

Modeling and Analysis of A New Decoupled Control Strategy Applied to an Advanced Static VAR Compensator

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Abstract

A high performance advanced static VAR compensator (ASVC) which uses a voltage source inverter is presented and analyzed in this paper. The ASVC system is modeled using the d-q transform and employs a programmed PWM voltage wave shaping pattern to simplify the logic software and hardware requirements.

The inverter system can compensate leading and lagging reactive power supplied to the load connected to the supply. This model is used to design decoupled control strategy, which is based on the control of the modulation index and the phase angle of the switching pattern.

Simulated results obtained with MATLAB are also presented and discussed to validate the model.

Keywords : reactive power, inverter, programmed PWM, ASVC, d-q transform

Résumé

Un compensateur statique d'énergie réactive de type avancé qui utilise un onduleur à source de tension est étudié et analysé dans cet article. Le compensateur statique d'énergie réactive sera modélisé dans les axes de Park et utilisera la technique de MLI (modulation de la largeur d'impulsion) programmée pour simplifier les exigences d'une réalisation pratique.

Le système obtenu peut compenser une puissance réactive capacitive ou inductive. La modèle mathématique obtenu va être utilisé pour la conception d'une commande par découplage basée sur le contrôle de l'indice de modulation et la phase de l'onde de la MLI.

Des résultats de simulation obtenus avec le logiciel MATLAB seront présentés et interprétés.

Mots clés : puissance réactive, onduleur, MLI programmée, Compensateur statique de puissance réactive, transformation d-q

1. INTRODUCTION

Until now, reactive power has not yet a real physical meaning, but it is recognized as an essential factor in the design and good operation of the power system.

Real and reactive power on a transmission line in an integrated network is governed by the line impedance, voltage magnitudes, the angle difference at the line ends, and the role line is playing in maintaining network stability under dynamic contingencies. Power transfer in most integrated transmission systems is constrained by transient stability, voltage stability, and/or power stability. Reactive power (VAR) compensation or control is an essential part in a power system to minimize power transmission losses, to maximize power

transmission capability, and to maintain the supply voltage. It is increasingly becoming one of the most economic and effective solutions to both traditional and new problems in power transmissions systems. It is well-established practice to use reactive power compensation to control the magnitude of the voltage at a particular bus bar in any electric power system. In the past, synchronous condensers, mechanically switched capacitors and inductors, and saturated reactors have been applied to control the system voltage in this manner [1][2].

Since the late 1960s, thyristor controlled reactor (TCR) devices together with fixed capacitor or thyristor switched capacitor (TSC) have been used to inject or absorb reactive power [1].

Series compensation is the control of the equivalent line impedance of a transmission line. The introduction of external components (either capacitive or inductive) is used to change the apparent reactance of the line. The controllable series compensator such as the thyristor controlled series compensation (TCSC) has been developed to change the apparent impedance of a line by either inductive or capacitive compensation, facilitating active power transfer control. The thyristors control the conduction period of the reactor to vary the overall effective impedance of the circuit. The TCSC suffers from the disadvantages that it generates low order harmonic components into the power system.

TCSC's are usually connected in series to conventional line series capacitors. They may consist of one or several identical modules. Each module has a small thyristor controlled reactor in parallel to the segment series capacitor. Although the TCSC is primarily used for regulating the power flow, though varying its effective reactance inserted in series with the transmission line, it may also be used for voltage stabilization. In this case, the output reads terminal voltage within a tight band.

Recently, voltage source converter using GTO thyristor have been developed to operate as static VAR compensators [3-6]. These are known as ASVC. Such converters may resemble the operation of synchronous condensers but in a static manner. For these devices, a converter transformer is always needed to complement the function of the power electronics switches to perform system VAR compensation and may also be used to connect the device to the high voltage bus. The converter supplies reactive power to the network by increasing the synthesized inverter output voltage. Similarly, the ASVC absorbs VARs from the network by reducing the output voltage below the network voltage, no large power components such as capacitor banks or reactors are used. Only a small capacitor is employed to provide the required reference voltage level to the inverter. In contrast to the TCR/FC or TCR/TSC schemes bulky and experimental passive elements are not required.

The proposed static VAR compensator uses a programmed PWM voltage wave shaping pattern which has the advantage of less harmonic components of the reactive current and better displacement factor of the supply current. It can be easily stored in an EPROM

thus simplifying logic software and hardware requirements.

