Abstract—This paper presents a new approach for the dynamic control of a current source inverter (CSI)-based STATic synchronous COMPensator (STATCOM). The dq-frame model and the steady-state characteristic of the CSI STATCOM are proposed as a basis for control design. Use of traditional PI controllers leads to a poorly damped high frequency oscillation between the inductance and capacitance of the CSI output filter. The new approach includes a fast ac current control inner loop and a slower dc current control outer loop. The inner loop, which is a combination of multivariable full state feedback and integral control, allows for rapid nonsociatory dynamics of the ac current without overshoot or steady-state error. Experimental tests on a 5-kVA laboratory CSI STATCOM setup validate the proposed control design as well as the simulation results.

Index Terms—Current source inverter (CSI), dynamic control, FACTS, STATic synchronous COMPensator (STATCOM).

I. INTRODUCTION

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EACTIVE power control is traditionally realized by connecting or disconnecting capacitor or inductor banks to the bus through mechanical switches, which are slow and imprecise. Thyristor-controlled static Var compensators have also been developed[1], in which the effective reactance connected to the system is controlled by the firing angle of thyristors. The advantages of introducing force-commutated inverters to achieve advanced reactive power control have been confirmed by many researchers [1]–[3]. These advantages include potential size, weight, and cost reduction, precise and continuous reactive power control with fast response. Such a device is called STATic synchronous COMPensator (STATCOM) [4].

There are actually two different kinds of STATCOMs, classified by their inverter configuration: using voltage source inverters (VSIs) and current source inverters (CSIs). The VSI is the dominant topology in reactive power control, with several VSI-based STATCOMs now operating in transmission systems [5]–[7]. While most of the literature focuses on the VSI, the CSI is less well discussed. Compared with the VSI, the CSI topology offers a number of inherent advantages, including: 1) directly controlling the output current of inverter; 2) implicit short-circuit protection, the output current being limited by the dc inductor; 3) high converter reliability, due to the unidirectional nature of the switches and the inherent short-circuit protection; 4) fast start-up, where no additional start-up rectifier is needed. In addition, unlike the VSI STATCOM, the CSI STATCOM injects no harmonic into the ac network when it is operating at zero reactive current. These features, combined with the availability of large reverse blocking devices, make the CSI a potential device for reactive power control.

In the CSI-based STATCOM, pulswidth modulation (PWM) is used to suppress low frequency harmonics and to reduce harmonic filtering requirements. The limited literature on the CSI for Var compensation concentrates on the steady-state characteristic analysis and main circuit design [8], [9]. These references employ a PWM switching pattern for the CSI which is precalculated for harmonic elimination, where the modulation index is fixed and the CSI is controlled by its firing angle. Reference [10] points out that a high frequency instability associated with GTO-CSI induction machine drive systems exists and is caused by an LC resonance between the machine leakage inductance and the output filter capacitor. Similar resonance will occur in a CSI-based STATCOM if no special care is taken in the control design. The CSI inherently exhibits a poorly damped high frequency oscillation between the output filter L and C if it is open loop controlled. When a firing angle controller is adopted, there is a conflict between suppressing high frequency oscillation and obtaining fast dynamic response. To achieve a fast dynamic response, a high proportional gain is needed. On the other hand, a low proportional gain is necessary to add the damping ability for high frequency oscillation.

In fact, there are two control variables for the CSI: the modulation index and phase angle. This paper presents a new CSI control approach, i.e., a combination of full state feedback for assigning the nonsociatory fast system dynamics and integral control for ensuring the elimination of steady-state errors. This controller adjusts the modulation index and firing angle of the CSI simultaneously and is able to eliminate the high frequency oscillation. With such a new control approach, the dynamic behavior of the CSI is greatly improved.

II. THE CSI STATCOM DYNAMIC MODEL

The topology of the CSI STATCOM presented in this paper is shown in Fig. 1. It can be explained by considering a controllable current source connected to a main ac system. The controllable current source generates a three-phase sinusoidal current.
waveform, leading or lagging by 90° with respect to the corresponding phase voltage. In an actual device, the current is set to lead or lag the phase voltage by an angle which deviates slightly from 90° so that the CSI absorbs sufficient real power from the ac system to compensate any losses.

