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Comparative analysis for optimum position of A PWM based UPFC and ASVC applied to multi-machine systems with non-linear load model

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ABSTRACT

In this paper, a comparative analysis between two FACTS Devices in Power System has been carried out. In a power system network consisting of Multi-machine systems, transmission lines, transformers, and non-linear load model. In this case, a Unified Power Flow Controller (UPFC) and Advanced Static VAR Compensator (ASVC) are applied between two buses separately and their effects are analyzed and compared. Active and reactive Power flow between different buses and voltage regulation of the above FACTS devices is found out. Simulation of the system was carried out using MATLAB Program and the converters in both FACTS devices are analyzed and modeled based on pulse-width Modulation (PWM) method. From the simulation results, it is demonstrated that by varying the modulation index of the two devices it can control the distribution of active and reactive power flows. Furthermore, the comparison for the optimum operation for the two devices has been performed.

1. Introduction

Recent development of power electronics introduces the use of flexible ac transmission systems (FACTS) controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the voltage stability, steady state and transient stabilities of a complex power system (Kumkratug, 2009; Kumar and Nagaraju, 2007; Kazemi and Mahamnia, 2008; Panda and Patel, 2006). Among the available FACTS devices, the Unified Power Flow Controller (UPFC) is the most versatile one that can be used to improve steady state stability, dynamic stability and transient stability (Noroozian et al., 1997; Pandey and Singh, 2009; Zanench et al., 2009; Al-Mawsawi and Qader, 2001; Al-Mawsawi et al., 2002). The UPFC can independently control many parameters since it is the combination of Static Synchronous Compensator (STATCOM). In general, FACTS devices offer an alternative mean to mitigate power system oscillations. It has been reported in many papers that UPFC can improve stability of single machine infinite bus (SMIB) system and multi-machine system (Ghandhari et al., 2001; Kumkratug and Haque, 2003).

The installation of the Unified Power Flow controller (UPFC) (Gyugyi, 1992) and Advanced Static VAR Compensator (ASVC) in power systems has recently come under intensive investigation into its modelling and various control functions, including damping control for multi-machine power systems. Work has been done to model the UPFC and ASVC into multi-machine power systems in a steady-state mode of operation for studying power flow control (Ali and Al-Mawsawi, 2017; Al-Qallaf et al., 2014; Wang, 1999a; 1999b; Fuerte-Esquivel and Acha, 1997). Recently, some recent publications have been reported in comparison between FACTS devices. Damor et al. (2014) investigated the improvement of transient stability of a two-area power system, using a SVC, STATCOM, UPFC, and TCSC. The performance of UPFC is compared with other FACTS devices such as Thyristor Controlled Series Capacitor (TCSC), (STATCOM) and Static Var Compensator (SVC) respectively. Paramvir et al. (2016) did a comparative analysis of SVC, STATCOM and UPFC for voltage regulation in power system. Bawazir and Wazir (2014) focused to use two different devices of FACTS; Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller UPFC) in order to improve the voltage profile. The two devices are located in interconnected power system based on Loss Sensitivity Index (LSI) where LSI is compared with Continuation Power Flow (CPF) in term of system loss.

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However, all the above reported works done were based on the assuming that the load is linear of infinite bus. This assumption practically is not true.

This paper deals with the mathematical modelling and analysis of a Pulse-Width-Modulation (PWM) based UPFC and ASVC operating as voltage regulators implemented on a multi-machine power systems connected to a non-linear load model. The steady-state performance simulation results of the system are presented and compared for different value of modulation index. In addition, the optimum position of the UPFC and ASVC is investigated and compared.

2. Steady-state model of UPFC and ASVC

In recent years UPFC has been proposed to increase power flow as well as an aid for system stability through the proper design of their controllers (Gyugyi, 1989). It is becoming to be one of the most important FACTS devices since it can provide various types of compensation, i.e., voltage regulation, phase shifting regulation, impedance compensation and reactive compensation. The UPFC is implemented practically by using two similar solid-state phase voltage source converters (shunt compensation block and series compensation block) which are connected through a common DC link capacitor as shown in Figs. 1 and 2 and each converter is coupled with a transformer. In the last few years, a number of publications have appeared in the literature, which described the basic operating of the UPFC. Gyugyi et al. (1995) has proposed the concept of using the UPFC to control independently the real and reactive power flows at both the sending and receiving ends of the transmission line.