The use of an optimized PWM voltage wave shaping patterns allows significant reduction in the filter components values and size.

In this paper, the mathematical model of the proposed static VAR compensator is used to design decoupled control strategy, which is based on the control of the modulation index and the phase angle of the switching pattern.

Simulated results obtained with MATLAB are also presented and discussed to validate the model.

2. MAIN OPERATING PRINCIPLES OF THE ASVC

2.1 Main circuit configuration

The proposed static VAR compensator (ASVC) which uses a programmed PWM switching pattern for the DC-to-AC converter of the voltage source type is shown in Fig. 1.

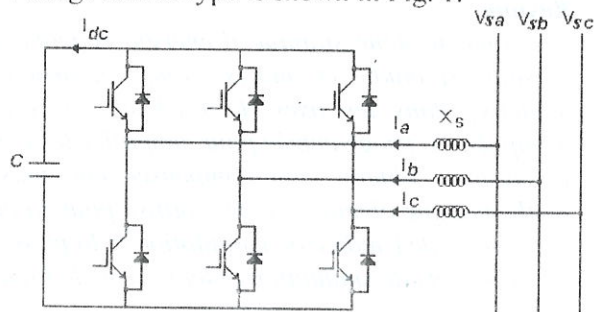


Fig.1 Power Circuit of the ASVC.

The major system component is a three phase PWM forced commutated voltage source inverter. The ac terminals of the inverter are connected to the ac mains through a first order low pass filter. Its function is to minimize the damping of current harmonics on utility lines. The dc side of the converter system is connected to a dc capacitor which carries the input ripple current of the inverter and is the main reactive energy storage element. The dc supply provides a constant dc voltage and the real power necessary to cover the losses of the system.

Fig. 2 shows a simplified equivalent circuit of the ASVC as given in [7]. In this representation, the series inductance L_s accounts for leakage of the transformer and R_i represents the active losses of the inverter and transformer. C is the capacitor on the dc side. V_{oa} and V_{sa} are the amplitude of the fundamental of the output voltage of the converter and phase voltage of the supply respectively.

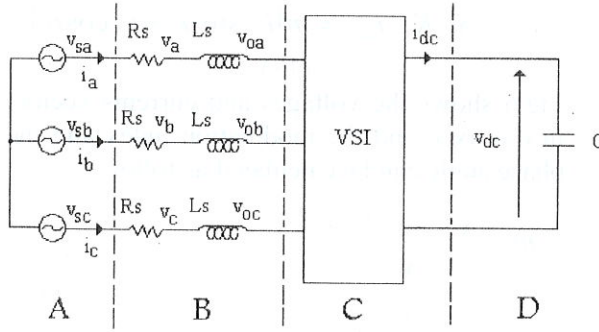


Fig.2 Simplified Circuit of the ASVC

2.2 Main circuit configuration

The ASVC in steady state will generate a leading reactive current when the amplitude of the fundamental of the output voltage V_{oa1} is larger than the voltage of the supply V_{sa} , and it will draw a lagging current from the supply when V_{oa1} is smaller than V_{sa} as shown in Fig.3. The circuit is therefore a static equivalent of synchronous compensator. The basic operating principle means that the circuit can produce rated or even overload VARs over a wide range of AC voltage conditions and give a significantly wider operating range in comparison to a conventional TSC-TCR SVC [1] [2] [7].

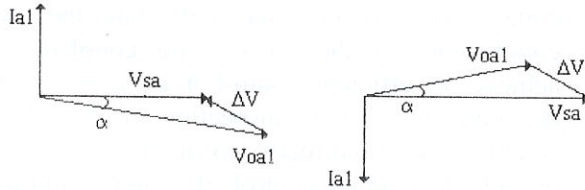


Fig.3 Phasor Diagram for leading and lagging mode.

2.3 Programmed PWM generation pattern

A programmed PWM switching pattern which allows the elimination of selected number of harmonics is continuously applied to the six controlled switches. This method is used because it offers better voltage utilization and lower switching frequencies thus less stress on switching devices and reduction of the switching losses (increase of the efficiency of the converter).

The size of the ac side reactance filter is minimized, and the output voltage is controlled by applying previously stored switching patterns to the six controlled switches.

The switching angles of the programmed PWM pattern are obtained by the resolution of a set of nonlinear equations as shown in [8], [9].

