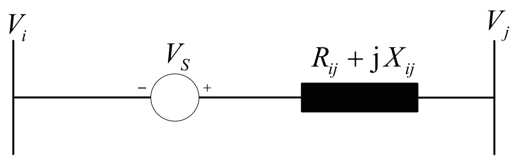

Fig. 5 – PWMSC *equivalent circuit.*

Fig. 4 implies as follows:

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

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

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

$$I_s = \frac{V_S}{R_{ij} + \mathrm{j}X_{ij}} = -\frac{\mathrm{j}X_s I_{se}}{R_{ij} + \mathrm{j}X_{ij}} . \tag{5}$$

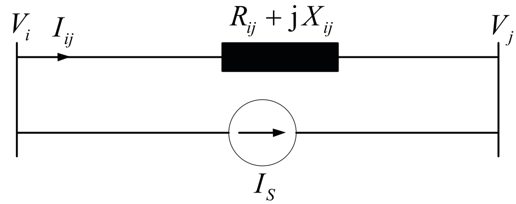

Fig. 6 – *Replacing voltage across the* PWMSC *by a current source.*

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

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

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

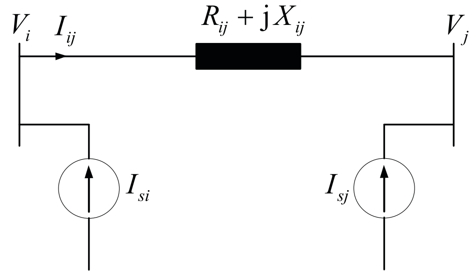

Fig. 7 – *Proposed current injection model for* PWMSC.

2.6 Dynamic control model of PWMSC

Fig. 8 shows a schematic diagram of the dynamic control model of PWMSC for typical oscillatory stability studies. It can be noticed that following a similar modeling approach, as in the case of another series compensator, line reactance is assumed to be controlled through the duty cycle *D*. This model does not consider power oscillation damping controller. The model includes an input signal and a reference signal $X_{S\mathrm{ref}}$ which is the initial value of the series compensator. These inputs are summed to produce an error signal which is fed into a first-order lag block. The lag block is associated with the duty cycle control and natural response of the PWMSC, and is represented by a single time constant T_{PWMSC}. 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, 23].

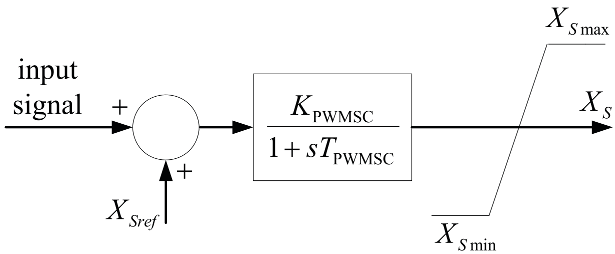

Fig. 8 – *The dynamic control model of* PWMSC.

3 Simulation Results

To investigate the proposed current injection 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 and for oscillation damping, the test system with PWMSC depicted in Fig. 9 is considered for analysis. The system [24] comprises a thermal generation station consisting of four 555 MVA, 24 kV, 60 Hz units connected to an infinite bus through a step-up transformer followed by two transmission circuits. The four generators are represented by an equivalent synchronous generator which has a 4$^{\text{th}}$ order model equipped with an automatic voltage regulator Type III of Simulink library (see Section 5.1). The full data of the system are presented in the Section 5.2. The following cases are included for the evaluation of the performance and effectiveness of the proposed dynamic and the study of damping low frequency oscillations using PWMSC.

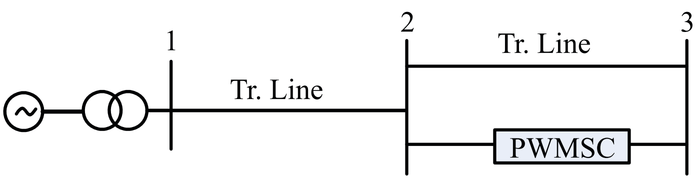

Fig. 9 – *Test system with* PWMSC.

***Case a*:** To assess the performance of the proposed model, a small disturbance of 0.2 p.u. input torque is applied to the machine at $t = 1$ s. The study is performed at nominal operating condition ($P = 0.75$ p.u. and $Q = 0.24$ p.u.). The results are shown in Figs. 10, 11, 12 and 13. The results suggest that the PWMSC with proposed current injection model achieves good performance and enhances greatly the dynamic stability of the power systems. Therefore, the use of PWMSC in a power network will improves the stability further even if the PSS is not installed on synchronous machine.

