Research on the Multilevel STATCOM based on the H-bridge Cascaded

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Abstract—This paper mainly studies the main circuit topology, the working principle, modulation technique and control strategy of the STATCOM based on H-bridge. The STATCOM direct power control algorithm based on the virtual flux is used to control the AC side reactive power compensation, and in accordance with the principle of conservation of power, the DC side voltage imbalance factors are analyzed, and a distributed DC voltage control algorithm is also introduced. The DC side control algorithm is divided into upper and lower control parts, of which the upper control section is aimed at the average of DC side capacitor voltage of the sub-module unit for the STATCOM device, the lower control part is mainly for each sub-module DC side capacitor voltage. Finally, the control strategy is verified in a three level chain STATCOM system with VME control box as its core controller, and the experimental results show that the algorithm is feasible.

Index Terms—Cascade Multi-Level; STATCOM; Carrier Shift Phase PWM; Direct Power Control; Distributed Control System

I. INTRODUCTION

Flexible AC Transmission System (FACTS) is an important technical means for power grid to reduce energy consumption and improve power quality. As FACTS core equipment, static synchronous compensator (STATCOM) based on H-bridge cascade, which takes the full-controlled power electronic devices constitute a voltage source inverter (IGBT) as the core, and uses the cascade multi-level and PWM technology, has many advantages, such as: small output harmonic currents, less area, short response time, a wide range of reactive power compensation, easy to maintain, easy to expand, and low cost etc. So it has become the focus of research of domestic and foreign experts, and gradually applied to the high-voltage transmission grid [1, 2, 3, 4].

Nowadays, STATCOM AC side control algorithm has been widely used in power decoupling PWM control, which has achieved the decoupling of power model by the PI regulator. It is easy to use and has small amount of calculation; however, to guarantee its normal operation, the network voltage as well as the network voltage transformer are required [5, 6]. The power system is strongly coupled and nonlinear, and the local linearization control of the control theory of nonlinear system is used [7]. This method achieves the Taylor expansion of STATCOM nonlinear state equation, and carries out local linearization at a certain point to obtain the localized linear equation. Then, the modern control theory is adopted to design the controller based on the obtained equation. Although this method has excellent properties of control, the local linearization method has limited the operation range of STATCOM to some extent.

The virtual flux-based STATCOM direct power control algorithm has introduced the concept of virtual flux to obtain the information about network voltage indirectly, thus omitting the network voltage transformer, which has optimized the control structure of the system and improved its reliability [8, 9, 10].

Firstly, the paper studies the main circuit structure and working principle of the STATCOM based on the H-bridge cascade and carrier phase shift PWM (CPS-SPWM) technology; Secondly, On the basis of the STATCOM direct power control algorithm based on virtual flux, the distributed DC side voltage control algorithm is introduced through the principle of power conservation. Finally, the control strategy is verified on three chain STATCOM system controlled by a VME chassis.

II. MAIN CIRCUIT STRUCTURE AND PRINCIPLE OF THE STATCOM BASED ON THE H-BRIDGE CASCADE

The STATCOM based on H-bridge cascaded, which is constituted by the H-bridge module unit in series, has both triangle and star connection mode. Star connection is
shown in Figure 1, equipment capacity can be improved by a simple increase in the number of link module, and it is low cost, easy to implement and small footprint. Ideally, an equivalent circuit diagram of the STATCOM is shown in Figure 2. $L_c$ and $R_c$ are the total inductance and resistance in the apparatus main loop (including the connecting reactance and the inverter impedance). $V_s$ is the grid voltage, $V_c$ is output voltage of the STATCOM, $i_c$ is absorption current of the STATCOM equipment.

The phase and amplitude of the current absorbed by STATCOM from the grid can be controlled by changing the STATCOM output voltage amplitude and phase with respect to $V_s$. And the nature and magnitude of the reactive power can be further controlled [3, 4], Figure 3 shows the voltage and current vectors diagram when the reactive power compensation system connects to the grid through an ideal inductor current. $X_c$ is the value of loop inductance, $\sigma$ is the angle of the STATCOM output voltage with the grid voltage. According to Figure 3, when the STATCOM output voltage amplitude $V_c$ and phase changes, the size and nature of active and reactive power of which absorbed by the STATCOM also vary accordingly[5, 6, 7].