Based on Fig. 1 the differential equations for the system are derived in the abc frame and then transformed into the synchronous dq frame [11].

\[
\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \\ v_{rd} \\ v_{rq} \\ i_{rd} \\ i_{rq} \\ i_{rd} \\ i_{rq} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega_0 & 1 & \frac{1}{L} & 0 & 0 \\
-\omega_0 & -\frac{R}{L} & 0 & \frac{1}{L} & 0 & 0 \\
-\frac{1}{3C} & 0 & 0 & \omega_0 & \frac{I_{std}}{3C} & \frac{I_{stq}}{3C} \\
0 & -\frac{1}{3C} & -\omega_0 & 0 & \frac{I_{std}}{3C} & \frac{I_{stq}}{3C} \\
0 & 0 & -\frac{I_{std}}{L_{dc}} & -\frac{I_{stq}}{L_{dc}} & \frac{R_{dc}}{L_{dc}} & \frac{1}{L_{dc}} \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \\ v_{rd} \\ v_{rq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \begin{bmatrix} -v_{rd} \\ -v_{rq} \\ L & 0 \\ L & 0 \end{bmatrix} 
\]

where \( \omega_0 \) is the rotation frequency of the dq frame and is equal to the nominal frequency of the system voltage. \( I_{std} \) and \( I_{stq} \) are the control signals of CSI and can be expressed by

\[
\begin{bmatrix} I_{std} \\ I_{stq} \end{bmatrix} = M \begin{bmatrix} \cos \delta \\ \sin \delta \end{bmatrix}
\]

where \( M \) is the modulation index and \( \delta \) is the phase angle of CSI output current with respect to the system phase voltage, \( V_s \).

In order to simplify the analysis, let the d-axis of the dq frame coincide with the space vector of the system voltage, i.e.,

\[
\begin{bmatrix} v_{rd} \\ v_{rq} \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \end{bmatrix}
\]

In addition, the equivalent resistor \( R_{dc} \) on the dc side of the inverter is neglected here.

III. STEADY-STATE CHARACTERISTICS OF CSI STATCOM

From the above equations, the steady-state operation point of the CSI STATCOM is derived

\[
L_d = \frac{V_s}{R} \cos^2 \delta, \quad L_q = -\frac{V_s}{2R} \sin 2\delta \\
V_{rd} = V_s \sin \delta \left( \sin \delta + \frac{X_f}{R} \cos \delta \right) \\
V_{rq} = -V_s \cos \delta \left( \sin \delta + \frac{X_f}{R} \cos \delta \right) \\
I_{dc} = \frac{1}{M} \left[ \frac{V_s}{X_c} \sin \delta - \frac{V_s}{R} \cos \delta \left( 1 - \frac{X_f}{X_c} \right) \right]
\]

where \( X_f \) and \( X_c \) are the reactance values of output filter \( L \) and \( C \), \( X_f = \omega_0 L \), \( X_c = (1/3\omega_0 C) \).

In steady-state operation, the output reactive current is only dependent upon \( \delta \), and modulation index only influences the dc side current. The CSI STATCOM may be operated using one of the two distinct control methods:

- Type I: phase angle \( \delta \) control while the modulation index is kept constant;
- Type II: the modulation index and \( \delta \) are both controllable.

Fig. 2 shows the \( I_q \sim \delta \), \( M \times I_{dc} \sim \delta \), \( M \times I_{dc} \sim I_q \) curves of the CSI STATCOM under steady-state conditions.
IV. CONTROL SYSTEM DESIGN FOR TYPE I CSI

There is an LC oscillation mode with low damping (because the resistor \( R \) is small) at the output terminal of the CSI. The oscillation frequency is

\[
\omega_{osc} = \frac{1}{2\pi\sqrt{L/C}} = \frac{f_0}{\sqrt{X_0/X_c}}
\]

where \( f_0 \) is the base frequency of the system voltage. In the output filter design, the \( L \) and \( C \) parameters normally satisfy \( X_L \ll X_C \), so \( \omega_{osc} \gg f_0 \) thus it is a high frequency oscillation. If a traditional PI controller is adopted for the Type I CSI STATCOM, low proportional gain is required to reduce the oscillation yet this leads to slow dynamic behavior. Fig. 3 depicts the block diagram of Type I CSI control loop.