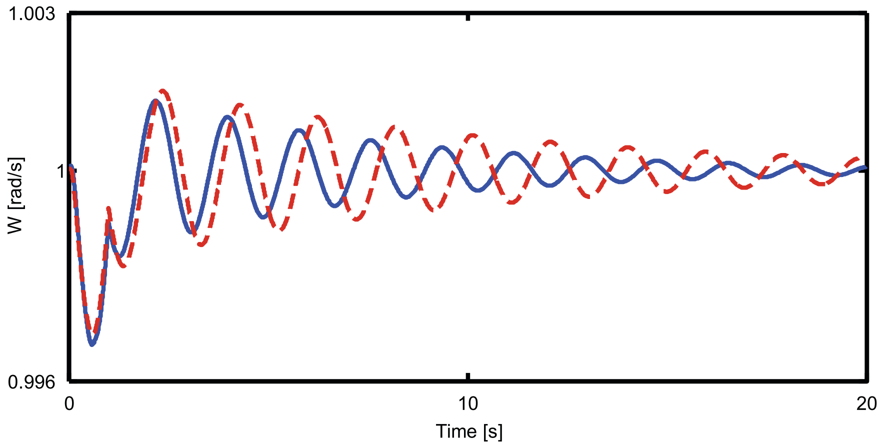

Fig. 10 – *Dynamic response for ω in case a*;
Solid (*with* PWMSC) *and Dashed* (*without controller*).

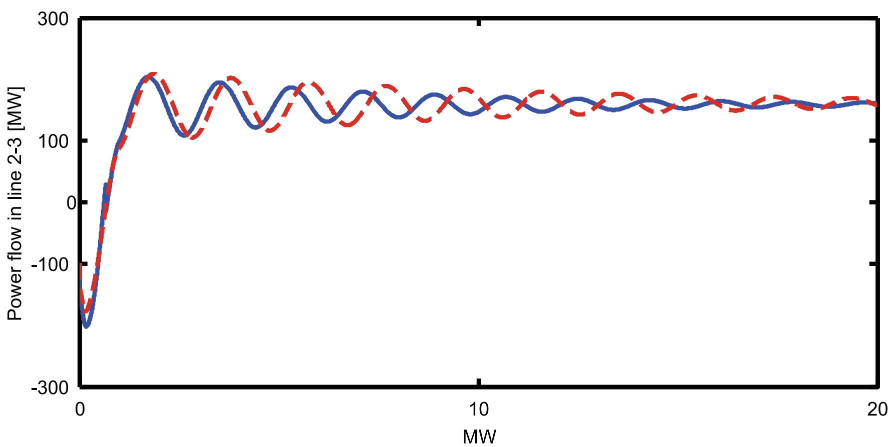

Fig. 11 – *Dynamic response for power flow in case a*;
Solid (*with* PWMSC) *and Dashed* (*without controller*).

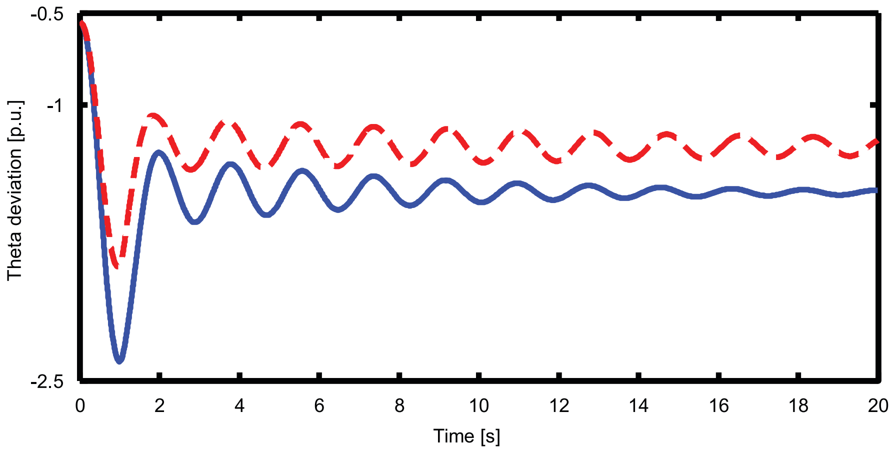

Fig. 12 – *Dynamic response for* $\Delta\delta$ *in case a*;
Solid (*with* PWMSC) *and Dashed* (*without controller*).