The programmed PWM used in this paper is obtained by eliminating 13 harmonics and the

modulation index varying from 0 to 1.15. The switching angle trajectories obtained are shown in Fig. 4.

3. MODELING AND ANALYSIS OF THE SYSTEM

Before making control design a mathematical model based on d-q reference frame will be established, the original circuit is partitioned to several basic sub-circuits as shown in Fig.2.

All quantities will be transformed in d-q reference frame using matrix K given by :

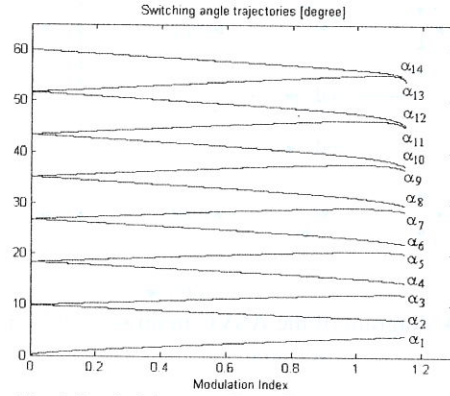


Fig.4 Switching angle trajectories for eliminating 13 harmonics

$$K = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ \sin(\omega t) & \sin(\omega t - 2\pi/3) & \sin(\omega t + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (1)$$

$$K^{-1} = K^T \quad (2)$$

$$X_{qdo} = K X_{abc} \quad (3)$$

3.1 Transform of part A

The voltage source of the supply is given by :

$$v_{s,abc} = \sqrt{\frac{2}{3}} V_s \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 2\pi/3) \\ \sin(\omega t + 2\pi/3) \end{bmatrix} \quad (4)$$

In d-q frame it given by :

$$v_{s,qdo} = K v_{s,abc} = \begin{bmatrix} 0 \\ V_s \\ 0 \end{bmatrix} \quad (5)$$

3.2 Transform of part B

Voltages and currents in the part of resistor and inductor are expressed as follows:

$$\frac{di_{abc}}{dt} = -\frac{R_s}{L_s} i_{abc} + \frac{1}{L_s} (v_{s,abc} - v_{o,abc}) \quad (6)$$

in the d-q frame :

$$\frac{d}{dt} \begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & -\omega \\ \omega & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} v_{sq} - v_{oq} \\ v_{sd} - v_{od} \end{bmatrix} \quad (7)$$

From equation (7), the block diagram of the ASVC main system in d-q frame is established and depicted in Fig.5.

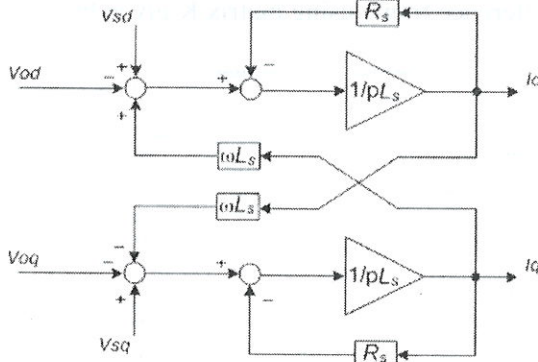


Fig.5 Block diagram of the ASVC main system in d-q frame.

3.3 Transform of part C and D

Under the assumption that harmonic components generated by the switching pattern are negligible, the switching function S can be defined as follows:

$$S = \begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} = \sqrt{\frac{2}{3}} m \begin{bmatrix} \sin(\omega t + \alpha) \\ \sin(\omega t + \alpha - 2\pi/3) \\ \sin(\omega t + \alpha + 2\pi/3) \end{bmatrix} \quad (8)$$

The modulation index is given by:

$$MI = v_{o,peak} / v_{dc} = \sqrt{\frac{2}{3}} m \quad (9)$$

α is the phase angle which relates the phase difference between source voltage and output voltage of inverter.