III. MODULATION ALGORITHM OF H-BRIDGE CASCADE MULTILEVEL CONVERTER

Currently, the modulation algorithm H-bridge cascade multilevel converter mainly includes: the ladder wave modulation [11], space voltage vector method [12, 13] and carrier phase shift PWM method [14, 15]. Ladder wave modulation is a baseband modulation method, the switching frequency is low, and conducive to high-power implementation of STATCOM, but the harmonic content of the output voltage is great, only in the case of a large number of level is high-quality output voltage obtained; In contrast, space voltage vector method with a high DC voltage utilization is easy to facilitate the digitization method, but with the increase in the number of output level, especially after more than 5 level, it is difficult to achieve, and the amount of controller operations is increased; CPS-SPWM is a multi-carrier SPWM modulation algorithm. PWM trigger pulse is generated through a multi-channel carrier moving on the timeline $T_c/(2 \cdot N)$ ($T_c$ is carrier cycle, $N$ is the number of modules in series).

Figure 4 is a schematic diagram of the 2 modules in series CPS-SPWM, this method is simple to be designed, and easy to be implemented, and can make the same as the number of switching cycles of the equipment unit module, and is also easy to implement the DC side of capacitor voltage equalizer control.

IV. STATCOM CONTROL STRATEGY BASED ON H-BRIDGE CASCADE

A. STATCOM Direct Power Control Based on Virtual Flux

1) Principle of Virtual Flux Observer
The principle of virtual flux is that overall grid side with converter access is seen as a three-phase AC motor, as is shown in the dark part of the box of Figure 1 and Figure 2, STATCOM converter grid voltage \( v_{cc} \) is equivalent to induced electromotive force which is generated by the AC motor air gap magnetic field in the stator winding, the inductor \( Lc \) and the resistor \( Rc \) are equivalent to the equivalent resistance of the stator winding and the stator leakage inductance respectively, so it can be seen that three-phase grid voltage is gotten through a virtual air gap flux induction. Thus the application flux can be applied instead of the grid voltage in accordance with the relationship that flux phase lags induced electromotive force phase angle of 90°.

According to the relationship between flux and induced electromotive force, the estimated value \( \psi_{ss} \), \( \psi_{cc} \) of virtual flux in \( \alpha, \beta \) coordinate system are:

\[
\psi_{ss} = \int v_{ss} \, dt
\]
\[
\psi_{cc} = \int v_{cc} \, dt
\]  

(1)

Among (1), \( v_{ss} \), \( v_{cc} \) are the grid voltage component in the \( \alpha, \beta \) coordinate system, according to STATCOM voltage equation under the coordinate system

\[
v_{ss} = Lc \frac{di_{ss}}{dt} + v_{ss} + Rc \cdot i_{ss}
\]
\[
v_{cc} = Lc \frac{di_{cc}}{dt} + v_{cc} + Rc \cdot i_{cc}
\]  

(2)

Among (2), \( i_{ss} \), \( i_{cc} \) are the STATCOM current flows in the \( \alpha, \beta \) coordinate system, if the equivalent resistance \( Rc \) is ignored, the estimated value of virtual flux is:

\[
\psi_{ss} = \int \left[ \frac{1}{2} \sum_{i=1}^{n} v_{ai} \left( \sum_{i=1}^{n} S_{ai} - \frac{1}{2} \left( \sum_{i=1}^{n} S_{si} + \sum_{i=1}^{n} S_{ci} \right) \right) + L_{s} i_{ss} \right] \, dt
\]
\[
\psi_{cc} = \int \left[ \frac{1}{2} \sum_{i=1}^{n} v_{ci} \left( \sum_{i=1}^{n} S_{ci} - \frac{1}{2} \left( \sum_{i=1}^{n} S_{si} + \sum_{i=1}^{n} S_{ai} \right) \right) + L_{c} i_{cc} \right] \, dt
\]  

(3)

Among (3), \( v_{dc} \) is the H-bridge module sub-unit DC bus voltage, \( S_{ai} \), \( S_{si} \), and \( S_{ci} \) are respectively \( i \)-th unit of each bridge arm switching state.

