Study on a Novel STATCOM with LC Series Filter

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***Abstract*—In order to effectively restrain the high-frequency harmonic components in compensation current and reduce the reactive power compensation claim to the dc voltage amplitude, we present a new topology of Static synchronous compensator (STATCOM). This method changes the property of impedance by connecting capacitor in ac branch. Then, the evolution relation between new and traditional topologies of STATCOM is analyzed by the theory of circuit, and the decoupling mathematical model is deduced. Its dynamic and steady performance indexes, such as the dc voltage amplitude and total harmonic distortion of current (THD$_i$), are better than traditional topology. Finally, the simulation results correspond well with the theoretical analysis.**

Keywords-STATCOM; series filter; decoupling control; dual circuits.

I. INTRODUCTION

Being its faster response, wider adjustable range and relative small size, Static synchronous compensator (STATCOM) have been applied to regulate bus voltage and to provide power factor control in distribution system in recent years [1]. The harmonic current produced by STATCOM based on inverting circuit and pulse modulation technique (PWM) injects into system. In order to improve better wave quality of compensator current, there are two main ways to be adopted. One is to change the ac filter configuration, such as the LC filter [2][3] and LCL [4][5], the other is increasing the ac filter inductance. For the latter, it not only increases the cost, but also raises the reactive power compensation demand for the dc voltage amplitude. In addition, there is a new control method that the dc voltage in STATCOM dynamically be changed according to variation of reactive power proposed [6]. However, those above measures don't reduce the demand of the dc voltage amplitude.

For the STATCOM having same capacity, the lower dc voltage, the lower cost and the lower demand for the dc voltage amplitude, and it is possible to be used in high voltage field. Moreover, it may reduce harmonic components of compensation voltage for the serial power quality controller which connected with parallel power quality by sharing dc link [7]. Based on traditional topology of STATCOM, the new topology in which the ac capacitor connected in series with ac filter inductor is proposed. Because the property of impedance of ac filter branch is changed, the fundamental component of output voltage is always lower than the source voltage when the load is inductive. Thus, the demand for the dc voltage amplitude may be reduced and the total harmonic distortion of current (THD$_i$) gets small. The relation between new and traditional topology of STATCOM is analyzed by duality principles of electrical circuits, and the corresponding control method is deduced. Finally, the simulation model using PSIM is established and its simulation results correspond well with the theoretical analysis.

II. TOPOLOGY OF STATCOM

The STATCOM compensated distribution system is shown in fig.1. We denote the source voltage by u_s and the fundamental component of voltage source converter (VSC) by u_c.

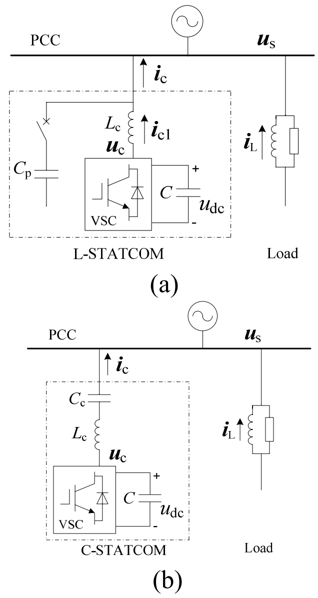


Figure 1. The reactive power compensation system based on STATCOM. (a) L-STATCOM. (b) C-STATCOM

As shown in fig.1 (a), the hybrid reactive power compensated distribution system abbreviated L-STATCOM composed of by traditional STATCOM and a parallel capacitor C_p. In order to realize bidirectional reactive power compensation and in view of one-way reactive power demand of load, both of them compensate 50% reactive power. The new topology of STATCOM, abbreviated C-STATCOM shown in fig.1 (b), is characterized in that capacitor C_c is connected in series with ac filter inductor L_c. Obliviously, there is dual relation between L-STATCOM and C-STATCOM.

