State feedback control strategy and voltage balancing scheme for a transformer-less STATic synchronous COMpensator based on cascaded H-bridge converter

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Abstract: In this study, a transformer-less STATic synchronous COMpensator (STATCOM) based on cascaded H-bridge (CHB) multilevel converter with floating DC links is presented. This study introduces a control strategy based on state feedback control algorithm in order to supply reactive power to the grid and to compensate the total losses in the internal H-bridge cells. Using this strategy, the converter stability and the fast dynamic response are guaranteed. Moreover, a voltage balancing strategy is proposed, which not only regulates the DC-link voltage of H-bridge cells to the reference value, but also evenly distributes total reactive power among the converter cells, even when there is difference between the losses of H-bridge cells. A 21-level CHB-based STATCOM is simulated in PSCAD/EMTDC environment to evaluate the performance and effectiveness of the new control strategy. Furthermore, the validity of new method is verified on a down-scaled 7-level CHB prototype.

1 Introduction

In recent years, by introducing more stringent standards for control of power networks, improving power quality has become a necessity. Power electronic industry has responded to these requirements by utilising flexible AC transmission systems (FACTs) which improve the controllability and transmission capability of the power grids [1]. Among the FACT controllers, STATic synchronous COMpensator (STATCOM) is a shunt-type device which improves power transmission capability, the power factor and the voltage profile of electric lines by injecting or absorbing adequate amount of reactive power [2, 3]. Moreover, a STATCOM with high dynamic response can improve the system stability under fault conditions [4], can mitigate the voltage fluctuations in wind generation systems [5, 6] and can alleviate the flicker problems caused by arc furnaces in the point of common coupling (PCC) [7, 8].

Conventional STATCOMs consist of three main parts which are an inverter, a coupling transformer and a control system. Multilevel inverters which are made of a series connection of identical modules can be connected directly to medium-voltage networks and can eliminate the necessity to bulky low-frequency transformers [9, 10]. Moreover, these converters can employ well-established insulated gate bipolar transistors (IGBTs), which are capable to operate at medium frequencies (up to several kilohertz (kHz)). Three basic topologies of multilevel inverters are cascaded H-bridge (CHB), neutral point clamped and flying capacitor [11]. Among these topologies, CHB converter has fewer number of power components at the same power rate [12] and also has more controllability when it is used in reactive power compensation applications [13]. Moreover, in a CHB-based STATCOM, the necessity for bulky and heavy coupling transformers and isolated DC power sources can be avoided [14]. The control system of CHB-based STATCOM, however, should regulate the voltage of DC-link capacitors in addition to principal goals [15].

Masrourghi and Imameini [16] present a direct voltage control strategy, where the current sensor feedback is eliminated from the control system. Using this approach, the system reliability increases, but a derivative term appears in the control system, which makes it sensitive to disturbances and reduces the stability margin. In [17, 18], an internal control system based on decoupling current control has been presented. In [18], two additional sub-systems named as ‘cluster balancing’ and ‘individual balancing’ have been added to the internal system. In these approaches, by increasing the number of proportional (P) and proportional–integral (PI) controllers, the system dynamic response degrades and tuning the controllers becomes more complex. The proposed methods in [19, 20] for transformer-less STATCOM are based on predictive control algorithm. In these references, the system input vectors are determined based on a model for the prediction of system behaviour. In the mentioned control methods, high dynamic response is achieved; however, the sensitivity of controller to the system parameters increases. In [21], asymmetric CHB topologies have been proposed for the STATCOM applications. These topologies can generate voltage levels more than symmetrical CHBs, but they lose the modularity. Furthermore, in [21], a modified hybrid pulse width modulation (HPWM) algorithm has been proposed for the modulation of CHB inverter. By applying HPWM, the converter switching loss reduces; however, the control system becomes more complex. In [22], a hybrid CHB-based STATCOM with delta configuration has been presented which is controlled by injecting a zero-sequence current in the delta loop. However, the application of this method is limited to simple structures with just two cells in each cluster.

As it was mentioned before, in CHB-based STATCOMs, it is necessary to employ a voltage balancing strategy in addition to the reactive power control to guarantee the voltage balancing of DC-link capacitors. An imbalance condition may occur in the H-bridge cells of a CHB converter because of the following reasons:

- Unequal losses of H-bridge cells.
- Measurement errors in voltage/current sensors.
- Tolerance of passive elements, especially in DC-link capacitors [18].