Now, the output voltage of the inverter and the capacitor dc current can be expressed as follows:

$$v_{o,abc} = S v_{dc} \quad (10)$$

$$i_{dc} = S^T i_{abc} \quad (11)$$

In the d-q frame:

$$v_{o,qdo} = K S v_{dc} = m \begin{bmatrix} \sin \alpha \\ \cos \alpha \\ 0 \end{bmatrix} v_{dc} \quad (12)$$

$$i_{dc} = S^T K^{-1} i_{qdo} = m (i_q \sin \alpha + i_d \cos \alpha) \quad (13)$$

Fig.6 shows the voltages and currents vectors in d-q axis, and the modulation index and the phase angle can be calculated as follows:

$$m = \frac{\sqrt{v_{oq}^2 + v_{od}^2}}{v_{dc}} \quad (14)$$

$$\alpha = \tan^{-1} \left(\frac{v_{oq}}{v_{od}} \right)$$

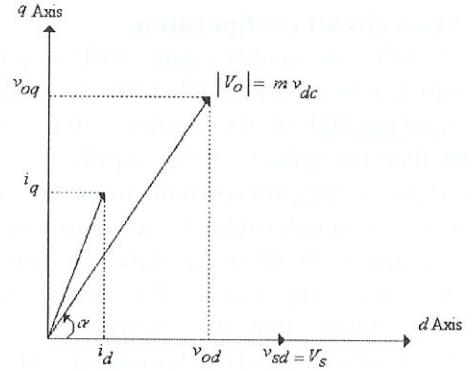


Fig.6 ASVC Voltages and Currents in d-q frame

4. CONTROL DESIGN

It can be shown that the matrix given by equation (7) is not diagonal, thus the two components of the current are coupled. To achieve an efficient control it is necessary to decouple the system, inspection of the whole equations leads directly to a rule that will provide decoupling control of i_q and i_d and the inverter voltage vector can be controlled as follows:

$$v_{oq} = -x_1 - \omega L_s i_d + v_{sq} \quad (15)$$

$$v_{od} = -x_2 + \omega L_s i_q + v_{sd} \quad (16)$$

Substitution of equation (15) and (16) into equation (7) yields:

$$\frac{d}{dt} \begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & 0 \\ 0 & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (17)$$

Where x_1 and x_2 are the output of the two P.I controller of i_q and i_d as follows:

$$x_1 = (k_1 + \frac{k_2}{p}) (i_{qref} - i_q) \quad (18)$$

$$x_2 = (k_1 + \frac{k_2}{p})(i_{dref} - i_d) \quad (19)$$

The proposed advanced static VAR compensator control scheme is illustrated in the block diagram of Fig.7. A decoupling control is proposed as shown Fig.8.

Referring to equation (12), the inverter voltage vector v_{oq} and v_{od} can be independently controlled if the dc voltage v_{dc} is kept sufficiently high.

The control is performed using feedback variables in the synchronous reference frame. The reactive current i_q is controlled to generate or absorb the desired reactive power, and the real current i_d is regulated by varying i_{dref} in response to error in the dc voltage via a PI controller.

The vector PLL detects the phase angle of the supply voltage which is added to the control variable α . This sum and the modulation index calculated using equation (14) in transient state give to the counter whose address will be first read in the look-up table where the inverter states switches are stored for modulation index step 0.01. The switching pattern for each modulation index is stored in the look-up table with 4096 ($=4 \times 1024$) point data per fundamental cycle.

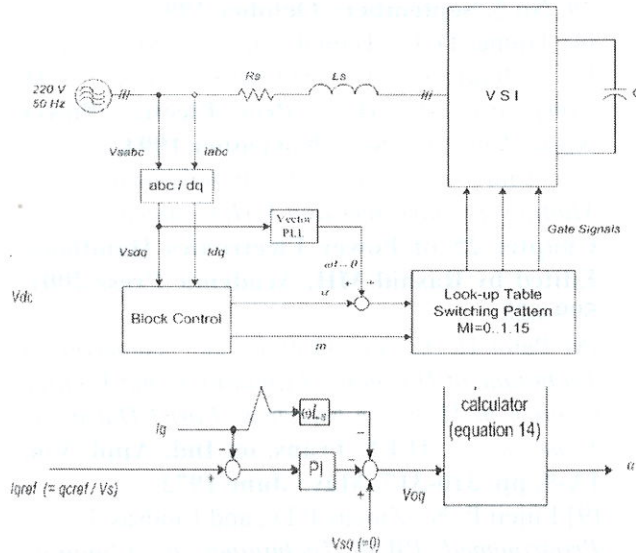


Fig.7 Main circuit and control block diagram of the proposed system.

Fig.8 details of the control block diagram.

5. SIMULATION RESULTS

To check the validity of the proposed analysis and design, computer simulation is done using the system parameters given by :

$$V_s = 220 \text{ V}, f = 50 \text{ Hz}, R_s = 1 \Omega, L_s = 5 \text{ mH}, C = 5000 \mu\text{F}$$

PI controllers parameters for active and reactive current : $K_p = 100$, $K_i = 20000$

For dc voltage : $K_p = 100$, $K_i = 20000$.