It is assumed that SPWM modulation method is used to VSC, and λ represents the modulation index. According to the principle of PWM modulation, the ac/dc voltage relationship can be written as:

$$U_c = \frac{k_c \lambda u_{dc}}{\sqrt{2}} \tag{1}$$

Where k_c=1/2. U_c in fig.1 (a) is bigger than U_s, where $\lambda \in [0,1]$, U_c in fig.1 (b) is smaller than U_s, where $\lambda \in [-1,1]$.

III. PARAMETERS AND CHARACTERISTIC OF C-STATCOM

A. Parameter selection

The relationship between I_c of C-STATCOM and L-STATCOM and U_c is shown in fig.2. Line segment AB indicates the bidirectional characteristic of traditional STATCOM. Line segment EF indicates the characteristic of L-STATCOM, and CD indicates the characteristic of C-STATCOM.

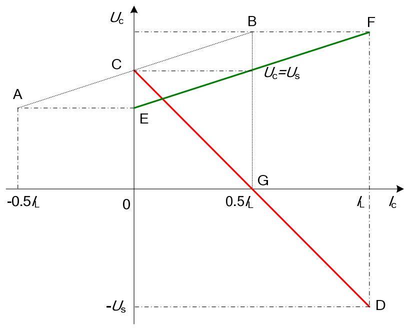


Figure 2. The relation between I_c and U_c

Fig.2 infers that the amplitude of U_c in L-STATCOM varies around U_s, and its variation depends on the reactance ratio of filter inductor. The amplitude of U_c in C-STATCOM varies from $-U_s$ to U_s.

The ac equivalent circuit of VSC in fig.1 is show in fig.3.

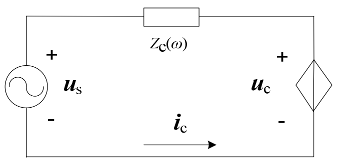


Figure 3. The ac equivalent circuit of STATCOM

In fig.3, we denote the fundamental-frequency impedance of ac filter branch as $Z_c(\omega)$, then its corresponding equations of L-STATCOM and C-STATCOM are given as follows:

$$Z_{c.L}(\omega) = R_c + j\omega L_c \tag{2}$$

$$Z_{c.C}(\omega) = R_c + j\left(\omega L_c - (\omega C_c)^{-1}\right) \tag{3}$$

Where ω is angular frequency of u_s, and R_c is equivalent resistance of L_c and VSC loss, and its value ranges from 5 to 10%ωL_c. It is usually omitted in order to simplify formula derivation. L_c in $Z_c(\omega)$ is decided by selecting principle of traditional STATCOM. The selection of C_c should satisfy $Z_{c.C}(\omega_s) \approx Z_{c.L}(\omega_s)$ (ω_s is angular frequency of carrier signal) in order to be compared with L-STATCOM.

Assuming load reactive power is Q_N and its inductive characteristic is positive. After reactive power is completely compensated, C_c can be written as:

$$C_c = \frac{Q_N}{\omega\left(\omega L_c Q_N + 3U_s\left(U_s - U_c\right)\right)} \tag{4}$$

B. Property analysis and control

The property index of STATCOM can be measured primarily by total harmonic distortion of current (THD$_i$) and cost of main components of VSC. Therefore, the properties of C-STATCOM should be analyzed.

Combined the equation (1) and reactive power compensation mechanism of STATCOM, it can be induced that

$$u_{dc} = \frac{\sqrt{2}\left(3U_s^2 + (-1)^k \left|Z_c(\omega)\right| Q_N\right)}{3k_c \lambda U_s} \tag{5}$$

Where k=-1 when $Z_c(\omega)=Z_{c.L,}$ and k=1 when $Z_c(\omega)=Z_{c.L}$.

