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AN ADVANCED STATIC VAR COMPENSATOR BASED ON A THREE LEVEL IGBT INVERTER MODELLING ANALYSIS AND ACTIVE POWER FILTERING

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This paper presents the dynamic performance analysis of an Advanced Static Var Compensator (ASVC) using three-level neutral point-clamped voltage source inverter. The paper presents the principles of operating and the method of reference currents generation. The dynamic behaviour of the system is further analysed using Matlab/Simulink with SimPower Systems toolbox through a set of simulation tests. The results obtained have been applied to an active power filter which might lead to the design of a robust controller for current harmonics and reactive power applications.

K e y w o r d s: three level inverter, robust control, ASVC, PI control, Harmonics, Reactive power, active filter, IGBT

1 INTRODUCTION

Harmonics are usually generated by three-phase converters such as variable-frequency drives, dc-adjustable speed drives, and switch-mode power supplies. Classical solutions use passive filters, to reduce line current harmonics and to compensate the reactive power [1].

The fast growing development of ultra rapid power switching devices and the desire to reduce such harmonics has lead to the increase in use of converters for large scale reactive power compensation [2]. However, for very high power application and voltages these SVC's are unsuitable. Moreover, Active Power Filters (APF) have been developed since 1983, when one of the first prototype based on instantaneous power theory was reported in [3, 4]. Such an APF is made up of two level voltage source inverter and presents a fast response time, reduced harmonic pollution. However, for very high power application and voltages to minimize harmonics injection from an APF into the system, various multilevel voltage source inverter configurations have been suggested in [5].

Recently, a neutral point clamped inverter or three-level inverter has been reported in the literature [3]. It has the advantages that the blocking voltage of each switching device is one half of dc link voltage and the harmonics contents output voltage are far less than those of two-level inverter at the same switching frequency.

This paper presents the modelling and analysis of this type of inverter used for static var compensation as well as for active power filtering and reactive power compensation. The APF uses three-level voltage source inverter (VSI) transforming a DC component to AC through a set of capacitors, which are used, as a power storage device. Furthermore, a simplified mathematical model of the ASVC is derived, operation principle and control algorithm of the APF is derived, and various simulation results are presented using MATLAB Simpower Systems toolbox [6, 17, 20].

2 PROPOSED SYSTEM CONFIGURATION

2.1 Main circuit configuration

The static VAR compensator (ASVC) which uses a three-level converter of the voltage source type is shown in Fig. 1.

The main circuit consists of a bridge inverter made up of twelve power IGBT's with antiparallel diodes, which is connected to the three-phase supply through a reactor, X_s of small value. Two capacitors are connected to the dc side of the converter.

2.2 Operating principle

The operation principles of the system can be explained by considering the per-phase fundamental equivalent circuit of the ASVC system as was shown in [10]. Figure 2 shows the equivalent circuit of the APF system.

Shunt active power filter injects AC power current i_c to cancel the main AC harmonic contents. The line current i_s is the result of summing the load current i_L and the compensating current i_c

$$i_s = i_L + i_c \,.$$

3 MATHEMATICAL MODEL OF THE ASVC

The modelling of the system is carried out under the following assumptions [3]:

1) all switches are ideal,
2) the source voltage are balanced,

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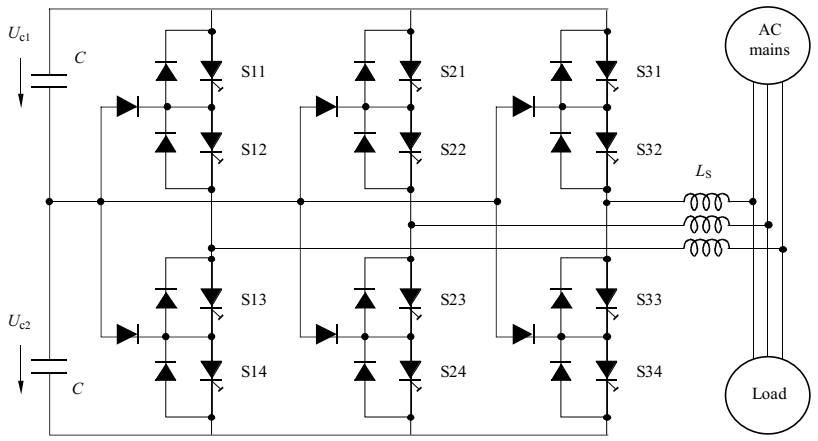