In [23], a method has been proposed which distributes the active power among the H-bridge cells by superimposing the cosine value of grid voltage to the reference modulating voltage of each cell. This
method, however, will cause unequal distribution of reactive power and current flow among the H-bridge cells which affects the equal distribution of power losses among the power switches and the reliability. In [24], a balancing algorithm has been suggested in which the added term to the reference voltage of each cell is in-phase with the current and is proportional to the loss of that cell. This algorithm has high stability margin and well balances the voltage of capacitors. However, the existing harmonics in the AC current are transferred into the reference modulating voltage of H-bridge cells. This issue will deteriorate the quality of modulating signal. Therefore the multilevel converter can synthesize a \((2N + 1)\)-level voltage waveform in AC terminal of each leg.

In [25], a modified PWM switching algorithm has been proposed for voltage balancing. This algorithm resolves the previous drawbacks, but it uses a high-burden algorithm and needs an extra field programmable gate array for hardware implementation. In [26], the voltage balancing scheme is based on adjusting the phase angle of cells’ output voltages. This strategy has a fast dynamic response and good regulation capability, but is sensitive to disturbances. In [27], the proposed voltage balancing method uses the STATCOM current as a reference for the rotational \(d-q\) reference frame. In this method, it is assumed that the three-phase voltage sources are balanced and are defined by the following equations

\[
\begin{align*}
    v_a &= v_m \sin(\omega t + \varphi) \\
    v_b &= v_m \sin(\omega t + \varphi - \frac{2\pi}{3}) \\
    v_c &= v_m \sin(\omega t + \varphi + \frac{2\pi}{3})
\end{align*}
\]

where \(v_m\) is the amplitude of the grid voltage. Assuming that each current shaping inductor has a series resistance, the following equations are derived for the phase currents

\[
\begin{align*}
    \frac{di_a}{dt} &= \frac{1}{L_a}(v_m - v_{ca} - R_a i_a) \\
    \frac{di_b}{dt} &= \frac{1}{L_b}(v_m - v_{cb} - R_b i_b) \\
    \frac{di_c}{dt} &= \frac{1}{L_c}(v_m - v_{cc} - R_c i_c)
\end{align*}
\]

Under symmetrical conditions, it can be assumed that \(R_a = R_b = R_c = R_s\)

In Fig. 1, \(v_a\), \(v_b\), and \(v_c\) are three-phase grid voltages at the PCC and \(v_{ca}\), \(v_{cb}\), and \(v_{cc}\) represent the voltage of converter at the AC terminals. The vertical inductors \(L_a\), \(L_b\), and \(L_c\) are used to shape the current and the horizontal inductors \(L_{sl}, L_{sh}\) and \(L_{sc}\) represent the stray inductance of connections and cables. The stray inductance is much smaller than filter inductance and can be neglected in the modelling and analysis of the converter. The control system in STATCOM adjusts the amount of output reactive current by controlling the amplitude of fundamental harmonic at the AC side of converter, that is, \(v_{ca1}\), \(v_{cb1}\) and \(v_{cc1}\). Furthermore, the amount of active power which flows from the grid to STATCOM to compensate the loss of H-bridge cells is controlled by providing a little phase shift between the grid voltage and AC terminals.

### 3 Proposed control strategy for CHB-based STATCOM

#### 3.1 System dynamic model

First, it is assumed that the three-phase voltage sources are balanced and are defined by the following equations

\[
\begin{align*}
    v_a &= v_m \sin(\omega t + \varphi) \\
    v_b &= v_m \sin(\omega t + \varphi - \frac{2\pi}{3}) \\
    v_c &= v_m \sin(\omega t + \varphi + \frac{2\pi}{3})
\end{align*}
\]

where \(v_m\) is the amplitude of the grid voltage. Assuming that each current shaping inductor has a series resistance, the following equations are derived for the phase currents

\[
\begin{align*}
    \frac{di_a}{dt} &= \frac{1}{L_a}(v_m - v_{ca} - R_a i_a) \\
    \frac{di_b}{dt} &= \frac{1}{L_b}(v_m - v_{cb} - R_b i_b) \\
    \frac{di_c}{dt} &= \frac{1}{L_c}(v_m - v_{cc} - R_c i_c)
\end{align*}
\]

Under symmetrical conditions, it can be assumed that \(R_a = R_b = R_c = R_s\)

![Fig. 1](image-url)  

*Fig. 1 Circuit configuration of \((2N + 1)\)-level CHB-based STATCOM*
and \( L_a = L_b = L_c = L_r \). Meanwhile, the balanced three-phase quantities can be transferred into the rotational synchronous two-phase coordinate system (or \( d-q \) reference frame) by the matrix \( C_{dq} \)

\[
C_{dq} = \frac{2}{3} \begin{bmatrix}
\sin(\omega t + \varphi) & \sin(\omega t + \varphi - \frac{2\pi}{3}) & \sin(\omega t + \varphi + \frac{2\pi}{3})
\cos(\omega t + \varphi) & \cos(\omega t + \varphi - \frac{2\pi}{3}) & \cos(\omega t + \varphi + \frac{2\pi}{3})
\end{bmatrix}
\]