According to the calculation principle of THD$_i$, it can be written as

$$\mathrm{THD}_i = \frac{3U_s^2 + (-1)^k \left|Z_c(\omega)\right| Q_N}{\pi k_c \lambda Q_N} \sqrt{\sum_{k=1,n=1}^{\infty} \frac{J_k^2\left(\frac{\lambda n \pi}{2}\right)}{n^2 \Delta}} \tag{6}$$

n=1,3,5…,k=2l,k≠6l(l=1,2,3…),n=2,4,6…,k=2l-1,k≠6l-3 (l=1,2,3…), $J_k(x)$ is n order Bessel function. When $Z_c(\omega)=Z_{c.L}(\omega)$, Δ in THD$_i$ calculation can be given as

$$\Delta = \left(\left(k\omega \pm n\omega_s\right)L_c\right)^2$$

When $Z_c(\omega)=Z_{c.C}(\omega)$, Δ in THD$_i$ calculation can be given as

$$\Delta = \left(\left(k\omega \pm n\omega_s\right)L_c - \left(\left(\left(k\omega \pm n\omega_s\right)C_c\right)^{-1}\right)\right)^2$$

Combine (5) and (6), the relationship of THD$_i$ between L-STATCOM (without C_p) and of C-STATCOM is

$$\frac{\mathrm{THD}_{i.C}}{\mathrm{THD}_{i.L}} \approx \frac{u_{dc.C}}{u_{dc.L}} \tag{7}$$

From (7), decreasing the demand of dc voltage can efficiently improve the quality of its output current in condition of same operation conditions and parameters.

The mathematical model of traditional STATCOM is shown in reference [6]. This paper mainly discusses the mathematical model of C-STATCOM. By inspecting fig. 1(b), the voltage equilibrium of ac branch can be written as

$$\begin{cases} L_c \dfrac{d\boldsymbol{i}_c}{dt} + \boldsymbol{u}_{cs} + \boldsymbol{u}_c = \boldsymbol{u}_s \\ \boldsymbol{i}_c = C_c \dfrac{d\boldsymbol{u}_{cs}}{dt} \end{cases} \quad (8)$$

Assuming A phase voltage of u_s and d axis of synchronization frame as reference phase, we get the dq axis components expression of Laplace transformation corresponding to (8).

$$\begin{cases} \begin{bmatrix} U_{c.d} \\ U_{c.q} \end{bmatrix} = \begin{bmatrix} -sL_c & \omega L_c \\ -\omega L_c & -sL_c \end{bmatrix} \begin{bmatrix} I_{c.d} \\ I_{c.q} \end{bmatrix} + \begin{bmatrix} U_s \\ 0 \end{bmatrix} - \begin{bmatrix} U_{cs.d} \\ U_{cs.q} \end{bmatrix} \\ \begin{bmatrix} I_{c.d} \\ I_{c.q} \end{bmatrix} = \begin{bmatrix} sC_c & -\omega C_c \\ \omega C_c & sC_c \end{bmatrix} \begin{bmatrix} U_{cs.d} \\ U_{cs.q} \end{bmatrix} \end{cases} \quad (9)$$

This paper uses the feedforward decoupling method to deal with coupling term. The details are shown in fig.4.

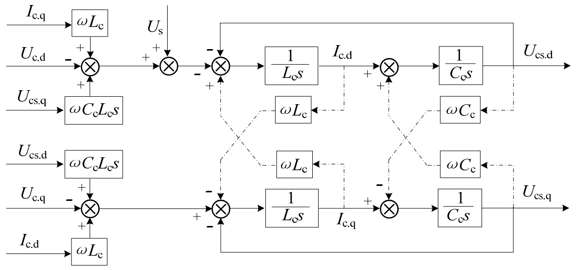


Figure 4. The decoupling model of ac branch of VSC in synchronous frame

After decoupling, dq axis coupled mathematical model in (9) is transformed to dq axis mutual independent mathematical model. Because dq axis has same control structure, taking q axis for example, fig.5 shows its control structure.

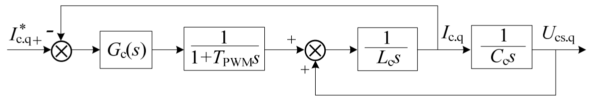


Fig.5: The control structure of reactive current

In fig.5, $I^*_{c.q}$ represents the reactive command current, $G_c(s)$ represents q axis current controller, T_{PWM} is approximate equivalent for PWM to control delay action.