Fig. 1. Power Circuit of the ASVC

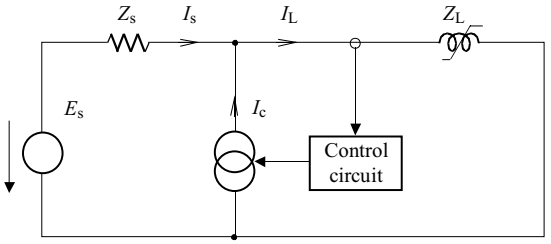

Fig. 2. APF equivalent circuit

3) the total losses in the inverter are represented by lumped resistor Rs,
4) the harmonic contents caused by switching action are negligible.

Figure 3 shows a simplified equivalent circuit of the ASVC. Using matrix form, the mathematical model per phase is given by

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & 0 & 0 \\ 0 & -\frac{R_s}{L_s} & 0 \\ 0 & 0 & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} v_a - e_a \\ v_b - e_b \\ v_c - e_c \end{bmatrix}. \tag{1}$$

The model of inverter output voltage is given by

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \left\{ \begin{bmatrix} F_{11}F_{12} \\ F_{21}F_{22} \\ F_{31}F_{32} \end{bmatrix} U_{c1} - \begin{bmatrix} F_{13}F_{14} \\ F_{23}F_{24} \\ F_{33}F_{34} \end{bmatrix} U_{c2} \right\} \tag{2}$$

with F_{ki}: function of connection, defining the state of the switch, $F_{ki} = 1$ if the switch is closed and 0 otherwise,
K: number of the arms ($k = 1, 2, 3$),
I: number of the switches of the arm ($I = 1, 2, 3, 4$)
and the dc side currents are given by

$$\begin{aligned} i_{d1} &= F_{11}F_{12}\, i_a + F_{21}F_{22}\, i_b + F_{31}F_{32}\, i_c \\ i_{d2} &= F_{13}F_{14}\, i_a + F_{23}F_{24}\, i_b + F_{33}F_{34}\, i_c\,. \end{aligned} \tag{3}$$

The mode of the capacitor voltage is given by

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} U_{c1} \\ U_{c2} \end{bmatrix} = \frac{1}{C}\begin{bmatrix} i_{d1} \\ -i_{d2} \end{bmatrix}. \tag{4}$$

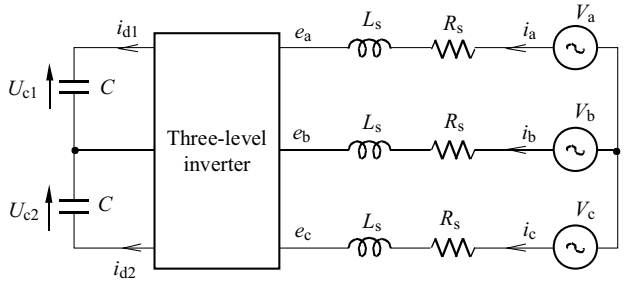

Fig. 3. Equivalent Circuit of the ASVC

4 PROPOSED CONTROL STRATEGY

4.1 Controller Design

In order to synthesize the control strategy of the system, the analysis is carried out on an analysis on (qd) axes [4] and the inverter is controlled by a programmed PWM strategy [5]. This PWM is used to eliminate the harmonics of level 3,5,7, and 9, [4] Fig. 4.