By the formula (3), virtual flux signal can be seen as the system phase-locked loop to participate in the system control, phase lock circuit and the grid voltage sensor are omitted, at the same time, when the grid voltage distorts, the satisfied grid angular information can be obtained because of the existence of the integral part.

Since the pure integral part of the formula (3), if the integral initial value isn’t selected properly, The DC bias will be introduced to the virtual flux. Usually a low pass filter is used instead of a pure integrator in order to eliminate the steady state DC offset.

According to the literature [12], the improved virtual flux observer using cascade inertia instead of the pure integral part is shown in Figure 5, the transfer function of the cascade inertia.

\[
H(s) = \frac{N}{s + \alpha_{c}} \cdot \frac{N}{s + \alpha_{c}} = \frac{N^2}{(s + \alpha_{c})^2} \cdot \frac{1}{s}
\]  

(4)

No difference in amplitude and phase shift should be ensured when the pure integrator is replaced. Under these two conditions, the relationship can be obtained as follows.

\[
N = \sqrt{2} \omega_{c}, \quad \alpha_{c} = \omega_{c}
\]  

(5)

\[
\begin{align*}
\psi_{ss} & = \psi_{ss} + \psi_{cc} \\
\psi_{cc} & = \psi_{cc} + \psi_{cc}
\end{align*}
\]

Figure 5. Improved virtual flux observer

2) Instantaneous Power Detection Based on Virtual Flux

Improved virtual flux observer is able to achieve fast and accurate flux estimates. According to the instantaneous power theory, the instantaneous power absorbed by the STATCOM device can be expressed as:

\[
\begin{align*}
p &= \text{Re}(\psi_{ss} \cdot \dot{i}_{c}) \\
q &= \text{Im}(\psi_{ss} \cdot \dot{i}_{c})
\end{align*}
\]  

(6)

where, \( \dot{v}_{ss} \) is the grid voltage vector, \( \dot{v}_{cc} \) is the inflow of the STATCOM current vector. In accordance with the principles of the virtual flux the grid voltage is:

\[
\dot{v}_{ss} = \frac{d}{dt} \psi_{ss} = \frac{d}{dt} (\psi_{ss} e^{i\omega t})
\]
\[
= \frac{d}{dt} \psi_{ss} + \frac{d}{dt} \psi_{cc} + j \omega (\psi_{ss} + j \omega \psi_{cc})
\]  

(7)

Binding of formula (6) and (7), and when the system meets the three-phase balanced sinusoidal line voltage, the virtual flux amplitude is constant. It is possible to obtain the instantaneous power absorbed by the STATCOM:

\[
\begin{align*}
p &= \omega (\psi_{ss} \dot{i}_{cc} - \psi_{cc} \dot{i}_{ss}) \\
q &= \omega (\psi_{ss} \dot{i}_{ss} + \psi_{cc} \dot{i}_{cc})
\end{align*}
\]  

(8)
According to the formula (4) and (8), the STATCOM direct power control system block diagram based on virtual flux is shown in Figure 7 the upper control is the STATCOM direct power control based on virtual flux, \( \theta \) is grid voltage orientation angle. As Figure 7 is shown, the STATCOM control strategy does not require a grid voltage transformer through introducing virtual flux theory. So it can effectively overcome the problem of the detection error due to a voltage transformer, the algorithm is simple and easy to digital implementation.

B. The Control Strategy in the Distributed DC Side

DC capacitor of each module of STATCOM based on H-bridge cascade is independent of each other, and switching losses, circuit losses, the switch allocation status and pulse delay differences, which led to the DC bus voltage imbalance exists [17,18]. In this paper, the DC side control strategy of the hierarchical distributed which is divided into the upper control and lower control is adopted. The upper control stabilizes overall DC bus voltage, that is the average of the entire device module DC bus voltage; lower control stabilizes each module DC bus voltage.

The upper control takes all module DC voltage as a whole, according to the power balance, the mathematical models for the STATCOM DC side capacitor voltage in the \( d-q \) coordinate system is

\[
\frac{dv_{dc}}{dt} = \sqrt{\frac{3}{2}} \frac{K}{C} (i_d \cos \delta + i_q \sin \delta) + \frac{\sqrt{3} V_s}{L_c}
\]

(9)

where, \( v_{dc} \) is the average value of DC capacitor voltage, \( K \) is SPWM modulation ratio, \( C \) is the DC bus voltage, \( V_s \) is the AC grid voltage peak. \( \delta \) is angle between STATCOM output voltage vector and the grid-side voltage vector, if \( \delta \) is small, \( v_{dc} \) and \( i_q \) can be regarded as a linear relationship. So that the DC bus voltage upper control is designed for the outer ring of the active current.