For constant dc voltage controls applied in STATCOM, the equation of dc voltage can be written as

$$C\frac{du_{dc}}{dt} = i_{dc} \quad (10)$$

i_{dc} is given current $I^*_{c.d}$ which is the active power component of ac current for STATCOM to maintain given dc voltage. Its control structure is

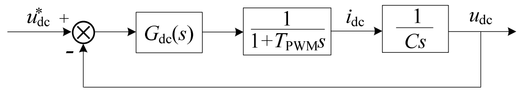


Figure 6. The control structure of dc voltage

u^*_{dc} is the given dc voltage, and $G_{dc}(s)$ is dc voltage controller.

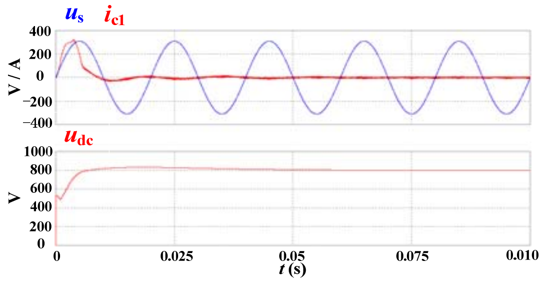
IV. SIMULATION RESULTS

Assuming that the three-phase load in distribution system is balancing, the reactive power compensation system based on L-STATCOM and C-STATCOM is shown in fig.1. And the related simulation parameters with PSIM are listed in Table 1.

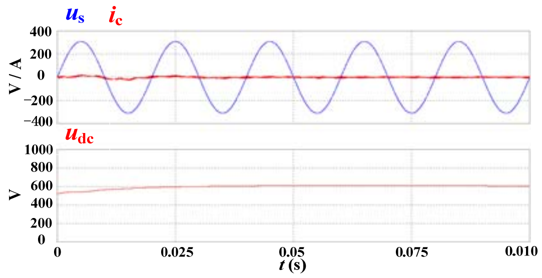
TABLE I. THE PARAMETERS OF STATCOM SIMULATION SYSTEM

Symbol	C-STATCOM	L-STATCOM
$\boldsymbol{u}_s$	380V/50H	380V/50H
Q_N	200kVar	200kVar
L_c	1mH	1mH
IGBT	1200V/600A	1700V/300A
C_c	1803μF	/
C_p	/	2193μF
u^*_{dc}	600V	800V

From two aspects of starting and running, the performance of the C-STATCOM is analyzed in the following discussion. Taking one phase of u_s for example, the waveform of $\boldsymbol{i}_{c1}$ and u_{dc}, which produced by L-STATCOM and C-STATCOM, are respectively shown in fig.7 (a) and (b).



(a)

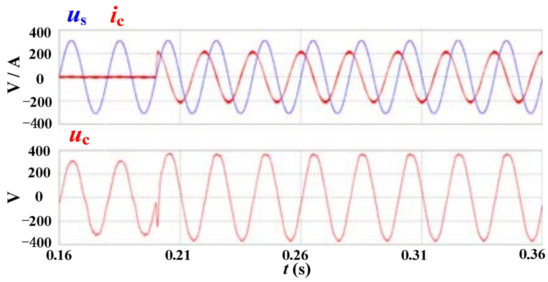


(b)

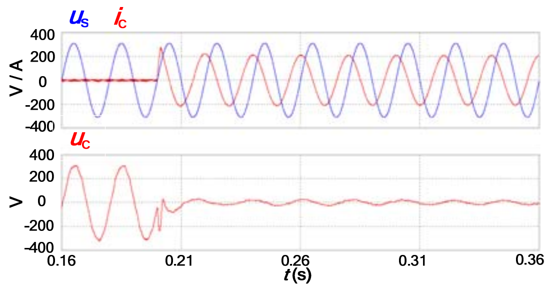
Figure 7. The waveform of $\boldsymbol{i}_{c1}$ and u_{dc} when STATCOM starts. (a) L-STATCOM. (b) C-STATCOM

Compared (a) with (b), the peak value of $\boldsymbol{i}_{c1}$ and u_{dc} produced by L-STATCOM is greater than C-STATCOM. Obviously, C-STATCOM is easy to start.