From Fig. 2(a), there are two distinct operation areas for CSI STATCOM which are around \( \delta = 90^\circ \) and \( \delta = -90^\circ \). For this special case, adoption of a regular PI controller does not yield a desirable performance. This problem is avoided by the introduction of a bias function \( \phi \) and its switch logic. The sum of the PI controller output \( \delta \) and \( \phi \) is used as the phase angle of the CSI. The bias function \( \phi \) and its switch logic are illustrated in Fig. 4. When the \( I_{dc} \) decreases to a low threshold, the phase angle of CSI jumps \( 180^\circ \) to obtain a smooth transit from one area to another.

V. CONTROL SYSTEM DESIGN FOR TYPE II CSI

For Type I CSI STATCOM, there is a contradiction between the fast transient response speed and the elimination of LC oscillation as illustrated in Section VI. Type II CSI STATCOM has two control variables, i.e., phase angle \( \delta \) and modulation index \( M \). It is expected to achieve a better transient performance by the utilization of the second control variable \( M \).

In steady-state operation, only a harmonic voltage is imposed on the dc inductor. By using two control variables the slow dynamics of the dc link may be decoupled from the fast dynamics of the ac side variables \( i_d, i_q, v_{dcl}, v_{qcl} \).

The development of the controller for type II CSI STATCOM is broken into two stages. The first deals with achieving good ac side closed loop behavior through a combination of full state feedback to assign fast dynamics and integral control to eliminate steady-state errors. Here \( i_{dc} \) is assumed to be a constant. The second stage of the development is to construct a dc current control loop to ensure constant dc link current operation.

A. AC Side Current Control

To design this loop, only the first four equations of (1) are considered. In order to simplify further analysis, the reduced state and disturbance vectors \( x = [i_d, i_q, v_{dcl}, v_{qcl}]^T \), and \( w = [v_{dcl}, v_{qcl}]^T \) are defined and the equations are written in the following standard format.

\[
\dot{x} = Ax + Bu + Gw.
\]

The output of the system is \( y = Ex \) where from (1)

\[
A = \begin{bmatrix}
-R & \omega_0 & 0 & 0 \\
-W_0 & -R & 0 & \frac{1}{L} \\
-\frac{1}{3C} & 0 & 0 & \omega_0 \\
0 & -\frac{1}{3C} & -\omega_0 & 0
\end{bmatrix}, \quad B = \begin{bmatrix}
0 & 0 \\
0 & \frac{1}{3C} \\
0 & 0 & 1
\end{bmatrix},
\]

\[
G = \begin{bmatrix}
-\frac{1}{L} & 0 \\
0 & \frac{1}{L} \\
0 & 0 \\
0 & 0
\end{bmatrix}, \quad E = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0
\end{bmatrix}
\]

and \( u \) is the input vector defined as \( u = [I_{std} i_{dc}, I_{stg} i_{dc}]^T \).

This reduced set of system equations is linear time invariant and may thus be regulated by a linear controller. All the subsequent discussion will deal with the input vector \( u \), although the final CSI system inputs will be derived from

\[
[I_{std} I_{stg}]^T = u_i^{dc}.
\]

and

\[
M \cdot e^{j\delta} = I_{std} + j \cdot I_{stg}.
\]

The dynamics of (2) can be assigned through use of a full state feedback controller [12]. The input required to assign the close loop dynamics is then \( u = -K(x - x_{ref}) + u_{ss} \), where \( x_{ref} \) is the steady-state solution of system and \( u_{ss} \) is a feed-forward component required to eliminate the steady-state error. This loop controls the ac current to a given reference

\[
r = [i_{dref} i_{qref}]^T.
\]
From these reference currents the entire reference state vector may be found, as well as the necessary feedforward component. \( \mathbf{x}_{\text{ref}} = \mathbf{N}_a \mathbf{r} + \mathbf{M}_a \mathbf{w} \) and \( \mathbf{u}_{\text{ss}} = \mathbf{N}_a \mathbf{r} + \mathbf{M}_a \mathbf{w} \), where

\[
\mathbf{N}_a = \begin{bmatrix}
1 & 0 \\
0 & 1 \\
R_1 & -X_L \\
X_L & R
\end{bmatrix}, \quad \mathbf{N}_u = \frac{1}{X_c} \begin{bmatrix}
X_c - X_L \\
R \\
X_c - X_L
\end{bmatrix},
\]

\[
\mathbf{M}_a = \begin{bmatrix}
0 & 0 \\
0 & 0 \\
1 & 0 \\
0 & 1
\end{bmatrix}, \quad \mathbf{M}_u = \frac{1}{X_c} \begin{bmatrix}
0 & -1 \\
1 & 0
\end{bmatrix}.
\]