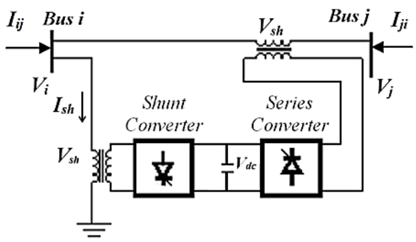

Fig. 1: A block diagram of UPFC

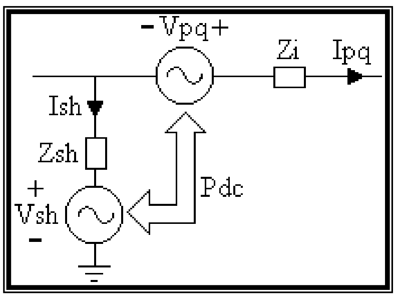

Fig. 2: Steady-state model of UPFC

The ASVC is composed of a three-phase GTO based voltage source inverter, shunt transformer and a dc voltage storage source. ASVC is one of the FACTS devices, which can compensate the reactive power in an efficient fast way. It is also called Static VAR Compensator (STATCOM) or Static Condenser (STATCON). The ASVC is a shunt FACTS device, which consists of a solid state three-phase source inverter, and it is used as a reactive power compensator. Its power electronic structure is illustrated in Figs. 3 and 4 by Wang (1999a, 1999b). The ASVC similar to UPFC can either absorb or supply reactive power whose capacitive or inductive output current can be controlled independent of the ac line voltage.

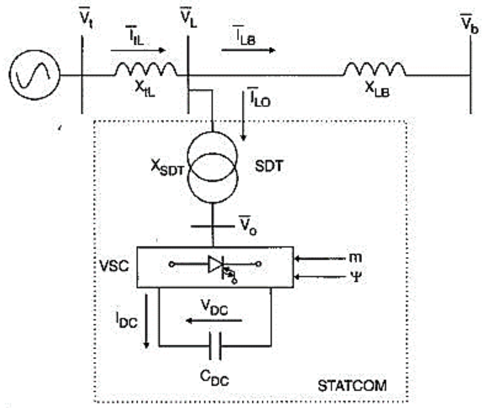

Fig. 3: Basic circuit arrangement of the ASVC

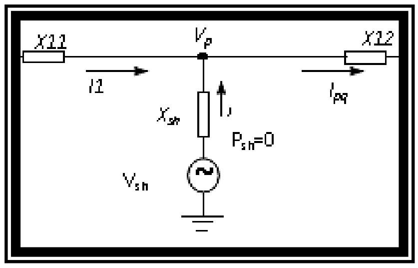

Fig. 4: Steady-state model of ASVC

3. Mathematical modeling of multi-machine systems with UPFC

The single line diagram of the study systems in which the UPFC and ASVC are implemented is shown in Fig. 5. Two synchronous machines feed active powers P_1, P_2 and reactive powers Q_1, Q_2 to the system transmission lines. V_1 is the sending end voltage of the synchronous machine (1), V_2 is the sending end voltage of the synchronous machine (2) with load angle δ_2, V_3 is the receiving end voltage with angle δ_1, and X_1, X_2, X_3, X_4 are the transmission lines impedance. For PWM based UPFC, V_{pq} is the series injected voltage of converter (2), and I_{pq} is the transmission line current passing through the series compensation block.

V_{sh} is the shunt voltage of converter (1) and X_{sh} is the leakage reactance of the shunt transformer, which is assumed to be pure inductive. If the system has a nonlinear load that depends on the terminal voltage V_3, then the active and reactive power could be characterized as follows:

$$P_3 = P_0 \times V_3^a \;\&\; Q_3 = Q_0 \times V_3^b \quad (1)$$

where, a and b are constant values and P_0 and Q_0 are the initial values of P_3 and Q_3 respectively.

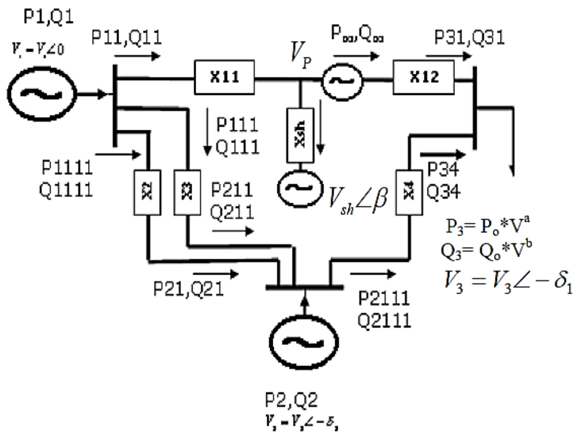

Fig. 5: The steady state model of the multi-machine systems with UPFC

Then the following equations can be developed from Fig. 5:

$$P_{sh} + P_{pq} = \frac{V_p \times V_{sh}}{X_{sh}}\cos(\emptyset - \beta + 90) - \frac{V_{pq} \times V_3}{X_{12}}\cos(-\emptyset + \delta_1 + 90) = 0 \quad (2)$$

$$\frac{V_3 \times (V_p + V_{pq})}{X_{12}}\cos(\emptyset - \delta_1 + 90) + \frac{V_2 \times V_3}{X_4}\cos(\delta_1 - \delta_2 + 90) - P_0 \times V_3^a = 0 \quad (3)$$

$$\frac{V_3 \times (V_p + V_{pq})}{X_{12}}\sin(\emptyset - \delta_1 + 90) - \frac{V_3^2}{X_{12}} + \frac{V_2 \times V_3}{X_4}\sin(\delta_1 - \delta_2 + 90) - \frac{V_3^2}{X_4} - Q_0 \times V_3^b = 0 \quad (4)$$

$$\frac{V_p}{X_{sh}}\cos(-\emptyset - 90) - \frac{V_{sh}}{X_{sh}}\cos(-\beta - 90) + \frac{(V_p + V_{pq})}{X_{12}}\cos(-\emptyset - 90) - \frac{V_3}{X_{12}}\cos(-\delta_1 - 90) + \frac{V_p}{X_{11}}\cos(-\phi - 90) = 0 \quad (5)$$

$$\frac{V_p}{X_{sh}}\sin(-\emptyset - 90) - \frac{V_{sh}}{X_{sh}}\sin(-\beta - 90) + \frac{(V_p + V_{pq})}{X_{12}}\sin(-\emptyset - 90) - \frac{V_3}{X_{12}}\sin(-\delta_1 - 90) - \frac{V_1}{X_{11}} + \frac{V_p}{X_{11}}\sin(-\phi - 90) = 0 \quad (6)$$

$$\frac{V_1 \times V_2}{X_2}\cos(-\delta_2 + 90) + \frac{V_1 \times V_2}{X_3}\cos(-\delta_2 + 90) + P_2 + \frac{V_2 \times V_3}{X_4}\cos(\delta_1 - \delta_2 + 90) = 0 \quad (7)$$

4. Mathematical modeling of multi-machine systems with ASVC

In order to operate the PWM based ASVC systems as a voltage regulator, the voltage injected by the ASVC is V_{sh} and it has a phasor angle β with respect to V_1. V_p is the transmission line voltage at which the device is connected with a phasor angle Φ with respect to V_1. In this case the reactive power is supplied or absorbed from the line, which will affect the power flow in the whole system. The steady-state model of ASVC presented in Fig. 4 has been replaced in Fig. 5 and the following equations have been developed:

$$P_{sh} = \frac{V_p \times V_{sh}}{X_{sh}}\cos(\emptyset - \beta + 90) \quad (8)$$

$$\frac{V_3 \times V_p}{X_{12}}\cos(\emptyset - \delta_1 + 90) + \frac{V_2 \times V_3}{X_4}\cos(\delta_1 - \delta_2 + 90) - P_0 \times V_3^a = 0 \quad (9)$$

$$\frac{V_3 \times V_p}{X_{12}}\sin(\emptyset - \delta_1 + 90) - \frac{V_3^2}{X_{12}} + \frac{V_2 \times V_3}{X_4}\sin(\delta_1 - \delta_2 + 90) - \frac{V_3^2}{X_4} - Q_0 \times V_3^b = 0 \quad (10)$$

$$\frac{V_p}{X_{sh}}\cos(-\emptyset - 90) - \frac{V_{sh}}{X_{sh}}\cos(-\beta - 90) + \frac{V_p}{X_{12}}\cos(-\emptyset - 90) - \frac{V_3}{X_{12}}\cos(-\delta_1 - 90) + \frac{V_p}{X_{11}}\cos(-\phi - 90) = 0 \quad (11)$$

$$\frac{V_1 \times V_2}{X_2}\cos(-\delta_2 + 90) + \frac{V_1 \times V_2}{X_3}\cos(-\delta_2 + 90) + P_2 + \frac{V_2 \times V_3}{X_4}\cos(\delta_1 - \delta_2 + 90) = 0 \quad (12)$$

$$\frac{V_p}{X_{sh}}\sin(-\emptyset - 90) - \frac{V_{sh}}{X_{sh}}\sin(-\beta - 90) + \frac{V_p}{X_{12}}\sin(-\emptyset - 90) - \frac{V_3}{X_{12}}\sin(-\delta_1 - 90) - \frac{V_1}{X_{11}} + \frac{V_p}{X_{11}}\sin(-\phi - 90) = 0 \quad (13)$$