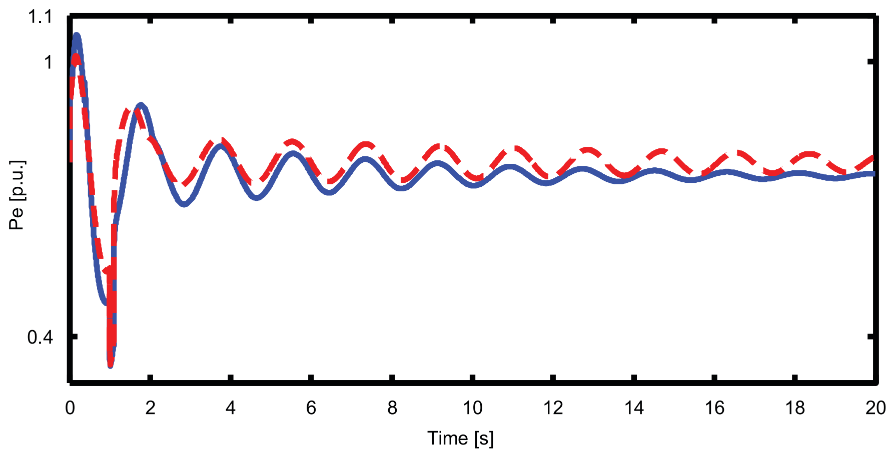

Fig. 13 – *Dynamic response for electrical power* (P_e) *in case a*;
Solid (*with* PWMSC) *and Dashed* (*without controller*).

***Case b*:** A three-phase fault of 100 ms duration is simulated at the middle of one of the line connecting Bus-2 and Bus-3. Figs. 14 and 15 present the speed of synchronous generator and power flow in line 2-3. It can be concluded that the PWMSC controller can effectively damp out very large oscillations with a good effect under the large disturbance.

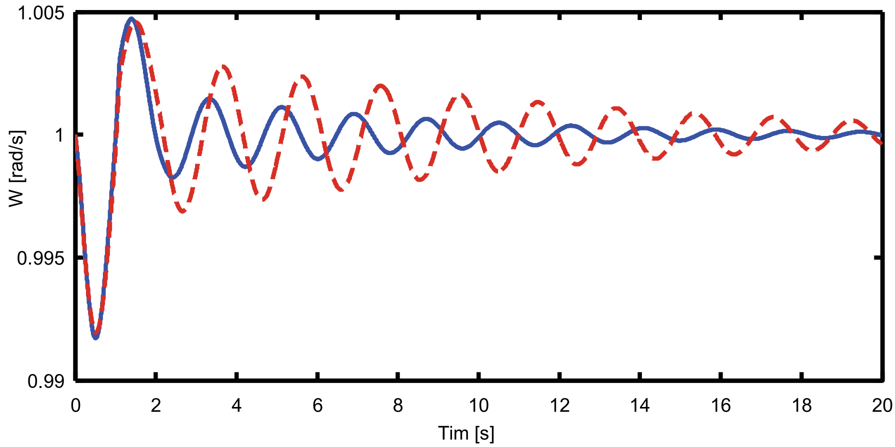

Fig. 14 – *Dynamic response for* ω *in case b*;
Solid (*with* PWMSC) *and Dashed* (*without controller*).

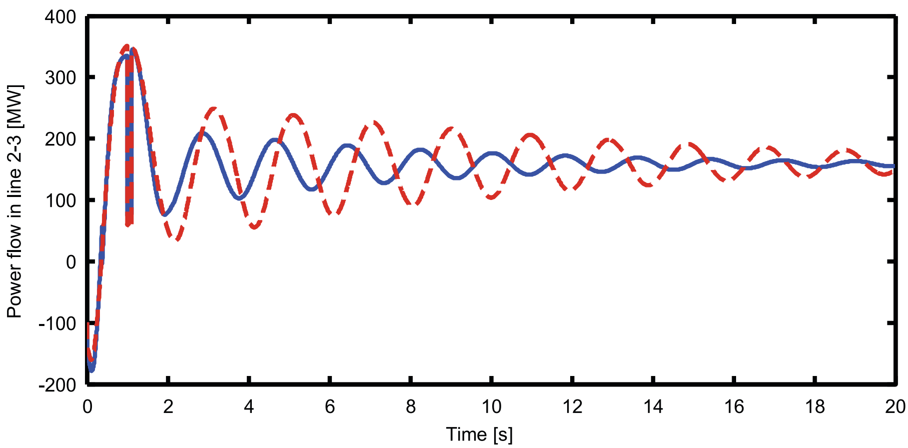

Fig. 15 – *Dynamic response for power flow in case b*;
Solid (*with* PWMSC) *and Dashed* (*without controller*).

***Case c*:** The operating condition is changed to another power level in p.u. such that $P = 0.85$, $Q_1 = 0.2$ with the fault unchanged. At this condition, the case study without controller becomes unstable, but PWMSC exhibit stable performance, which is depicted in Figs. 16 and 17. Therefore, the newly proposed controller is more flexible to change in operating condition of the system.

