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Three-phase STATCOM based on a single-phase current source inverter

Natália M. R. Santos[a], V. Fernão Pires[a]

[a]Escola Sup. Tecnologia Setúbal / Inst. Politécnico Setúbal, 2910-761 Setúbal , Portugal
[b]Second affiliation, Address, City and Postcode, Country

Abstract

This paper presents a three-phase STATic synchronous COMpensator (STATCOM) based on a current source inverter. Instead of the typical three-phase current bridge inverter it is used a power converter topology with only a single-phase current bridge inverter. A dynamic model of the STATCOM in $\alpha\beta$ coordinates is used as a basis for control design. The control system uses a cascade structure where a fast ac current inner loop and a slow dc current control outer loop is used. For the inner loop, is used a sliding mode technique to generate $\alpha\beta$ space-vector modulation. This fast and robust controller the ac currents of the STATCOM are actively shaped, being possible to maintain the desired currents even with high ripple DC inductor current. For the outer loop, is used a PI controller. Computer simulations are presented allowing validating the proposed STATCOM and their control system.

Keywords: STATCOM; current source inverter; single-phase; sliding mode controller;

1. Introduction

Reactive power compensation is an important issue in electrical power systems. In this way, several equipments are used to control the reactive power flow to the power network. The classical equipment is realized by connecting or disconnecting capacitor or inductor banks to the bus through mechanical switches. However, this equipment is slow and imprecise. To overcome this problem, shunt FACTS devices such as, Thyristor-controlled static Var compensator (SVC) and STATic synchronous COMpensator (STATCOM) has been introduced [1, 2].

SVC is a thyristor based controller based controller, in which the effective reactance connected to the system is controlled by the firing angle of the thyristors. However, this equipment has problems related with harmonics. The STATCOM uses fully controlled switches allowing overcoming the SVC problem.

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This device allows generating or absorbing reactive power with various switching converters. The STATCOM can be classified by their inverter configurations. According to this, there are two different configurations: using a voltage source inverter (VSI) or a current source inverter (CSI) (Fig 1). The conventional STATCOM a three-phase inverter with a three leg and six switches configuration [xxxx]. Other voltage source inverters with only two legs and four switches have also been proposed [5,6]. The CSI topology requires power switches with bipolar voltage blocking capability and the control system is more complex. However, this topology presents advantages such as, limiting the inrush current and implicit shot circuit protection.

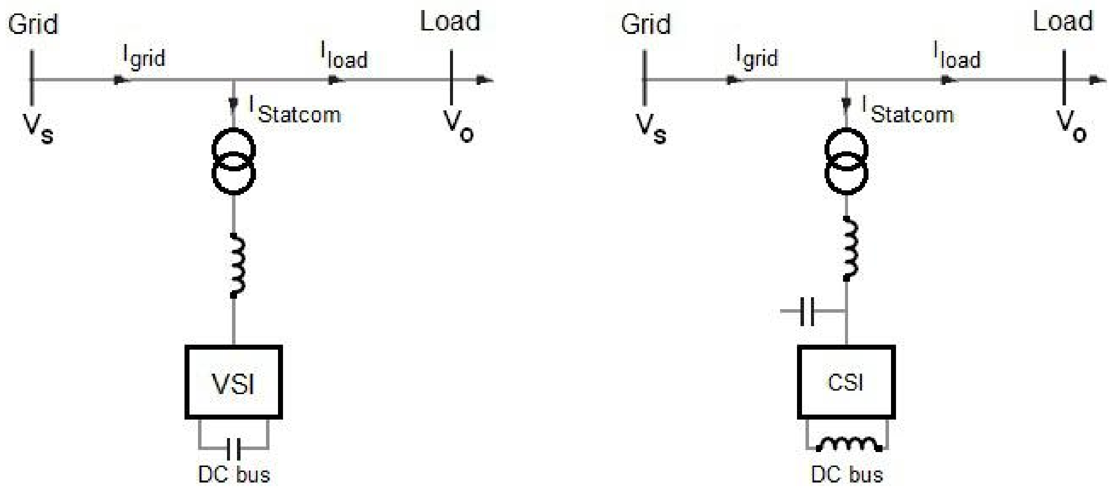

Fig. 1. (a) voltage source inverter configuration; (b) current source inverter configuration

