Chapter 32
Robust Control Techniques of ASVC-Based Var Flow Compensation

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Abstract Advanced Static Var Compensators (ASVCs) are high power electronics based devices used to provide fast variable reactive power compensation to power networks. They should be properly controlled to ensure fast and continuous reactive power to meet a certain fluctuating load demand and enhance the transient stability of the power system. The effectiveness of these compensators depends on the choice of the control strategy.

In this paper, we deal with the application of the Internal Model Control technique (IMC) and the State Feedback Control (SFC) concept to adjust the ASVC Var flow with the ac transmission network. These controllers are evaluated under a variety of operating conditions where performances and robustness have been analyzed and compared to a conventional PI controller.

Simulation results in the case of a non linear model show that SFC and IMC controllers, suitable for real time implementation, lead to improved transient response and hence provide fast reactive power compensation to ac transmission networks.

Keywords FACTS • ASVC • IMC control • State feedback control

32.1 Introduction

The configurations of static compensators of reactive power based on switched inverters are today the most used in electric current transmission systems. The apparition of high-powered electronic devises in the design of power electronic converters has resulted in a solid-state Var source with a more simple structure namely the Advanced Static Var Compensator (ASVC) [4, 6]. The ASVC uses a

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I. Dincer et al. (eds.), *Progress in Sustainable Energy Technologies Vol II: Creating Sustainable Development*, DOI 10.1007/978-3-319-07977-6_32

PWM controlled dc/ac Voltage-Source Inverter (VSI) with a capacitor as a dc power storage device.

The ASVC is connected in derivation that can operate in networks of transport as well as of distribution to generate or absorb reactive power, without using bank of condensers or inductors, in order to provide fast variable and continuous reactive power compensation following large, fluctuating load demands.

Power transmission performances with higher long line transmission capacity and transient stability are achieved by controlling the reactive current injected or absorbed from the transmission line. The effectiveness of these compensators depends mainly on the choice of the control strategy which allows greater control of the power flow in real time taking into account network condition changes and responding almost instantaneously to stability problems. Various control approaches have been proposed in the literature [1, 2, 5, 8] where conventional voltage regulation loops used are based principally on a proportional-integral (PI) controller. These produce satisfactory performance only for limited operating range conditions. In this paper, we consider the application of the Internal Model Control technique (IMC) and the State Feedback Control (SFC) concept to adjust the ASVC Var flow with the ac system. The performances of the closed loop control systems are analysed and the effectiveness of the ASVC proposed controllers under a variety of operating conditions are demonstrated and compared to a conventional PI controller.

32.2 Overview and Modeling of the ASVC

The basic ASVC scheme is illustrated in Fig. 32.1. The ASVC circuit consists of six-pulse VSI with a dc capacitor and a PWM modulator. Connection of the ASVC to the transmission line is via a coupling transformer where Rs and Ls are the coupling transformer active losses and leakage respectively as shown in the three-phase equivalent circuit of the ASVC connected to a transmission line of Fig. 32.2.

Basically, the ASVC supplies reactive power to the ac transmission system if the magnitude of the inverter voltage is greater than the ac terminal voltage. It draws reactive power from the ac transmission system if the magnitude of the ac terminal voltage is greater to the inverter voltage. Var exchange is zero when the two voltages are equal [7].

It is assumed that the source is a balanced sinusoidal three-phase voltage supply with frequency ω.

Applying d-q transform to the ac circuit and combining the dc circuit equation, the ASVC model is obtained as:

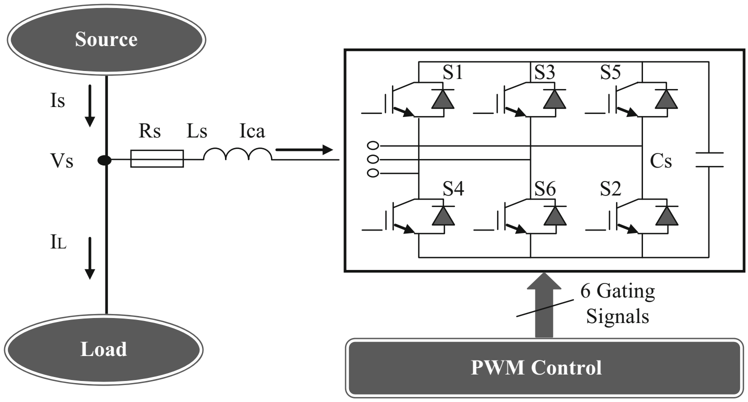


Fig. 32.1 Circuit diagram of the ASVC

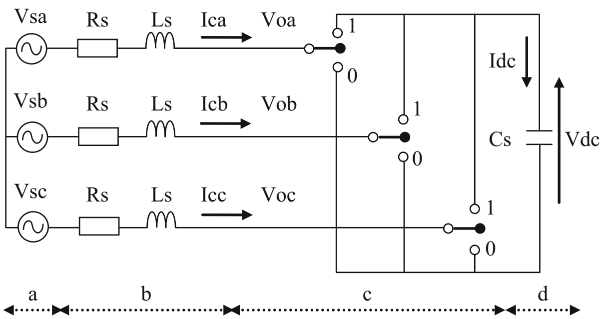


Fig. 32.2 Three-phase equivalent circuit of the ASVC. *a*—Three-phase source voltage, *b*–coupling transformer, *c*—PWM voltage source inverter, *d*—DC-side capacitor

$$\frac{d}{dt}\begin{bmatrix} i_q \\ i_d \\ V_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & -\omega & 0 \\ \omega & -\frac{R_s}{L_s} & -\frac{m}{L_s} \\ 0 & -\frac{m}{C_s} & 0 \end{bmatrix} \begin{bmatrix} i_q \\ i_d \\ V_{dc} \end{bmatrix} + \frac{V_s}{L_s}\begin{bmatrix} \sin\alpha \\ \cos\alpha \\ 0 \end{bmatrix} \tag{32.1}$$

The modulation index (MI) relates the maximum phase voltage to the dc link voltage.

$$MI = \sqrt{\frac{2}{3}}m = \frac{(V_0)_{peak}}{V_{dc}} \tag{32.2}$$

The state equation is non-linear with respect to the control variable α which is related to the phase difference between the source voltage and inverter output voltage. In the range of small values of α (|α| < 5°), the small signal equivalent state equations are expressed as:

$$\frac{d}{dt}\begin{bmatrix}\Delta i_q\\ \Delta i_d\\ \Delta V_{dc}\end{bmatrix}=\begin{bmatrix}-\frac{R_s}{L_s} & -\omega & 0\\ \omega & -\frac{R_s}{L_s} & -\frac{m}{L_s}\\ 0 & -\frac{m}{C_s} & 0\end{bmatrix}\begin{bmatrix}\Delta i_q\\ \Delta i_d\\ \Delta V_{dc}\end{bmatrix}+\frac{V_s}{L_s}\begin{bmatrix}-1\\ 0\\ 0\end{bmatrix}\quad\Delta\alpha \tag{32.3}$$

The system input is the control variable deviation Δα and the output is the generated reactive power given by:

$$\Delta Q_c=[-V_s\quad 0\quad 0] \tag{32.4}$$

Hence the system transfer function is given by:

$$\frac{\Delta Q_c(s)}{\Delta\alpha(s)}=\frac{V_s^2\left[\frac{s^2}{L_s}+\frac{R_s}{L_s}s+\frac{m^2}{L_s{}^2C_s}\right]}{s^3+2s^2\frac{R_s}{L_s}+\left(\omega^2+\frac{R_s{}^2}{L_s{}^2}+\frac{m^2}{L_sC_s}\right)s+m^2\frac{R_s}{L_s{}^2C_s}} \tag{32.5}$$

32.3 Control Scheme of the ASVC

32.3.1 Internal Model Controller

The overall closed loop control system is pictured in Fig. 32.3 and the basic architecture of a classical IMC is illustrated by Fig. 32.4 [3]. A system model is placed in parallel with the actual system. The difference is used to adjust the command signal. An attractive feature of IMC is that it produces an offset-free response even when the system is subjected to a constant disturbance.