To achieve fast dynamic response it is required to control the phase angle α of the inverter output voltage which in turn leads to a change of the capacitor voltages U_{c1} and U_{c2}. Small signal equivalent model system is used to calculate the transfer function of the system.

$$\frac{Qc(s)}{\alpha(s)} = \frac{N(s)}{M(s)}$$

with

$$N(s) = \frac{V_s^2}{L}\Big[s^2 + \frac{R_s}{L}s + \frac{d^2}{2LC}\Big]$$

$$M(s) = s^3 + \frac{2R_s}{L}s^2 + \Big\{\Big[\frac{R_s}{L}\Big]^2 + \frac{d^2}{2LC} + \omega^2\Big\}s + \frac{d^2R_s}{2L^2C}\,.$$

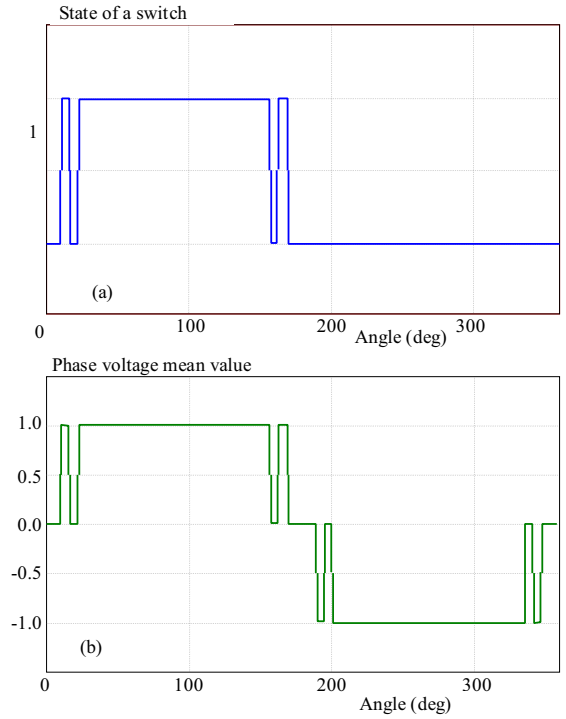

Fig. 4. Proposed switching pattern with selective harmonic elimination

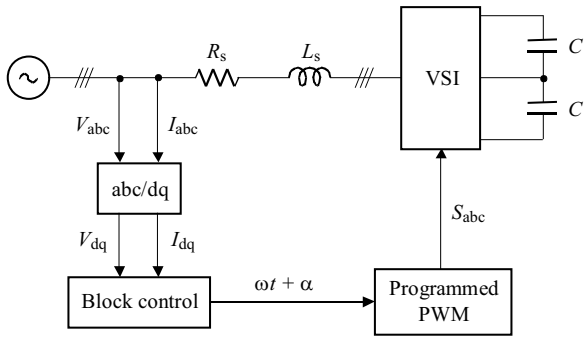

Fig. 5. Main circuit and control block diagram

The ASVC control scheme is illustrated in the block diagram of Fig. 5. For simplicity a conventional PI controller to study dynamic behaviour of the system is ussed. In the other hand we will use the first results to synthesize robust controller.

4.2 Control algorithm

The control algorithm of the proposed APF is based on the strategy resulting from the instantaneous reactive power theory initially developed by Akagi *et al* [2].

The Generalized Theory of instantaneous Reactive Power in three-phase circuits, also known as instantaneous power theory, or p-q theory. The p-q theory consists of an algebraic transformation (Clarke transformation) of three-phase voltages and currents in the *abc* coordinates to the $o\alpha\beta$ coordinates, followed by the calculation of the $p-q$ theory instantaneous power components.

Figure 6 represents the states of harmonics currents references calculation (use this as a reference). The load currents and the AC side voltages are measured and transformed into $\alpha\beta$ components using equations $(2, 3)$.

The instantaneous active and reactive power components flowing in the load are calculated by equations $(4, 5)$. The gating signals are obtained using multilevel hysteresis comparison to determine the switching instants of each phase leg [7–9].

The approach is to use two hysteresis bands, each band representing the switching between two adjacent voltage levels.