The feedforward component \( \mathbf{N}_a \mathbf{r} \) is often not used because it is sensitive to the main circuit parameters \( R_1, X_c, \) and \( X_L \). The preferred method of providing for zero steady-state error is typically through integral control.

Defining a new integral vector \( \mathbf{x}_f = \int_0^t \mathbf{y} \, dt = \int_0^t \mathbf{E} \mathbf{x} \, dt \) from the output of the original system results in an augmented system. The new system can be expressed by

\[
\begin{bmatrix}
\dot{x} \\
\dot{x}_f
\end{bmatrix} = \begin{bmatrix}
\mathbf{A} & 0 \\
\mathbf{E} & 0
\end{bmatrix} \begin{bmatrix}
x \\
x_f
\end{bmatrix} + \begin{bmatrix}
\mathbf{B} \\
0
\end{bmatrix} \mathbf{u} + \begin{bmatrix}
\mathbf{G} \\
0
\end{bmatrix} \mathbf{w}.
\tag{5}
\]

Because the introduction of integral control can automatically correct the steady-state error, the final controller has a concise format

\[
\mathbf{u} = -[\mathbf{K} \quad \mathbf{K}_f] \left[ \begin{bmatrix}
x \\
x_f
\end{bmatrix} - \begin{bmatrix}
x_{\text{ref}} \\
\int_0^t r \, dt
\end{bmatrix} \right].
\tag{6}
\]

where \( x_{\text{ref}} \) may simply be selected as \( x_{\text{ref}} = M_a \mathbf{w} \). The new overall gain matrix \([\mathbf{K} \quad \mathbf{K}_f]\) is determined using a pole placement algorithm.

In order to eliminate the cross coupling between the \( d \) and \( q \) axis components, the six poles of closed loop controller should be selected as \( s_1, s_1, s_2, s_2, s_3, s_3 \) where \( s_1, s_2, s_3 \) satisfy Case 1 or Case 2: Case 1, \( s_1 \) on the negative real axis and \( s_2, s_3 \) is a couple of conjugate complex poles in the left half complex plane; Case 2, three poles \( (s_1, s_2, s_3) \) are all on negative real axis. For both cases, the closed loop transfer function from \([i_{d,\text{ref}} \quad i_{q,\text{ref}}]\) to \([i_d \quad i_q]\) is

\[
G(s) = -\frac{s_1 s_2 s_3}{(s - s_1)(s - s_2)(s - s_3)}.
\tag{7}
\]

For Case 1, there will be some oscillation and overshoot in the transient response. Case 2 leads to a nonoscillatory transient response without overshoot. Thus, the poles selected are \( s_1, s_1, s_2, s_2, s_3, s_3 \) (where \( s_n < 0, n \in \{1, 2, 3\} \)) in order to obtain a fast, smooth, nonoscillatory transient response without overshoot, and eliminate the cross coupling between \( d \) and \( q \) axis component as well.

### B. DC Current Control Loop

Fig. 5 gives the block diagram used for the dc current control loop design. The inner current loop may be represented by the transfer function \( G(s) \) from (7). Standard bode plot control techniques may be applied to this single input single output model. The output of the dc current controller is the \( d \)-axis reference current given to the ac current control loop. Fig. 6 shows the complete block diagram of the Type II CSI STATCOM controller.

### VI. SIMULATED DYNAMICS

A simulation study based on the model (1) is carried out to compare three different control modes. First is the open loop control where the modulation index and \( \delta \) are given directly to the CSI STATCOM; second is phase angle control for Type I CSI STATCOM; third is the proposed control scheme for Type II CSI STATCOM. Fig. 7 gives the simulated dynamics of all three control modes.