With reference to Fig. 32.4, the control and output signal are expressed as:

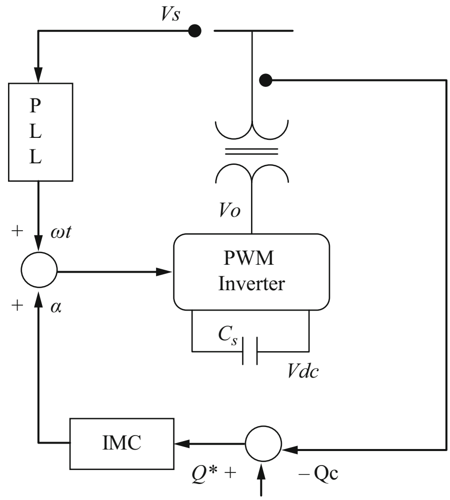
$$\alpha(z)=\{1+C_0(z)[G(z)-G_m(z)]\}^{-1}C(z)[Q^*(z)-D(z)]$$
$$Q_c(z)=G(z)\{1+C_0(z)[G(z)-G_m(z)]\}^{-1}C(z)[Q^*(z)-D(z)]+D(z)$$

If a perfect model is assumed (G(z) = Gm(z)) then the closed loop system is stable if the controller C(z) and the system are stable. However under mismatch conditions (G(z) ≠ Gm(z)), a low pass filter is introduced in the feedback loop to improve the controller robustness with respect to modeling errors.

The design filter has the following transfer function

$$F(z)=\frac{(1-\beta)\quad z}{(z-\beta)}\qquad 0<\beta<1 \tag{32.6}$$

Fig. 32.3 ASVC closed loop control system



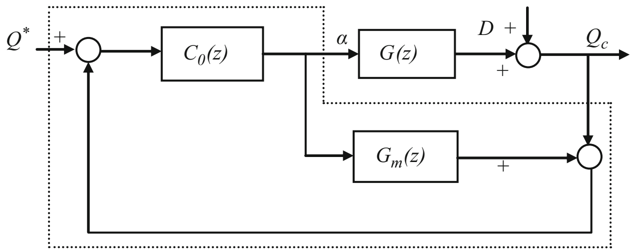


Fig. 32.4 Basic IMC structure

In what follows β has been fixed to 0.002.

Since the controller is the inverse of the system model (i.e. C0(z) = Gm(z)−1) then Qc(z) = Q*(z) and consequently the inverse system model should be stable. Furthermore if C0(1) = Gm(1)−1 the controller produces an offset-free response.

With Ts = 0.005 s, the discrete-time transfer function of the system is obtained as:

$$G(z) = \frac{220^2(0.3441z^2 + 0.3819z + 0.2207)}{z^3 + 0.269z^2 - 0.187z - 0.1353} \tag{32.7}$$

By taking Gm(z) = G(z) then the poles and zeroes of Gm(z) are p1,2 = −0.407 ± j0.2943, p3 = 0.5404, and z1,2 = −0.5549 ± j0.5775.

Then, the controller transfer function is given by:

$$C_0(z) = \frac{1}{220^2}\left[\frac{z^3 + 0.269z^2 - 0.187z - 0.1353}{0.9467z^3}\right] \tag{32.8}$$