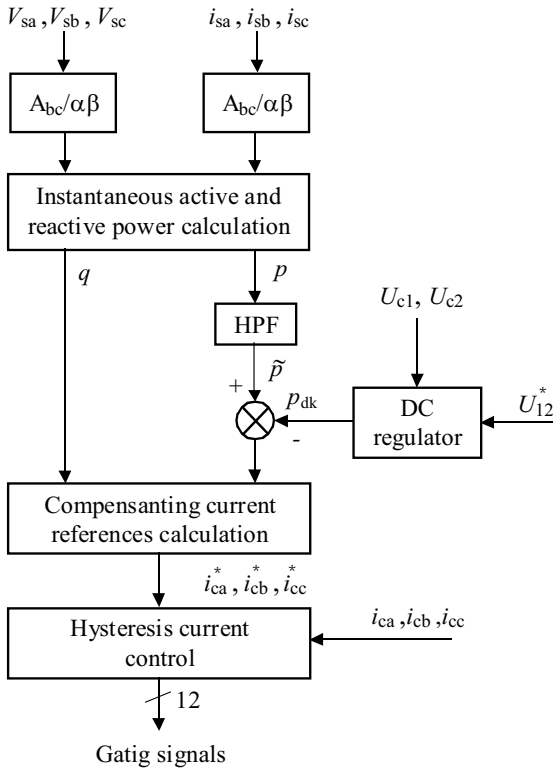

Fig. 6. State diagram of harmonics currents references calculation

5 SIMULATION RESULTS

To check the validity of the model described above a set of simulations tests have been carried out to analyse the system under steady state and transient conditions using MATLAB. This will certainly lead to the design of a robust controller [6, 7, 14].

Computer simulation is carried out using the system parameters given by $f = 60\,(\text{Hz})$, $W = 2\pi fVs = 550\,(\text{V})$, $Rs = 0.4\,(\Omega)$, $L = 10\,(\text{mH})$, $C = 1000\,(\mu\text{F})$. Based on the linear model described above and using root locus technique the parameters of the controller are found to be [8]