By applying \( C_{dq} \) into (2), the following state equations are derived for the phase currents in \( d-q \) rotational reference frame

\[
\begin{align*}
\frac{di_d}{dt} &= \frac{1}{L_d}(v_d - v_{cd} + \omega L_q - R_i i_d) \\
\frac{di_q}{dt} &= \frac{1}{L_q}(v_q - v_{cq} - \omega L_d - R_i i_q)
\end{align*}
\]

(4)

where \( i_d \) and \( i_q \) are the current terms, \( v_d \) and \( v_q \) are the grid voltage components and \( v_{cd} \) and \( v_{cq} \) are the converter output voltage components, in the \( d \)-axis and \( q \)-axis, respectively. Hence, the state-space equations of the AC circuit can be written as

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) \\
y(t) &= Cx(t) + Du(t)
\end{align*}
\]

(5)

where

\[
x(t) = \begin{bmatrix} i_d \\ i_q \end{bmatrix}, \quad A = \begin{bmatrix} -\frac{R_i}{L_d} & \omega \\ -\omega & -\frac{R_i}{L_q} \end{bmatrix}, \quad B = \begin{bmatrix} -\frac{1}{L_d} & 0 \\ 0 & -\frac{1}{L_q} \end{bmatrix}, \quad u(t) = \begin{bmatrix} v_{cd} - v_d \\ v_{cq} - v_q \end{bmatrix}, \quad C = \begin{bmatrix} \frac{3}{2}v_d & -\frac{3}{2}v_q \\ -\frac{3}{2}v_q & \frac{3}{2}v_d \end{bmatrix}, \quad y(t) = \begin{bmatrix} P_s \\ Q_s \end{bmatrix}
\]

and \( D = 0 \). Note that \( u(t) \) and \( y(t) \) are the system input and output vectors, respectively. Besides, \( P_s \) and \( Q_s \) represent the active and reactive powers injected into the grid by STATCOM, respectively.

To derive the dynamic equation of each DC-link capacitor, it is assumed that the internal losses of each cell can be modelled with a resistor in parallel with the corresponding DC link. Now, since the input active power to each cell is equal to the sum of cell losses and the DC-link power, the following relations can be derived for the dynamics of DC-link capacitors in \( d-q \) coordinate system

\[
\begin{align*}
\frac{d^2\bar{v}_{ca}(s)}{dt^2} + \frac{C_{aq}}{R_{aq}}\frac{d\bar{v}_{ca}(s)}{dt} &= \frac{1}{2}(\bar{v}_{caq}(s)\bar{i}_{aq} + \bar{v}_{cq}(s)\bar{i}_{aq}) \\
\frac{d^2\bar{v}_{cb}(s)}{dt^2} + \frac{C_{bq}}{R_{bq}}\frac{d\bar{v}_{cb}(s)}{dt} &= \frac{1}{2}(\bar{v}_{cbq}(s)\bar{i}_{bq} + \bar{v}_{cq}(s)\bar{i}_{bq}) \\
\frac{d^2\bar{v}_{ca}(s)}{dt^2} + \frac{C_{cq}}{R_{cq}}\frac{d\bar{v}_{ca}(s)}{dt} &= \frac{1}{2}(\bar{v}_{caq}(s)\bar{i}_{cq} + \bar{v}_{cq}(s)\bar{i}_{cq})
\end{align*}
\]

(6)

where \( C_{aq}, C_{bq} \) and \( C_{cq} \) represent the size of DC-link capacitors and \( R_{aq}, R_{bq} \) and \( R_{cq} \) model the losses of the \( i \)-th cell in phases \( a, b \) and \( c \), respectively. In addition, \( \bar{v}_{caq}(s) \) and \( \bar{v}_{cq}(s) \) represent the \( d \)-axis and \( q \)-axis components of the AC terminal voltage in the \( i \)-th cell of phase \( a \). Similarly, \( \bar{v}_{cbq}(s) \) and \( \bar{v}_{cq}(s) \) and \( \bar{v}_{caq}(s) \) are the corresponding components in phases \( b \) and \( c \), respectively.

According to (4) and (6), a \((2N+1)\)-level CHB-based STATCOM can be described by \( 3N + 2 \) state variables which are \( i_{dq} \) and \( v_{cd} \) and the capacitor voltages \( \bar{v}_{caq}(s) \), \( \bar{v}_{cbq}(s) \) and \( \bar{v}_{caq}(s) \) where \( i=1, 2, \ldots, N \).

### 3.2 Active and reactive power control system

The proposed active and reactive power control system in this paper should satisfy three major aims:

1. To inject (or absorb) the necessary reactive power into (or from) the grid.
2. To compensate the loss of H-bridge cells through transferring adequate active power to the cells.
3. Achieving fast dynamic response and enough stability margin.