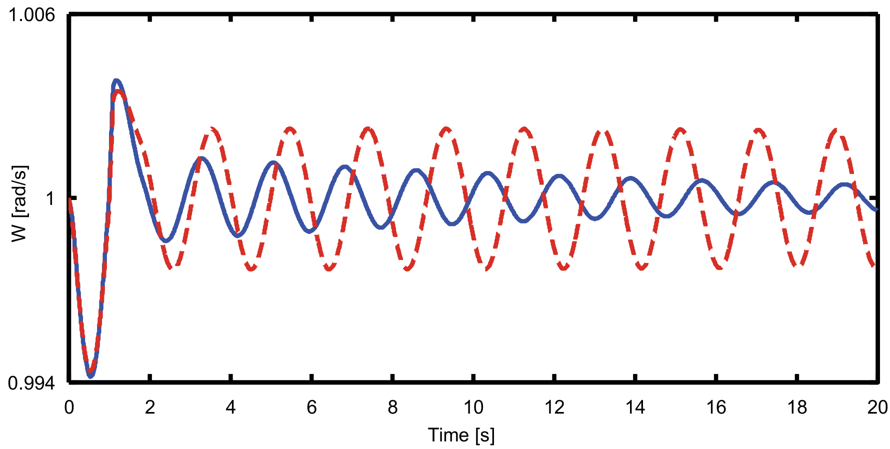

Fig. 16 – *Dynamic response for* ω *in case c*;
Solid (*with* PWMSC) *and Dashed* (*without controller*).

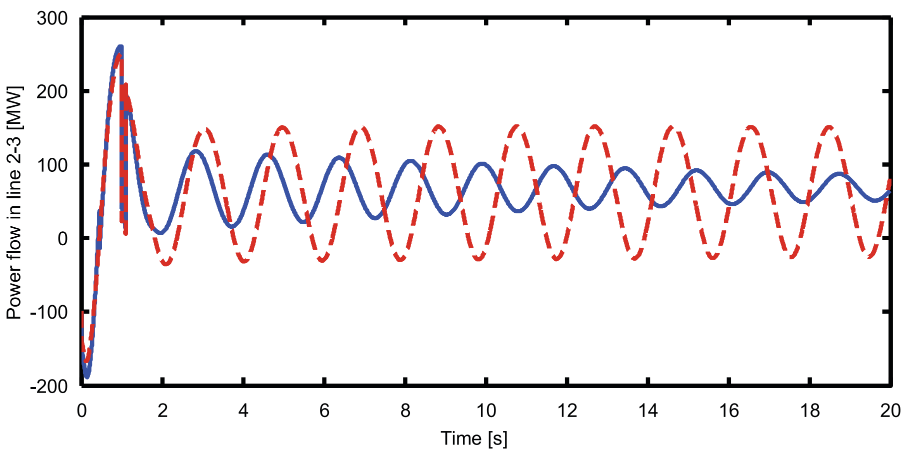

Fig. 17 – *Dynamic response for power flow in case c*;
Solid (*with* PWMSC) *and Dashed* (*without controller*).

4 Conclusion

A theory and the modeling technique of new controller based on PWM based switches were proposed and discussed in this paper. The basic module, steady state operation, mathematical analysis, current injection modeling, dynamic control model and performance of the PWMSC were also presented. The proposed model of the PWMSC is explained mathematically, and can be implemented in MATLAB/Simulink environment. It can further be extended for different applications in single machine power systems. The simulation results showed that the proposed method can effectively damp power system oscillations following small and large disturbances. Hence, it may be concluded that the PWMSC is certainly a competitive, given that the direct AC link converter principle of the PWMSC leads to generally more compact, more simple and durable controller, with no large DC link energy storage components and a more simple PWM based controller.

5 Appendix

5.1 The dynamics of the synchronous machine

$$\dot{\delta}_i = \omega_b(\omega_i - 1),$$

$$\dot{\omega}_i = \frac{1}{M_i}(P_{mi} - P_{ei} - D_i(\omega_i - 1)),$$

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}}(E_{fdi} - (x_{di} - x'_{di})i_{di} - E'_{qi}),$$

$$\dot{E}_{fdi} = \frac{1}{T_{Ai}}(K_{Ai}(v_{refi} - v_i + u_i) - E_{fdi}).$$

5.2 System parameters in per unit (p.u.)

– Generator:

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

– Automatic voltage regulator:

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

– Transformer and transmission lines:

$X_{Tr} = 0.15$, $X_{12} = 0.015$, $X_{23} = 0.3$.

– PWMSC:

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

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