Under this context, this paper presents a current source inverter-based STATCOM with a reduced number of legs and power switches. So, instead of a classical three-phase bridge inverter with three legs and six switches it is used a single-phase bridge inverter. In this way, a STATCOM with only two legs and four switches is proposed. To control the proposed STATCOM it will be used a control cascade system with an inner ac current loop and an outer dc current loop. For the inner loop a fast sliding mode controller with a $\alpha\beta$ space-vector modulator is proposed. In order to implement this controller, a dynamic model in $\alpha\beta$ coordinates of the STATCOM is proposed. For the outer loop it will be used a PI controller. Comprehensive simulation studies carried out in the Matlab/Simulink environment are presented to show the successful design of the proposed topology and effectiveness of the adopted system controller.

2. Power Converter STATCOM topologies

The basic circuit configuration of the classical CSI based STATCOM is presented in Fig. 2 (a). This topology requires an input LC low-pass filter, six switches with bipolar voltage blocking capability and a dc inductor. Since the power switches must have bipolar voltage blocking capability, semiconductor such as punch-through IGBTs or MOSFETs, need additional series diodes. Due to this, a greater conduction loss will be associated with this topology.

In order to reduce the number of power switches, a CSI based STATCOM using a single-phase bridge inverter is proposed. The basic configuration of this STATCOM is presented in Fig. 2(b). As can be seen by this figure, this topology requires an input LC low-pass filter, four switches with bipolar voltage blocking capability and two dc inductors with magnetic coupling.

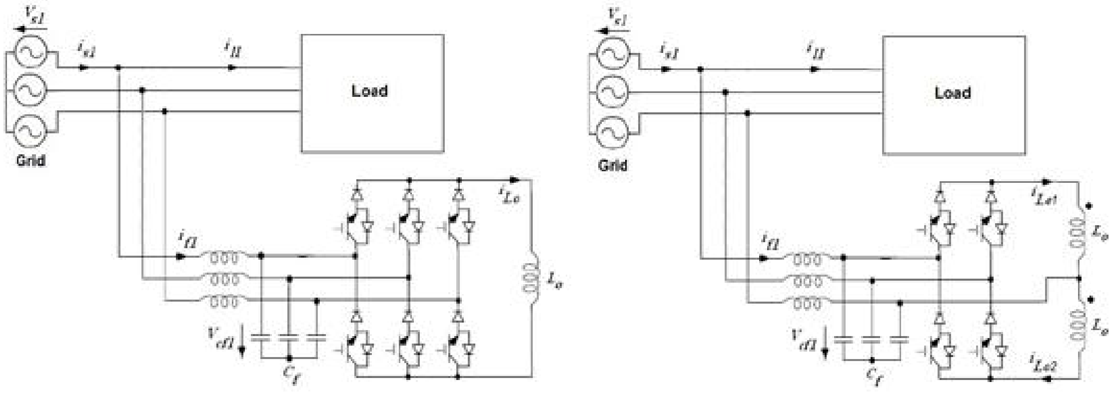

Fig. 2. (a) voltage source inverter configuration; (b) current source inverter configuration

Due to the reduced number of power switches of the proposed STATCOM structure, the efficiency can also be improved since the conduction losses of the power switches is reduced.

3. STATCOM Dynamic Model

In order to obtain the dynamic model of the STATCOM it will be assume zero losses in the inductors, capacitors and power semiconductors. So, based on Fig. 2 (b) the differential equations for the STATCOM in *abc* frame can be expressed by (1), where variables γ_k ($k \in 1,2,3$) is defined by (2).