A state feedback control algorithm has been employed to satisfy these aims. In this algorithm, the system eigenvalues and eigenvectors are assigned so that a high dynamic response and acceptable stability margins are achieved. Fig. 2 demonstrates the block diagram of the extracted state-space model of STATCOM and the state feedback control system. In Fig. 2, \( A, B, C \) and \( y \) are the parameters defined in (5) and \( r(t) \) is a vector consisting of the active and reactive power references which the STATCOM should inject into the grid

\[
r = \begin{bmatrix} P_s^* \\ Q_s^* \end{bmatrix}
\]

(7)

According to Fig. 2, the integral state \( \dot{q}(t) \) is defined as

\[
\dot{q}(t) = r - y(t)
\]

(8)
Referring to (7) and (8),  \( \dot{q}(t) \) is obtained as
\[
\dot{q}(t) = \begin{bmatrix} P_x - P_d \\ Q_x - Q_d \end{bmatrix} = \begin{bmatrix} \frac{\delta P_x}{\delta Q_x} \\ \frac{\delta Q_x}{\delta Q_x} \end{bmatrix} \tag{9}
\]

Considering two current state variables \((x(t))\) and two integral state variables \((q(t))\), the whole system depicted in Fig. 2, can be described by the following equations
\[
\dot{z}(t) = \begin{bmatrix} \dot{x}(t) \\ \dot{q}(t) \end{bmatrix} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ q(t) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ I \end{bmatrix} \tag{10}
\]
where
\[
\dot{y}(t) = \begin{bmatrix} x(t) \\ q(t) \end{bmatrix}, \quad A = \begin{bmatrix} A \\ C \end{bmatrix}, \quad B = \begin{bmatrix} \frac{-R_s}{L_s} & \frac{-R_s}{L_s} & 0 & 0 \\ \frac{-\omega}{3} & \frac{-\omega}{3} & 0 & 0 \\ \frac{3V_d^2}{3} & \frac{-3V_d}{3} & 0 & 0 \\ \frac{3V_d^2}{3} & \frac{-3V_d}{3} & 0 & 0 \end{bmatrix}
\]
\[
B = \begin{bmatrix} 0 \\ -1 \end{bmatrix}
\]
\[
\begin{bmatrix} 0 \\ 0 \end{bmatrix}
\]
From Fig. 2, the input vector, \(u(t)\) (the \(d\)-axis and \(q\)-axis terms of the reference voltage), can be written as
\[
u(t) = \begin{bmatrix} -K_v \\ -K_v \end{bmatrix} \begin{bmatrix} x(t) \\ q(t) \end{bmatrix} \tag{12}
\]
By inserting (12) into (10), it is obtained that
\[
\dot{z}(t) = \begin{bmatrix} A - BK_v & 0 \\ -C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ q(t) \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} \tag{13}
\]
In (13), \(\Phi\) indicates the whole system state-matrix. The objective of designing the control system is to generate \(u(t)\) in such a way that the control goals are satisfied. To determine \(K_v\), the following procedure is performed. First, the eigenvalues of the power control system \(\{\lambda_1, \ldots, \lambda_n\}\) are allocated to achieve fast dynamic response and enough stability margin, based on a compromise between high dynamic response and control effort. Then, according to [28], the following equation is valid for each eigenvalue
\[
[\bar{A} - BK_v]v_i = \lambda_i v_i, \quad i = 1, 2, \ldots, n \tag{14}
\]
where \(v_i\) is the corresponding eigenvector of \(\lambda_i\) and \(K_v\) is defined as
\[
K_v = \begin{bmatrix} K_v \\ K_v \end{bmatrix} \tag{15}
\]
The above equation may be rewritten as
\[
[\bar{A} - \lambda_i I] [\bar{B}] [v_i] - K_v v_i = 0 \tag{16}
\]
By defining \(q_i = -K_v v_i\), (16) can be rewritten as
\[
[\bar{A} - \lambda_i I] \bar{B} [v_i] = 0 \tag{17}
\]
where \([v_i \; q_i]^{T}\) should be located in the null space of \([\bar{A} - \lambda_i I] \bar{B}\).
Accordingly, the coefficients of \(K_v = \begin{bmatrix} K_v \\ K_v \end{bmatrix}\) are derived from the following equation
\[
[q_1 \cdots q_n] = \begin{bmatrix} -K_v v_1 & \cdots & -K_v v_n \end{bmatrix} \tag{18}
\]
The proposed active and reactive power control methods, based on state feedback control system, is shown in Fig. 3a. In Fig. 3a, the reference value of active power \(P_x\) is determined by the output of PI regulator, which is shown in Fig. 3b. PI regulator is used to regulate the mean value of DC-link voltages. In other words, \(P_x\) is used to compensate the internal losses in the H-bridge cells. The reference value of reactive power \(Q_x\) is determined by the upper layer controls and is not discussed in this paper.