Lower control is for sub-module DC bus voltage, according to the principle of power balance, as is shown in Figure 6, \( C \) is DC capacitor, \( R \) is module equivalent loss resistance, \( i_k \) is arm current, \( u_k \) is the module output voltage fundamental amount. The active amount absorbed and emitted by the sub-module unit is decided by \( i_k \) and their phase angle \( \theta \). Thus, the DC side capacitor voltage can be adjusted by adjusting the amplitude and phase of \( u_k \). The adjustment amount, which has relationship with the bridge arm current, is designed to P regulator, the output is superimposed to the output modulated wave of the reactive power compensation in the AC side, and this does not affect the reactive power control in the AC side.

According to the AC and DC side control algorithm analysis, the cascaded STATCOM control block diagram is shown in Figure 7. Where, \( s_{ak}, s_{bk}, s_{ck} \) are the modulation waves of the carrier shift phase PWM modulation.

V. EXPERIMENTAL VERIFICATION

To verify the above control strategy, a 3 H-bridge cascade STATCOM system in a star connection is developed. As is shown in Figure 7, the main circuit parameters are shown in Table 1. The host controller for experimental platform is control cabinet based on the VME bus produced by the wing company in United States, the laboratory equipments connect with 380V power grid through the auto-transformer.

Figure 8 shows the output of the converter line voltage \( v_{vdc}, v_{vca} \) and the grid line voltage \( v_{vab}, v_{vbc} \). The line output voltage of the converter is 13 level, it can be seen by comparing STATCOM output line voltage \( v_{vdc} \) with the grid voltage \( v_{vdc} \), according to the principle of virtual voltage, grid voltage phase directional meets the control requirements.

Figure 9 is the converter dynamic test waveform, the reactive power is measured by output of D / A board of the VME chassis. Figure 9(a) is transient waveform when STATCOM system absorbs the inductive reactive power, Figure 9(b) is transient waveform when it absorbs the capacitive reactive power, the system running the current value is 3.5 A. In the case of a capacitive mode, the output current THD of inverter is 2.8%, which is 3.2% in...
the case of inductive mode. The figure shows that the control system is stable, good dynamic performance, and the stability of the DC bus voltage is good.

TABLE I. MAIN PARAMETERS OF THE LABORATORY EQUIPMENT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage (rms) ( V )</td>
<td>230</td>
</tr>
<tr>
<td>Grid frequency ( f ) /Hz</td>
<td>50</td>
</tr>
<tr>
<td>Grid inductance ( L ) /mH</td>
<td>4mH</td>
</tr>
<tr>
<td>Module DC capacitor ( C )/uf</td>
<td>3400</td>
</tr>
<tr>
<td>DC bus voltage ( v_{in} )/V</td>
<td>63</td>
</tr>
<tr>
<td>Rated output current ( I_{out} )/A</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 10 is reactive power compensation system, in the case of a capacitive load, The STATCOM system is not put into operation firstly, and opened at time \( t \). The waveform shows that the system compensation effect is good and the current amplitude is significantly reduced.

Figure 8. The line voltage of the 3-cells cascade STATCOM and grid

Figure 9. The dynamic waveforms of the 3-cells cascade STATCOM

VI. CONCLUSION

The main circuit structure and principle of STATCOM based on the H-bridge cascade, the carrier phase shift PWM technology, direct power control algorithms based on virtual flux and distributed DC voltage control algorithm are studied in this paper. The control strategy on 3 H-bridge cascade STATCOM system controlled by a single VME chassis is tested by the experiment, the results show that the STATCOM direct power control algorithm based on the virtual flux is simple, the amount of calculation is small, grid voltage transformer is not needed, and the dynamic performance of the STATCOM system is good; The hierarchical, distributed DC voltage control algorithm can effectively suppress the DC bus voltage fluctuations. The above algorithm can also be extended to the multi-stage high-pressure STATCOM system based on H-bridge cascaded.

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