$$\frac{d}{dt}\begin{bmatrix} i_{f1} \\ i_{f2} \\ i_{f3} \\ V_{Cf1} \\ V_{Cf2} \\ V_{Cf3} \\ \psi_o \end{bmatrix} = \begin{bmatrix} -\frac{R_f}{L_f} & 0 & 0 & -\frac{2}{3L_f} & \frac{1}{3L_f} & \frac{1}{3L_f} & 0 \\ 0 & -\frac{R_f}{L_f} & 0 & \frac{1}{3L_f} & -\frac{2}{3L_f} & \frac{1}{3L_f} & 0 \\ 0 & 0 & -\frac{R_f}{L_f} & \frac{1}{3L_f} & \frac{1}{3L_f} & \frac{1}{3L_f} & 0 \\ \frac{1}{C_f} & 0 & 0 & 0 & 0 & 0 & -\frac{\gamma_1}{C_f L_o} \\ 0 & \frac{1}{C_f} & 0 & 0 & 0 & 0 & -\frac{\gamma_2}{C_f L_o} \\ 0 & 0 & \frac{1}{C_f} & 0 & 0 & 0 & -\frac{\gamma_3}{C_f L_o} \\ 0 & 0 & 0 & -\gamma_1 & -\gamma_2 & -\gamma_3 & 0 \end{bmatrix} \begin{bmatrix} i_{f1} \\ i_{f2} \\ i_{f3} \\ V_{Cf1} \\ V_{Cf2} \\ V_{Cf3} \\ \psi_o \end{bmatrix} + \begin{bmatrix} \frac{2}{3L_f} & -\frac{1}{3L_f} & -\frac{1}{3L_f} \\ -\frac{1}{3L_f} & \frac{2}{3L_f} & -\frac{1}{3L_f} \\ -\frac{1}{3L_f} & -\frac{1}{3L_f} & \frac{2}{3L_f} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{s1} \\ V_{s2} \\ V_{s3} \end{bmatrix} \quad (1)$$

$$\gamma_k = \begin{cases} 1 & , if\ (S_k\ is\ ON\ and\ S_{k+2}\ is\ OFF) \\ 0 & if\ (S_k\ is\ ON\ and\ S_{k+2}\ is\ ON) \\ -1 & , if\ (S_k\ is\ OFF\ and\ S_{k+2}\ is\ ON) \end{cases} \quad (2)$$

The STATCOM dynamic model can be simplified, transforming all three phase circuit variables to two-phase equivalents using the Concordia transformation [xxxx]. The α axis is aligned with the phase identified by k = 1. According to this, the stationary reference frame model can now be obtained, as can be seen by the following equation:

$$\frac{d}{dt}\begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \\ V_{Cf\alpha} \\ V_{Cf\beta} \\ \psi_o \end{bmatrix} = \begin{bmatrix} -\frac{R_f}{L_f} & 0 & -\frac{1}{L_f} & 0 & 0 \\ 0 & -\frac{R_f}{L_f} & 0 & -\frac{1}{L_f} & 0 \\ \frac{1}{C_f} & 0 & 0 & 0 & -\frac{\gamma_\alpha}{C_f L_o} \\ 0 & \frac{1}{C_f} & 0 & 0 & -\frac{\gamma_\beta}{C_f L_o} \\ 0 & 0 & 0 & 0 & -\frac{2-\gamma_\alpha^2-\gamma_\beta^2}{4L_o} \end{bmatrix} \begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \\ V_{Cf\alpha} \\ V_{Cf\beta} \\ \psi_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L_f} & 0 \\ 0 & \frac{1}{L_f} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{S\alpha} \\ V_{S\beta} \end{bmatrix} \quad (3)$$

The equivalent resistor on the dc side of the current source inverter is neglected here. This last model will be used to develop the input current controller and the regulator of the dc inductor current.

4. Control System

The control system of the proposed STATCOM is broken into stages. The first stage deals with the control of the ac currents of the STATCOM. The second stage ensures a constant dc link operation.