### 3.3 Proposed voltage balancing scheme

Fig. 4a represents the phasor diagram of an arbitrary cell’s AC terminal voltage, as well as, grid voltage and STATCOM current. The AC terminal voltage of converter is equal to the sum of cells’ AC side voltages. Considering that all cells have the same losses, before activation of voltage balancing scheme, the AC side cells voltages are equal. Therefore it can be written as
\[
v_c = \sum_{i=1}^{N} v_i = Nv_{cAV} \tag{19}
\]
By defining \(\bar{P}_i = \frac{1}{2} (v_{ciaV} v_i + v_{ciaV} v_i)\)
\(\bar{Q}_i = \frac{1}{2} (v_{ciaV} v_i + v_{ciaV} v_i)\)
According to Fig. 4b, in the proposed balancing algorithm, two terms, one in \(d\)-axis and the other in \(q\)-axis, are superimposed to the output voltage of each cell. Therefore the voltage vector of the \(i\)th cell would be
\[
v_c = (v_{ciaV} + \Delta v_{ciaV}) + (v_{ciaV} + \Delta v_{ciaV}) \tag{21}
\]
By modifying the \(i\)th cell voltage reference, the cell active and reactive powers will be derived as follows
\[
\bar{P}_i = \frac{1}{2} (v_{ciaV} + \Delta v_{ciaV}) v_i + (v_{ciaV} + \Delta v_{ciaV}) v_i = \bar{P}_i + \Delta \bar{P}_i \\
\bar{Q}_i = \frac{1}{2} (v_{ciaV} + \Delta v_{ciaV}) v_i - (v_{ciaV} + \Delta v_{ciaV}) v_i = \bar{Q}_i + \Delta \bar{Q}_i, \quad i = 1, 2, \ldots, N \tag{22}
\]
In (22), \(\Delta \bar{P}_i\) and \(\Delta \bar{Q}_i\) are the \(i\)th cell active and reactive power deviations from the mean values because of inserting \(\Delta v_{ciaV}\) and \(\Delta v_{ciaV}\). \(\Delta \bar{P}_i\) and \(\Delta \bar{Q}_i\) can be written as
\[
\Delta \bar{P}_i = \frac{1}{2} (\Delta v_{ciaV} v_i + (\Delta v_{ciaV} v_i), \quad i = 1, 2, \ldots, N \tag{23}
\]
The above equations may be written as

\[
\begin{bmatrix}
\Delta P_i \\
\Delta Q_i
\end{bmatrix}
= \frac{1}{2}
\begin{bmatrix}
i_d & i_q \\
-i_q & i_d
\end{bmatrix}
\begin{bmatrix}
\Delta V_{\text{cd}} \\
\Delta V_{\text{cq}}
\end{bmatrix}
\]  

(24)

As mentioned before, by applying the power control system, the loss of H-bridge cells is compensated through absorbing active power to the converter. Then, in the voltage balancing scheme, the absorbed active power is distributed among the H-bridge cells according to the loss of cells. In the proposed approach, \( \Delta P^*_i \) is determined.

---

**Fig. 3** Proposed control system according to the state feedback theory

- a Proposed active and reactive power control systems
- b Active power adjustment block

**Fig. 4** Phasor diagram of phase a

- a Cell’s AC side voltage, grid voltage and STATCOM current
- b Superposition of two terms to the ac side voltage of \( i \)th cell in the proposed voltage balancing algorithm
such that the corresponding DC-link voltage, that is, $V_{dc}$, is kept close to the mean value of the DC-link voltages, and $\Delta Q$ is set to zero to have an equal distribution of reactive power among the H-bridge cells. Thus, it can be written as

$$\Delta P = k_e (P_e - V_e) + k_i \int (P_e - V_e) \, dt \quad (25)$$

Using this approach, the total active power is distributed according to the loss of each cell and the reactive power is distributed evenly among the H-bridge cells. Knowing $\Delta P$ and $\Delta Q$, and referring to (24), one can derive the following equation for the required voltage injection

$$\begin{bmatrix} \Delta V_{c(i,d)} \\ \Delta V_{c(i,q)} \end{bmatrix} = \begin{bmatrix} i_d & i_q \\ -i_q & i_d \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (26)$$

In (26), $\Delta V_{c(i,d)}$ and $\Delta V_{c(i,q)}$ determine the reference values for the injections of $d$-axis and $q$-axis voltage terms to the modulating waveform of the $i$th cell. Applying these values to all H-bridge cells leads to voltage balance and equal distribution of reactive power among the cells. The block diagram of the proposed voltage balancing scheme is shown in Fig. 5.