5. Simulation results

Both systems have been modeled and simulated using Matlab package program. In both systems, an active power (P_2) supplied to the grid by the synchronous machine (2) is selected to be 2.479 p.u. and the active power (P_1) is considered as variable power demanded by the load. The impedance of the reactance of the transmission lines are selected to be: X_1=0.04 p.u., X_2=X_3=0.22 p.u. and X_4= 0.047p.u. (Stevenson, 1982). The constants a and b of the non-linear load given in Equations (1) and (2) are considered to be 1.38 and 3.22 respectively. The other parameters are P_0 = 6.381 p.u., Q_0 = 0.2458 p.u., V_1=1.018 p.u., and V_2=1.011 p.u.

Figs. 6, 7 and 8 show that at each position of the UPFC and ASVC, the voltage V_3, the active power P_3 and the reactive power Q_3 can be controlled by varying the modulation index. In case of UPFC, it can be seen that, V_3 is more sensitive to the variation of the modulation index as the position of the FACTS device is moving towards receiving end bus (V_3). In addition, it can be seen that the magnitude of V_3, P_3 and Q_3 when UPFC is installed at any position is higher than that obtained from ASVC. Finally, it was found that the optimum installation position for both devices is at the near to the sending terminal bus.

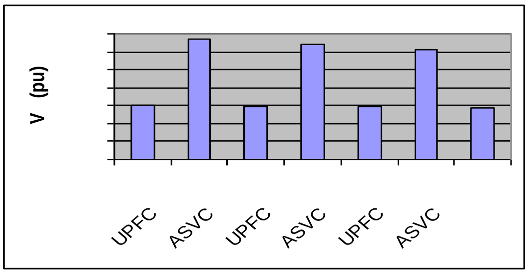

Fig. 6: The line voltage V_3 at different positions on the line with respect to bus terminal V_1

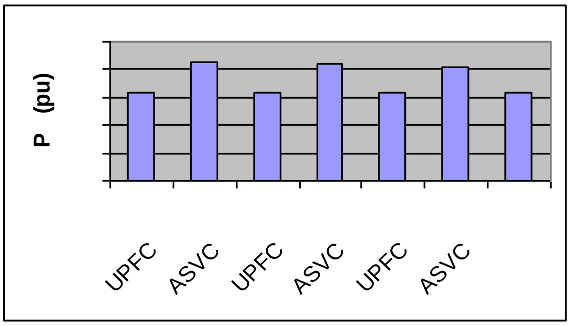

Fig. 7: The active power P_3 at different positions on the line with respect to bus terminal V_1

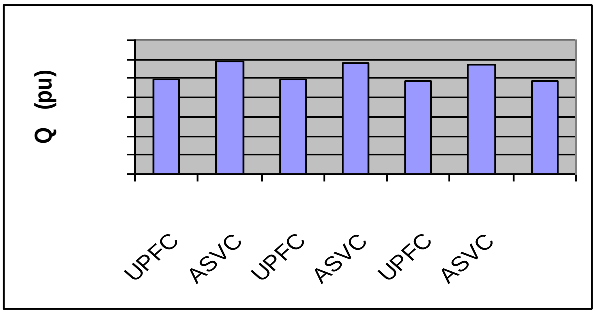

Fig. 8: The reactive power Q_3 at different positions on the line with respect to bus terminal V_1

6. Conclusion

The UPFC and ASVC as voltage regulator have been modeled. Both FACTS devices were investigated when they have been installed in multi-machine systems with non-linear load model. In both cases a PWM scheme has been used to control the operation of the converter in each FACTS device. It has been shown that by varying the modulation index in both devices, the active and reactive power flow distribution in the system transmission lines can be controlled. Furthermore, the simulation results have shown that the reactive power flow is highly sensitive to the variation of the modulation index in line connected to the devices, while it is much less sensitive to the variation of modulation index on the other lines. In addition, the effect of the installation location of such FACTS devises has been discussed. It was found that the magnitude of receiving terminal voltage, active and reactive output power when UPFC is installed at any position is higher than that obtained from ASVC. Furthermore, it was found that the optimum installation position for both devices is at the near receiving end bus.

Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

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