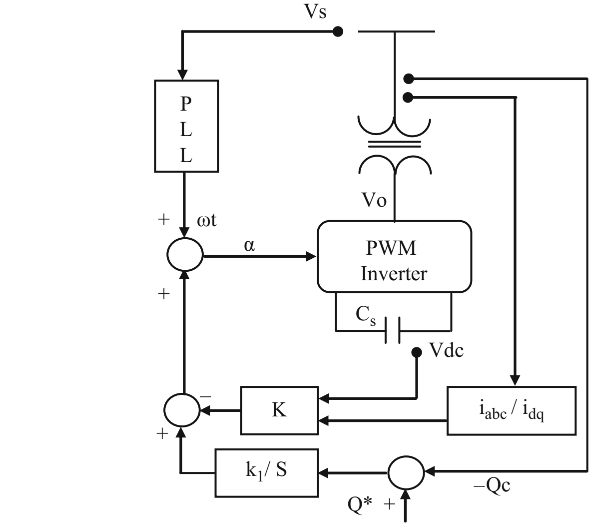


Fig. 32.5 ASVC closed loop control system

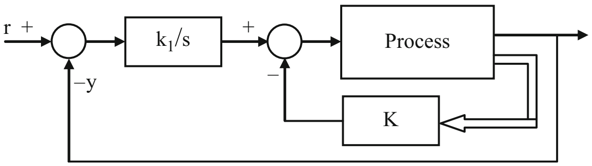


Fig. 32.6 Basic state feedback control structure

32.3.2 State Feedback Controller

The overall closed loop control system with SFC control technique is shown in Fig. 32.5 and the cascade control system of the state-feedback configuration is given in Fig. 32.6 [3]. The controlled variable y is compared with the set-point value r and the control error is fed back to an integrator. The former feedforward gain k1 is now the gain of the integrator. This configuration shows that the gain K in the internal closed-loop is a feedback parameter.

The basic principle of the designed system is to insert an integrator in the feed forward path between the error comparator and the process as shown in Fig. 32.7.

From this diagram we obtain:

$$\dot{x} = A\,x + B\,u \tag{32.9}$$

$$y = C\,x \tag{32.10}$$

$$u = -K\,x + k1\,\xi \tag{32.11}$$

$$\dot{\xi} = r - y = r - Cx \tag{32.12}$$

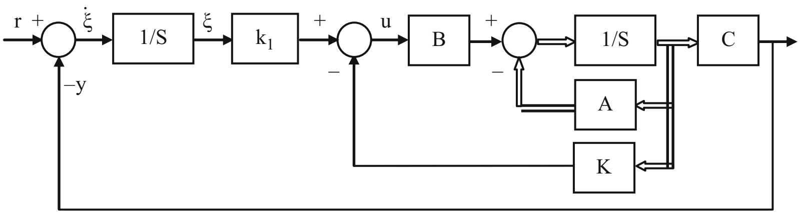


Fig. 32.7 Type 1 servo system where the plant has an integrator

We assume that the plant given by Eq. 32.9 is completely state controllable. The transfer function of the plant can be given by:

$$GP(s) = C\,[sI - A] - 1B \tag{32.13}$$

The system dynamics can be described by an equation that is combination of Eqs. 32.9 and 32.12.

$$\begin{bmatrix} \dot{x}(t) \\ \dot{\xi}(t) \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ \xi(t) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r(t) \tag{32.14}$$

$$y = [C \quad 0] \begin{bmatrix} x(t) \\ \xi(t) \end{bmatrix} \tag{32.15}$$

Where

$$u = [-K \quad k_1] \begin{bmatrix} x(t) \\ \xi(t) \end{bmatrix} \tag{32.16}$$

We shall design an asymptotically stable system such that $x(\infty)$, $\xi(\infty)$, and $u(\infty)$ approach constant values, respectively. Then, at steady state $\dot{\xi}(\infty) = 0$, and we get $y(\infty) = r$.

Where

$$\hat{A} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} \qquad \hat{B} = \begin{bmatrix} B \\ 0 \end{bmatrix} \tag{32.17}$$

32.4 State Space Method Control Applied to the ASVC System

The state space representation of the system becomes:

$$\dot{x} = A\,x + B\,u \tag{32.18}$$

$$Qc = C\,x \tag{32.19}$$

Where

$$A = \begin{bmatrix} -\frac{R_s}{L_s} & -\omega & 0 \\ \omega & -\frac{R_s}{L_s} & -\frac{m}{L_s} \\ 0 & -\frac{m}{C_s} & 0 \end{bmatrix} \qquad B = \frac{V_s}{L_s}\begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix} \qquad C = \begin{bmatrix} -Vs & 0 & 0 \end{bmatrix}$$

Hence

$$A = \begin{bmatrix} -200 & -314 & 0 \\ 314 & -200 & -129.3 \\ 0 & -1293.3 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} -44000 \\ 0 \\ 0 \end{bmatrix} \qquad C = [-220\ \ 0\ \ 0]$$

The poles selected for a good dynamic response of the closed loop system are determined by the Ackermann algorithm where:

$$p1 = -500;\ p2 = -600;\ p3 = -700;\ p4 = -750.$$

Hence

$$\hat{A} = \begin{bmatrix} -200 & -314 & 0 & 0 \\ 314 & 200 & -129.3 & 0 \\ 0 & -1293.3 & 0 & 0 \\ 220 & 0 & 0 & 0 \end{bmatrix} \quad ; \quad \hat{B} = \begin{bmatrix} -44000 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