4 Simulation results

To evaluate the performance of the proposed control strategy and voltage balancing scheme, a three-phase 21-level CHB inverter is chosen for the study and PSCAD/EMTDC software is used to perform the simulations. For this study, the CHB inverter is designed to connect directly into a 10 kV medium-voltage network and the compensation capacity is set to be ±1.5 MVar. The selected parameters for each leg are given in Table 1. The remaining parameters are given in Table 2.

The steady-state behaviour of STATCOM in both inductive and capacitive operating modes is verified in the first simulation, where the rate of reactive power is equal to the nominal value. Figs. 6a and b show the STATCOM steady-state waveforms of the current and grid voltage in inductive and capacitive modes, respectively. Moreover, Figs. 6c and d demonstrate the corresponding inverter AC terminal voltage and STATCOM current in inductive and capacitive modes, respectively. It is worth mentioning that in the inductive mode (Fig. 6c) the number of voltage levels reduces to 15 because of reduction of AC terminal voltage.

The dynamic behaviour of active and reactive power control system is evaluated in the second simulation. In this study, by assigning the eigenvalues listed in Table 2 to the control system, the coefficient matrices $K_1$ and $K_2$ are derived. To evaluate the dynamic performance, the STATCOM reactive power reference, $Q^*$, is changed from full inductive ($-1.5 \text{ MVAR}$) to full capacitive ($+1.5 \text{ MVAR}$) limits, in a step wise manner at $t=1 \text{ s}$. Fig. 7 shows the STATCOM dynamic response to the change in $Q^*$.

From Fig. 7, it is seen that the STATCOM has followed the new reference value in less than a half-cycle. Fig. 7c shows the DC-link voltages before, during, and after change of reactive power command. It can be seen that the voltage regulation is maintained in the whole period and the voltage ripple is lower than 5% for each DC link.

To compare the dynamic behaviour of the proposed strategy with the indirect current control method suggested in [16] and the decoupled current control approach in [17], the following investigation is done. First, the indirect current control method is applied to the CHB-based STATCOM (with the same parameters in Table 1) and the reference of reactive power is changed from half capacitive to full capacitive at $t=1 \text{ s}$. It should be noted that,

Table 1  Simulated system parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of cells in each leg</td>
<td>$N$</td>
<td>10</td>
</tr>
<tr>
<td>line-to-line voltage</td>
<td>$V_{lin}$</td>
<td>10 kV</td>
</tr>
<tr>
<td>nominal reactive power</td>
<td>$Q_{nom}$</td>
<td>±1.5 MVar</td>
</tr>
<tr>
<td>total cell losses</td>
<td>$P_{loss}$</td>
<td>30 kW</td>
</tr>
<tr>
<td>reference DC-link voltage</td>
<td>$V_{dc}$</td>
<td>1000 V</td>
</tr>
<tr>
<td>filter inductance</td>
<td>$L_f$</td>
<td>42 mH</td>
</tr>
<tr>
<td>filter resistance</td>
<td>$R_f$</td>
<td>0.1 Ω</td>
</tr>
<tr>
<td>switching frequency</td>
<td>$f_s$</td>
<td>500 Hz</td>
</tr>
<tr>
<td>DC-link capacitor</td>
<td>$C$</td>
<td>4 mF</td>
</tr>
</tbody>
</table>

Fig. 5  Block diagram of voltage balancing technique for a three leg converter ($i = 1, 2, ..., N$)

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in indirect current control, the change of reactive power from full inductive to full capacitive is not possible because of lack of stability. The obtained results in Figs. 8a and d show that the transient time lasts two cycles and the voltage ripple is higher than Fig. 7c, respectively. In the second comparison, the decoupled current control is applied to the CHB-based STATCOM and the reference of reactive power is changed from full inductive to full capacitive at $t = 1$ s. The obtained results in Figs. 8c and a reveal that the transient time lasts again two cycles and the behaviour of DC-link voltages is not as good as Fig. 7c, respectively. In brief, the obtained results confirm the better performance of the proposed strategy compared with the introduced methods in [16, 17].

The achieved dynamic performance in this paper is comparable with the proposed predictive control in [19, 20]. However, the quality of STATCOM current is better than predictive approach.