To control the ac currents a sliding mode controller is adopted. Electronic power converters can be regarded as variable structure systems due to their switching operation. In this way, due to its simplicity and intrinsic robustness against disturbances, sliding mode controller have been widely used in electronic power converters [xxx]. To design this current controller, only the first two equations of (3) will be used. So, using these equations the following state space model in the controllability canonical can be obtained:

$$\frac{d}{dt}\begin{bmatrix} i_{f\alpha} \\ \theta_\alpha \\ i_{f\beta} \\ \theta_\beta \end{bmatrix} == \begin{bmatrix} \theta_\alpha \\ -\frac{R_f}{L_f}\theta_\alpha - \frac{1}{L_f C_f} i_{f\alpha} + \frac{\sqrt{3}\,\omega}{\sqrt{2}\,L_f} V_{s\max} cos(\omega t) - \frac{\gamma_\alpha}{C_f L_o}\psi_o \\ \theta_\beta \\ -\frac{R_f}{L_f}\theta_\beta - \frac{1}{L_f C_f} i_{f\beta} - \frac{\sqrt{3}\,\omega}{\sqrt{2}\,L_f} V_{s\max} sen(\omega t - \pi) - \frac{\gamma_\beta}{C_f L_o}\psi_o \end{bmatrix} \quad (4)$$

Where variables θ_α and θ_β are defined by (5).

$$\begin{cases} \theta_\alpha = \dfrac{V_{s\alpha} - R_f\, i_{f\alpha} - V_{Cf\alpha}}{L_f} \\ \theta_\beta = \dfrac{V_{s\beta} - R_f\, i_{f\beta} - V_{Cf\beta}}{L_f} \end{cases} \quad (5)$$

From the state space model in the controllability canonical form (4), it is possible to verify that currents $i_{f\alpha}$ and $i_{f\beta}$ have a strong relative degree of two, since only its second-time derivative contains the control variables γ_α and γ_β. So, considering now the feedback errors as state variables, the sliding surfaces that ensures robustness of the closed loop system [14], are:

$$\begin{cases} S\left(e_{i_{f\alpha}}, e_{\theta_\alpha}, t\right) = e_{i_{f\alpha}} + k_\alpha\, e_{\theta_\alpha} = \left(i_{fref\ \alpha} - i_{f\alpha}\right) + k_\alpha\left(\theta_{ref\ \alpha} + \theta_\alpha\right) \\ S\left(e_{i_{f\beta}}, e_{\theta_\beta}, t\right) = e_{i_{f\beta}} + k_\beta\, e_{\theta_\beta} = \left(i_{fref\ \beta} - i_{f\beta}\right) + k_\beta\left(\theta_{ref\ \beta} + \theta_\beta\right) \end{cases} \quad (6)$$

At the output of the sliding mode controller a current space vector modulator that will generate the gating signals of the power switches. This modulator is based on the space vector representation of the ac currents in the $\alpha\beta$ plane. So, depending on the states of the γ_k variables (representing the states of the k^{th} switches of the current source inverter), the input currents of the proposed CSI can assume 5 available states.

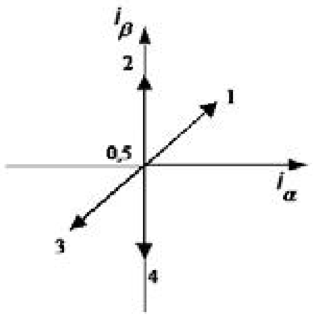

Fig. 3. Available current space vectors

The dc inductor current of the active power filter is sensed and fed to the PI controller. The goal of the PI controller is to maintain as constant as possible the current of the storage inductor.

5. System Results

A simulation study of the proposed STATCOM and adopted control system was carried out in the Matlab/Simulink environment. The simulations were performed using the following parameters: L_f=2*mH*, C_f=5 *uF*, L_o=1*mH*. Fig. 4 (a) shows the input voltage and current of the proposed STATCOM. From this result it is possible to verify that the current is shifted by 90.

To control the ac currents a sliding mode controller is adopted. Electronic power converters can be regarded as variable structure systems due to their switching operation. In this way, due to its simplicity and intrinsic robustness against disturbances, sliding mode controller have been widely used in electronic power converters [xxx]. To design this current controller, only the first two equations of (3) will be used. So, using these equations the following state space model in the controllability canonical can be obtained:

6. Conclusions

A simulation study of the proposed STATCOM and adopted control system was carried out in the Matlab/Simulink environment. The simulations were performed using the following parameters: L_f=2*mH*,

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