For open loop control, \( \delta \) jumps from \(-91.2^\circ\) to \(91.5^\circ\) at \( t = 0.02 \) sec while \( M \) is kept as 0.9. The high frequency oscillation in the current waveform is obvious and the transit from one state to another takes more than 100 ms. For the Type I CSI, the reactive current reference goes from \(-20\) A to \(20\) A at \( t = 0.05 \) sec. The \( i_q \) is regulated by the charge or discharge of the dc inductor. The oscillation phenomena can again be observed in the current waveforms. From Fig. 7(b), the specially designed phase angle bias function is seen to work very well and the \( 180^\circ \) transition of \( \delta \) does not cause a disturbance to \( i_q \). For Type II CSI STATCOM, the reactive current reference changes from \(-20\) A to \(20\) A at \( t = 0.05 \) sec and dc link current reference remains at 30 A. The proposed control strategy yields a fast dynamic response with no overshoot in the ac current waveform, furthermore, there exists no cross coupling between \( i_d \) and \( i_q \), thus the reactive current change introduces minimal disturbance to the dc side current. Such a transient response is desirable.
Fig. 7. Simulated dynamics for open loop control and closed loop control for CSI STATCOM. (a) Openloop Control. (b) Type I CSI STATCOM control. (c) Type II CSI STATCOM control.

Fig. 8. A 5-kVA CSI STATCOM experimental setup.

VII. EXPERIMENTAL VALIDATION

The results discussed above are validated experimentally. Fig. 8 depicts the 5-kVA laboratory system, with parameters as specified in the appendix. Controller implementation is on a TI-C40 controller board with an on-line gate drive pattern [13] generated in an FPGA. Based on the parameters of the experimental system, controllers are designed according to the method described above. The changes of phase angle or reference values are the same as those in the simulation studies. The experimental results are presented in Fig. 9.

Comparison between Figs. 7 and 9 shows that experimental results agree well with the simulated dynamics except that the small rating CSI setup exhibits more damping ability. Fig. 9 also reveals that the Type II CSI has a better transient response than the Type I because of the better utilization of both control variables. For the Type II CSI STATCOM, the reactive current tracks the reference value in less than half a period without any overshoot. The decoupling control of $i_d$ and $i_q$ was also achieved by the proposed control scheme. The disturbance on the dc current introduced by reactive current changes was negligible.

VIII. CONCLUSION

The $dq$-frame model of the CSI STATCOM is presented and its steady-state characteristics are derived based on the model. The Type II CSI STATCOM offers a better transient response than the Type I form due to better utilization of both control variables. Use of full state feedback results in rapid dynamics of the output ac current without overshoot. These dynamics are comparable to those obtained from a VSI STATCOM. Introduction of integral control in the presented manner is shown to both simplify the overall control design and eliminate the steady-state errors. Thus, the proposed control scheme, which is a combination of full state feedback and integral control, gives the CSI STATCOM a good dynamic response and excellent steady-state tracking ability. Simulation results demonstrate the need for both modulation index and phase angle control if high frequency oscillations are to be avoided in the ac side $LC$ filter. Experimental tests on a 5-kVA laboratory CSI STATCOM validate the proposed control design as well as the simulation results.
Fig. 9. Experimental results on a 5-kVA CSI STATCOM setup. (a) Open loop control. (b) Type I CSI STATCOM control. (c) Proposed control scheme for Type II CSI STATCOM.

APPENDIX

<table>
<thead>
<tr>
<th>PWM</th>
<th>CSI STATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{\text{sample}} = 3.24 \text{ kHz}$</td>
<td>$KVA_k = 5 \text{kVA}$</td>
</tr>
<tr>
<td>$f_{\text{switch}} = 1.62 \text{ kHz}$</td>
<td>$V = 110 \text{ V}$</td>
</tr>
<tr>
<td>$R = 0.15 \Omega (0.06 \text{ pu})$</td>
<td>$X = 0.44 \Omega (0.18 \text{ pu})$</td>
</tr>
<tr>
<td>$C = 30 \mu\text{F}$</td>
<td>$L_{\text{dc}} = 5 \text{ mH}$</td>
</tr>
</tbody>
</table>

REFERENCES


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