The behaviour of voltage balancing scheme in both steady-state and dynamic condition has been evaluated in the third simulation. At first, the H-bridge cells in phase ‘a’ are divided into three groups, where group #1 includes the first three cells, group #2 contains the next three cells and group #3 includes the last four cells. The losses in the cells of group #1, group #2 and group #3 are assumed to be 100, 2000 and 1000 W, respectively. The loss of H-bridge cells is selected much different to evaluate the performance of voltage balancing scheme. Fig. 9a shows the DC-link voltage of one cell from each group, and Figs. 9b and c demonstrate the corresponding cells’ active and reactive powers, respectively. As Fig. 9a shows, the proposed voltage balancing scheme has kept the voltage of DC links close to the reference value (1000 V), although the H-bridge cells have different amounts of losses. That is because of active power sharing according to the loss of H-bridge cells, which can be seen in Fig. 9b. Finally, Fig. 9c confirms the equal sharing of reactive power among the H-bridge cells which was described in Section 3.3.

Behaviour of the voltage balancing scheme before and after its activation in the control system is evaluated in the fourth simulation. Here, it is assumed that three cells which belong to different legs have unequal losses, for example, 300, 1000 and 2000 W. The voltage balancing system is inactive at first and the DC-link voltages have unequal values which could be seen in Fig. 9d. However, when the voltage balancing scheme is applied at $t = 0.5$ s, all voltages converge to the reference value in <70 ms.

The last simulation investigates the stability of the proposed state feedback control against variation of series input inductance, that is, $L_s$, which is the summation of filter inductance and the series stray inductance $L_{ss}$. In other words, one of the challenges in assigning the eigenvalues of power control system is noting to the control system sensitivity to variation of system parameters, such as filter inductance and resistance. In the previous sections, by adjusting the state feedback matrix coefficients, the power control system eigenvalues were assigned according to Table 2, where $L_s = 42$ mH and $R_s = 0.1$ Ω. Here, for evaluation of control system stability, the inductance value $L_s$ is changed intentionally up to $\pm 20\%$ around its nominal value. The location of eigenvalues in complex plane, before and after the change of $L_s$ is shown in Fig. 10a. Moreover, the converter behaviour during compensation is shown in Fig. 10b when the inductance value is changed. The obtained results confirm the satisfactory stability of control system against variation of inductance value.

### Table 2 Eigenvalues of active and reactive power control system

<table>
<thead>
<tr>
<th>Power control system eigenvalues</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>$\lambda_3$</th>
<th>$\lambda_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$-600 + j50$</td>
<td>$-600 - j50$</td>
<td>$-615$</td>
<td>$-630$</td>
</tr>
</tbody>
</table>

5 Experimental results

To verify the validity of the proposed control strategy, a scaled down prototype has been employed. The prototype is a single-phase 7-level CHB inverter which connects to the AC network via an

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**Fig. 6** STATCOM current and grid phase voltage in steady state in

a Nominal inductive mode
b Nominal capacitive mode

**Fig. 7**

c Nominal inductive mode
d Nominal capacitive mode

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Fig. 7  STATCOM response to the change of reactive power command

a Active and reactive power curves
b STATCOM reactive current and its reference value
c DC-link voltages during reactive power change at $t = 1$ s

Fig. 8  STATCOM response to the change of reactive power command when the indirect current control method in [16] and the decoupled current control approach in [17] are applied

a Active and reactive power curves in indirect control method
b DC-link voltages during reactive power change at $t = 1$ s in indirect control method
c Active and reactive power curves in decoupled control method
d DC-link voltages during reactive power change at $t = 1$ s in decoupled control method
autotransformer. In the single-phase prototype, the same power control system in Fig. 3 and voltage balancing scheme in Fig. 5 have been implemented. The difference is employing a single-phase $d-q$ transformation instead of a three-phase $d-q$ transformation. According to Gonzalez et al. [29], the single-phase $d-q$ transformation is the extension of three-phase $d-q$ transformation, in which a virtual circuit with identical parameters to the real circuit, but with a $\pi/2$ radian phase shift on its voltage and current signals is considered [29]. Using this approach, $d-q$ transformation can be applied even in a single-phase converter; hence, the validity of the proposed control system can be examined by the single-phase converter in practice. The designed converter can transfer \( \pm 200 \) VA and the switching frequency is limited to 500 Hz. In this prototype, a TMS-320F28335 DSP processor is used to perform the control algorithm and generate the switching signals based on PSC-PWM. The system parameters are listed in Table 3.

The behaviour of STATCOM in inductive and capacitive operating modes is verified in the first experiment. Figs. 11a and b demonstrate the steady-state current and grid voltage of STATCOM in inductive and capacitive modes, respectively. Moreover, Figs. 11c and d show the STATCOM AC terminal voltage and current in these two modes. Meanwhile, because of single-phase implementation of the hardware, a small passive filter has been utilised to reduce the third harmonic of the current.