$$K_p = 8.24 \times 10^{-6}\,, \quad Ki = 1.42 \times 10^{-4}$$

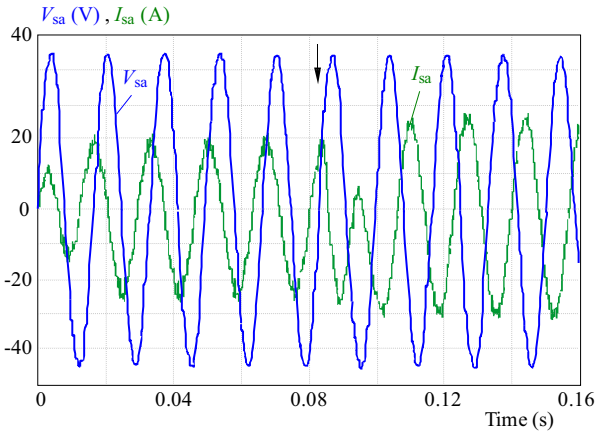

Fig. 7. State diagram of harmonics currents references calculation

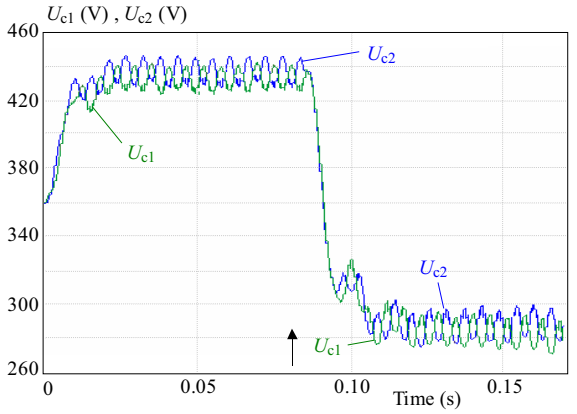

Fig. 8. Inverter dc bus voltages U_{c1} U_{c2}

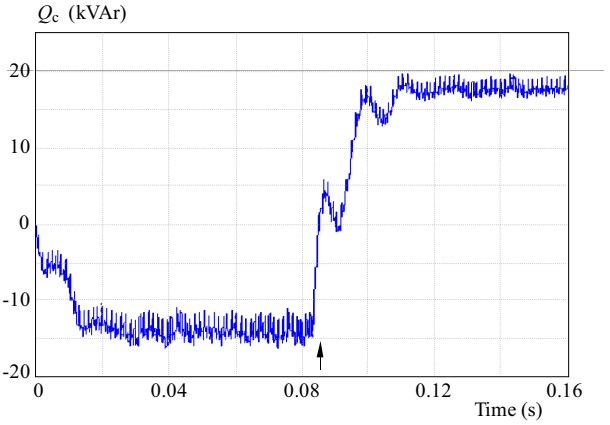

Fig. 9. Reactive power response

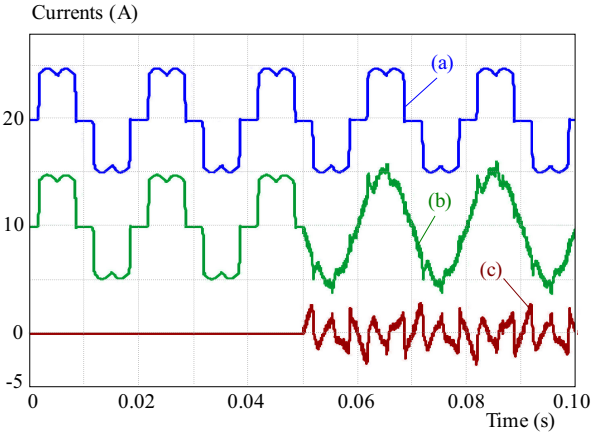

Fig. 10. (a) – load current, (b) – source current, and (c) – active filter current

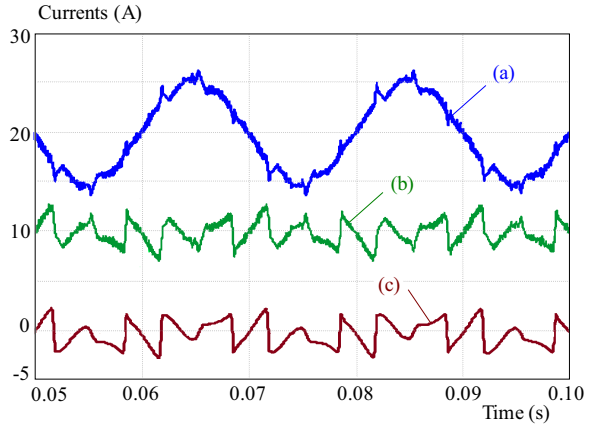

Fig. 11. (a) – line current, (b) – AC filter current, and (c) – reference filter current

The amplitude of the reference was adjusted to cause the system to swing from leading to lagging mode.

Figure 7 shows the simulated current and voltage waveforms to step reference changes from 20 kVAr leading to −20 kVAr lagging.

We notice an increase of the amplitude of the harmonic in leading mode with respect to lagging mode.

Figure 8 represents transient voltage across the two capacitors after a sudden change in reference.

We notice a fluctuation of voltages U_{c1} and U_{c2} round an average value and a difference of amplitude and waveforms of the voltage U_{c1} and U_{c2} for the two operating modes.

Figure 9 shows the simulated transient response of the reactive power response to a sudden change in reference.

The viability of the proposed active power filter was validated by computer simulation using Power systems Matlab/Simulink.

The active power filter control technique was proved by compensating the reactive power and current harmonic components generated by three-phase bridge rectifier (Figures 10 and 11).

The hysteresis bands were fixed at $\pm 0.1A$. DC capacitors voltages were rated at 310 V and the AC mains to 220 V_{rms}.

6 CONCLUSION

A mathematical modelling of the dynamic performance analysis of an Advanced Static Var Compensator (ASVC) using three-level voltage source inverter has been presented in this paper.

Moreover, an active power filter implemented with the same inverter has also been proposed in this paper. The

dynamic behaviour of the system was analysed using MATLAB through a set of simulation tests which have lead to the design of an inexpensive controller for reactive power applications.

The reference currents signals were generated using the instantaneous power theory. The gating signals were determined using multilevel hysteresis technique.

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