Fig.9 shows from top to bottom the simulated reactive current, the reactive current and voltage waveforms and the inverter dc bus voltage responses to a reactive current reference change from 0 A to 10 A capacitive with dc side voltage regulated at 500 V. It is obvious that the performance of the reactive current control is poor due to the dc voltage which is not sufficiently high to decouple the active and reactive current.

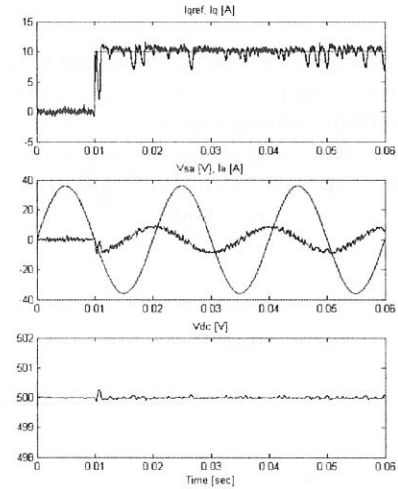


Fig.9 Top to bottom the simulated reactive current , the reactive current and voltage waveforms and the inverter dc bus voltage responses to a reactive current reference change from 0 A to 10 A capacitive ($v_{dc} = 500 \text{ V}$)

Fig.10 shows from top to bottom the simulated reactive current, the reactive current and voltage waveforms and dc bus voltage responses to reactive current reference change from 0 A to 10 A capacitive with dc side voltage regulated at 800 V. The performance of the reactive current control is best than with dc side voltage regulated at 500 V because the dc voltage is sufficiently high to decouple the active and reactive current.

Fig.11 shows the simulated reactive current, the reactive current and voltage waveforms and the dc bus voltage responses to reactive current reference change from 10 A capacitive to 10 A inductive with dc side voltage regulated at 800 V.

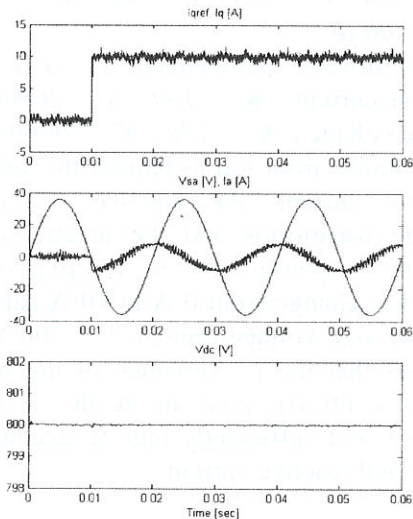


Fig. 10 Top to bottom the simulated reactive current , the reactive current and voltage waveforms and the inverter dc bus voltage responses to a sudden reactive current change from 0 A to 10 A capacitive ($v_{dc}=800$ V)

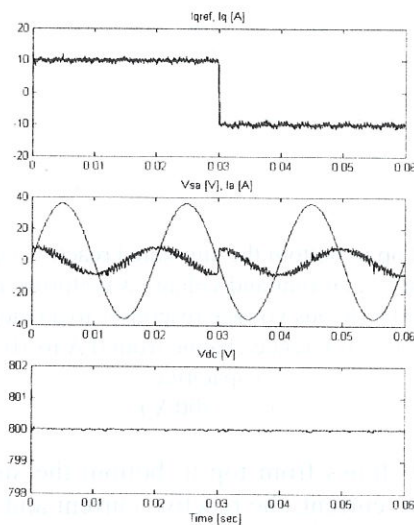


Fig.11 Top to bottom the simulated reactive current , the reactive current and voltage waveforms and the inverter dc bus voltage responses to a sudden reactive current reference change from 10 A capacitive to 10 A inductive ($v_{dc}=800$ V)

6. CONCLUSION

In this paper, a high performance static VAR compensator has been presented. The proposed system has thoroughly been modeled and analyzed. The mathematical model derived in this paper is the key of the development of the decoupled control scheme. The ASVC with the presented control scheme has fast dynamic

response for generating or absorbing reactive power. Programmed PWM switching pattern is used as a means of reducing the size of reactive components and to have a high quality reactive power in compensation.

Detailed simulation studies are carried out to demonstrate the effectiveness of the control scheme.

7. REFERENCES

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