**Fig. 9** Performance evaluation of voltage balancing scheme

| a | DC-link voltage of the cells with unequal losses |
| b | Corresponding active power sharing |
| c | Corresponding reactive power sharing |
| d | Dynamic performance of voltage balancing scheme |
Evaluating the obtained results reveals that the current waveform is not same as the simulation result owing to triplen harmonics in the current waveform. In other words, in a three-phase structure, the triplen harmonics will be eliminated automatically and the current waveform will be much similar to the simulation results in Fig. 6. Other source of difference is related to the number of voltage levels which is 21 in the simulation study and 7 in the experimental test. Accordingly, the THD of current will be lower in the simulations when the switching frequency is equal.

The dynamic behaviour of the active and reactive power control system is evaluated in the second experiment. In this test, the STATCOM reactive power reference is changed from 120 VAr capacitive to 120 VAr inductive, in a step-wise manner. From the obtained results in Fig. 12a, one can see that the STATCOM current has followed the command in less than a half-cycle. Moreover, the DC-link voltage (here, one DC link has been shown) remains at the reference value during the transient time. Fig. 12b shows similar behaviour when the STATCOM reactive power reference is changed from 100 to 200 VAr inductive. It is also seen that the DC-link voltage ripple is <5% and the overshoot of DC-link voltage in the worst-case condition, when the reactive power is changed from capacitive to inductive mode, is not higher than 15% and lasts no more than one cycle. Furthermore, higher fluctuation which is seen in the DC-link voltage of Fig. 12a is because of the change of STATCOM compensation mode in which the phase of AC current changes 180°, whereas in Fig. 12b the compensation mode or the current phase does not change.

Table 3  Down-scaled STATCOM prototype parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cells number in a leg</td>
<td>N</td>
<td>3</td>
</tr>
<tr>
<td>line voltage</td>
<td>( V_{\text{line}} )</td>
<td>50 V</td>
</tr>
<tr>
<td>nominal reactive power</td>
<td>( Q_{\text{nom}} )</td>
<td>±200 VAr</td>
</tr>
<tr>
<td>total cell losses</td>
<td>( P_{\text{Loss}} )</td>
<td>10 W</td>
</tr>
<tr>
<td>reference DC-link voltage</td>
<td>( V_{\text{dc}} )</td>
<td>30 V</td>
</tr>
<tr>
<td>filter inductance</td>
<td>( L_{\text{f}} )</td>
<td>4 mH</td>
</tr>
<tr>
<td>filter resistance</td>
<td>( R_{\text{f}} )</td>
<td>0.2 ( \Omega )</td>
</tr>
<tr>
<td>switching frequency</td>
<td>( f_{\text{sw}} )</td>
<td>500 Hz</td>
</tr>
<tr>
<td>DC-link capacitor</td>
<td>( C )</td>
<td>2 mF</td>
</tr>
</tbody>
</table>

Fig. 10  System response to the inductance value change

\( a \) Location of eigenvalues in complex plane when the inductance value is changed

\( b \) Reactive current, before and after the change of \( L_s \) (during compensation)

Fig. 11  STATCOM current and grid voltage in

\( a \) Nominal inductive mode

\( b \) Nominal capacitive mode

\( c \) STATCOM current and AC terminal voltage in

\( d \) Nominal inductive mode

\( d \) Nominal capacitive mode
Finally, because of single-phase implementation of the hardware and not using any extra passive filter (same as the previous experiment), the current waveform has substantial triplen harmonics and the THD is higher than 5%. However, as the simulation study confirms, this problem would not be seen in a three-phase structure.

The behaviour of the proposed voltage balancing scheme is evaluated in the last experiment. In this experiment, two 60 Ω resistors are connected in parallel with the DC links and the third one is not changed. Consequently, the converter cells will have different losses. As it can be seen in Fig. 12c, the voltage balancing system is inactive at first and the DC-link voltages are different. However, when the voltage balancing scheme is applied, all DC-link voltages converge to the reference value (30 V). This experiment confirms the correct operation of the proposed voltage balancing scheme.

6 Conclusions

In this paper, a control strategy was proposed for a transformer-less CHB-STATCOM which can be connected directly to medium-voltage networks. By employing state feedback algorithm, system eigenvalues and eigenvectors are appropriately assigned such that control system stability and high dynamic response are achieved. The simulation and experimental results show that the transient time from full capacitive mode to full inductive mode is <10 ms. Moreover, the presented voltage balancing algorithm is able to regulate the voltage of DC-link capacitors even when the loss of H-bridge cells is different. This algorithm, by injection of d-axis and q-axis voltage terms into the cells modulating waveforms, compensates the loss of H-bridge cells and distributes the reactive power evenly among the H-bridge cells. Simulation and experimental results confirm the validity and effectiveness of the proposed state feedback control strategy and the voltage balancing scheme.

7 References


17 Hassan, F., Crookes, W.: ‘Direct model predictive control for medium voltage modular multilevel STATCOM with and without energy storage’. IEEE Int. Conf. on Industrial Technology (ICIT), 2012, pp. 932–937