We shall determine the necessary state feedback gain matrix K using the pole placement technique, where:

$$\hat{K} = [K \vdots \quad -k_1] = [-0.0489 \quad -0.0537 \quad -0.0241 \quad -0.0973]$$

32.5 Results and Discussion

Simulations were performed under Matlab/Simulink environment with the following ASVC parameters:

$Rs = 1\,\Omega \quad Ls = 5.10-3\ H \quad Cs = 500.10^{-6}\ F \quad Vs = 220\ V$
$m = 0.646 \quad \omega = 100\pi\ rad/s$

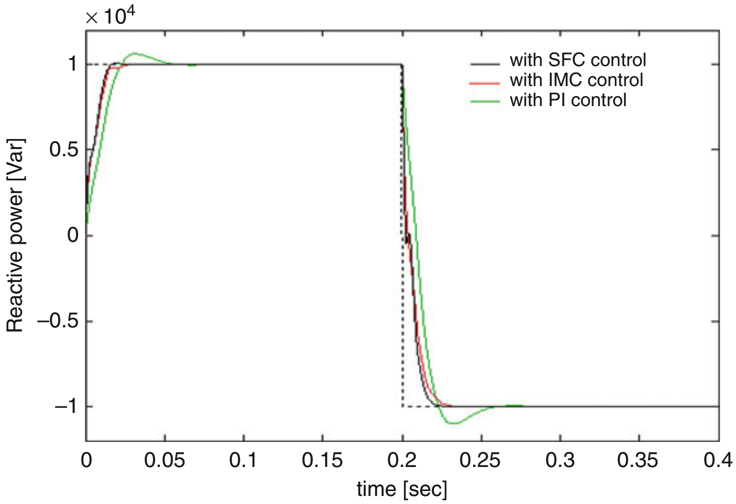


Fig. 32.8 Reactive power response under step change from inductive to capacitive with the non-linear model

The PI parameters are obtained using root locus design for a damping factor of 0.7 where the following controller gains are obtained: $Kp = 7.5 \times 10^{-6}$ $Ki = 2.5 \times 10^{-3}$.

The IMC and SFC controllers were evaluated under more realistic simulation condition when the ASVC devices were controlled by PWM control circuit.

Figure 32.8 shows the transient response in the case of IMC and SFC controllers based on the non-linear model of the ASVC. The Var command was varied from 10 Kvar (inductive) to −10 Kvar (capacitive) to swing the system from leading to lagging mode at time 0.2 s.

The results obtained show that by the IMC and the SFC controller lead to a faster transient response with a shorter settling time and with no overshoot. It can be observed also that the SFC control produces a better performance than IMC and PI control which demonstrates its robustness under model mismatch situations.

Figures 32.9 and 32.10 show the reactive power responses under IMC and SFC controllers compared to a PI controller and Figs. 32.11 and 32.12 show the current waveforms behavior. It is observed from Fig. 32.11 how the current injected into the transmission line swings instantaneously in response to a capacitive Var demand.

Figures 32.13 and 32.14 show the transient response of the dc-side voltage V_{dc}, and I_d, I_q ac current components respectively with IMC and SFC controllers. We notice that the response is faster and smooth in tw case of SFC control.

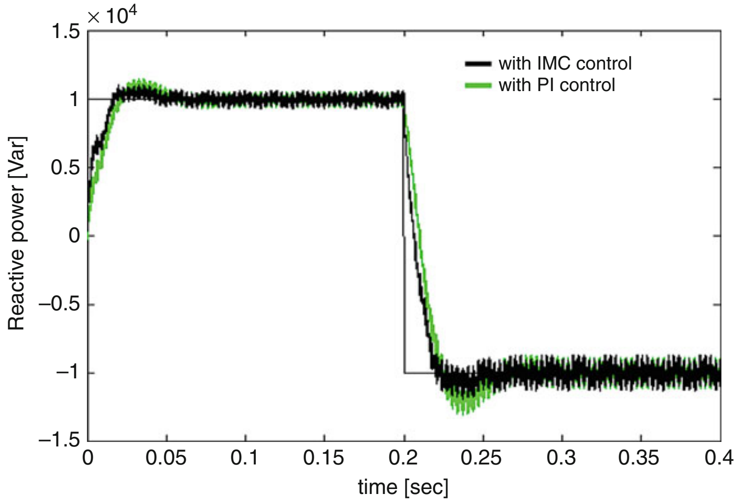


Fig. 32.9 Reactive power transient response under a step change from 10 Kvar leading to 10 Kvar lagging

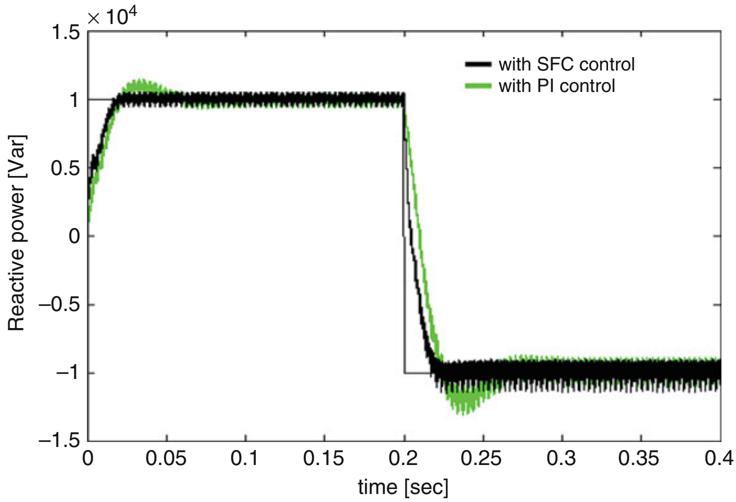


Fig. 32.10 Reactive power transient response under a step change from 10 Kvar leading to 10 Kvar lagging

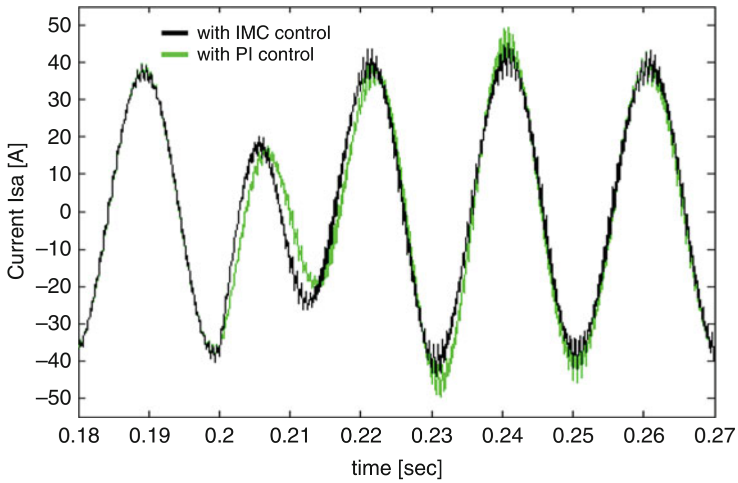


Fig. 32.11 Phase current response with IMC control

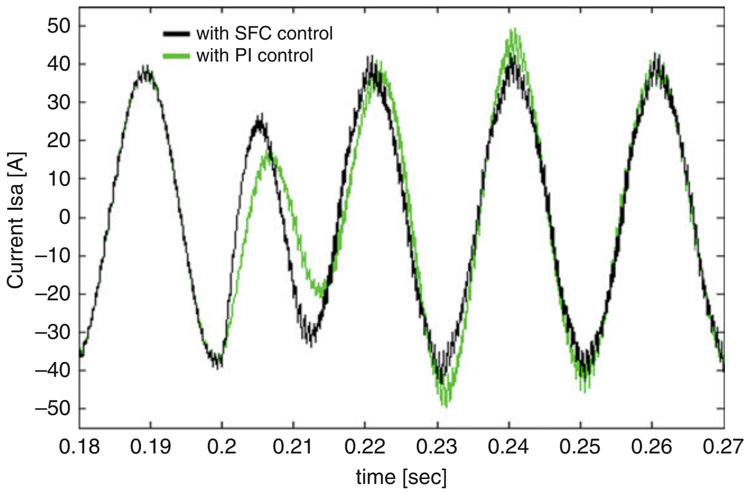


Fig. 32.12 Phase current response with SFC control

32.6 Conclusion

Internal Model Control and State Feedback Control techniques applied to an advanced static var compensator were presented in this work. Performance and robustness of IMC and SFC have been evaluated and compared to a conventional PI controller.

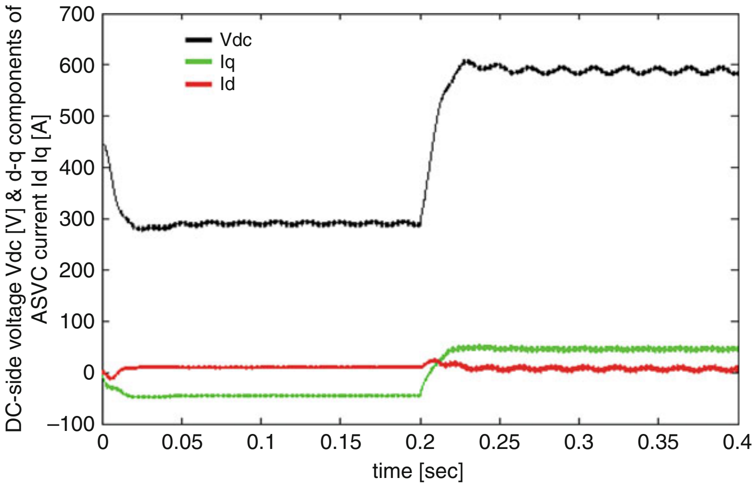


Fig. 32.13 DC-side voltage V_{dc}, and I_d I_q ac current components with IMC control

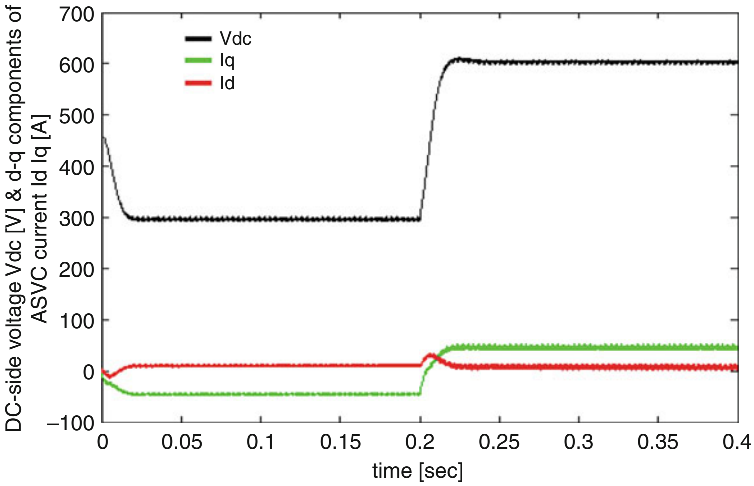


Fig. 32.14 DC-side voltage V_{dc}, and I_d I_q ac current components with SFC control

Simulation results demonstrate that the proposed strategy is feasible, it can be concluded that SFC and IMC control lead to improved transient response and hence provide fast reactive power compensation to the ac transmission network. Also the SFC controller is better than the IMC controller and can be easily tuned and very suitable for real time experimental implementation.

Nomenclature

Acronyms

ASVC	Advanced static Var compensator
IMC	Internal model controller
MI	Modulation index
SFC	State feedback controller

Subscript and Superscripts

ω	Supply frequency
A	$n \times n$ constant matrix
B	$n \times l$ constant matrix
C	$l \times n$ constant matrix
Co(z)	Controller transfer function
Cs	Source capacitor
F(z)	Filter transfer function
G(z)	Discrete-time transfer function
I_{ca} I_{cb}, I_{cc}	ASVC currents
I_s I_L	Source and load currents
K	Gain matrix K
Kp Ki	PI parameters
Ls	Source inductance
r	Reference input signal (step function scalar)
Rs	Source resistor
s	Laplace operator
u	Control signal (scalar)
V_{dc} I_{dc}	dc-side voltage and current
V_{sa} V_{sb}, V_{sc}	Source voltages
x	State vector of the plant (n-vector)
y	Output signal (scalar)

Greek Symbols

α	Control variable
$\Delta\alpha$	Control variable deviation
ξ	State variable

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