When reactive load, that is Q, changes from 0~0.5Q_N, the waveform of $\boldsymbol{i}_c$ and $\boldsymbol{u}_c$ produced by L-STATCOM (C_p is offline) and C-STATCOM are respectively shown in fig.8 (a) and (b).



(a)



(b)

Figure 8. The wave of parameters when Q from 0 to 0.5Q_N. (a) L-STATCOM. (b) C-STATCOM

$\boldsymbol{u}_c$ is acquired by first order lowpass filter whose cutoff frequency is 500Hz. Being its inherent delay characteristics, the phase of $\boldsymbol{u}_c$ is slightly lagging behind $\boldsymbol{u}_s$. Compared (a) with (b), the dynamic and steady performance of L-STATCOM and C-STATCOM are basically same. $\boldsymbol{u}_c$ produced by L-STATCOM is in phase with $\boldsymbol{u}_s$ but its amplitude is greater than the latter, and $\boldsymbol{u}_c$ produced by C-STATCOM is almost zero when Q equals 0.5Q_N. In addition, the relation between THD$_i$ and per-unit for Q that 0.5Q_N is as a benchmark is shown in fig.9.

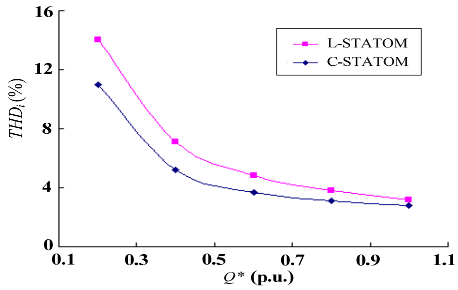
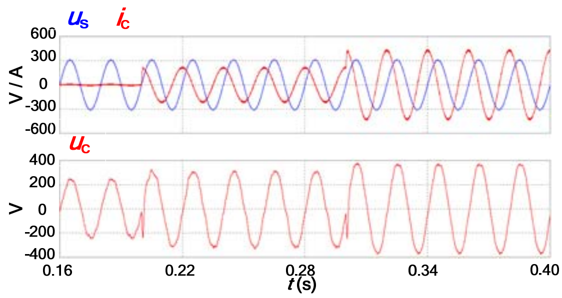
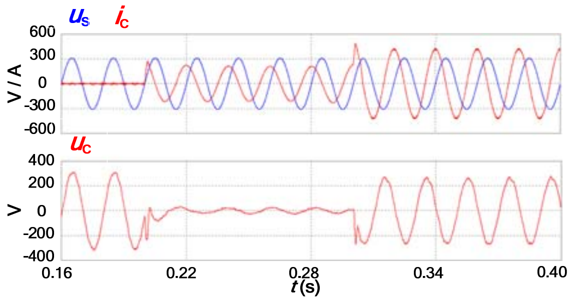


Figure 9. The comparison of THD$_i$ between L-STATCOM without C_p and C-STATCOM

When Q changes from 0.5Q_N to Q_N, the waveform of $\boldsymbol{i}_c$ and $\boldsymbol{u}_c$ produced by L-STATCOM (C_p is online) and C-STATCOM are respectively shown in fig.10(a) and (b).



(a)



(b)

Figure 10 The waves of parameters when Q from 0.5Q_N to Q_N. (a) L-STATCOM. (b) C-STATCOM

Compared (a) with (b), $\boldsymbol{u}_c$ produced by L-STATCOM is in phase with $\boldsymbol{u}_s$ but its amplitude is much greater than the latter, and $\boldsymbol{u}_c$ produced by C-STATCOM nearly equals $\boldsymbol{u}_s$ but two of them are reverse in phase when Q equals Q_N.

The relation between THD_i and per-unit for Q that Q_N is as a benchmark is shown in fig.11.

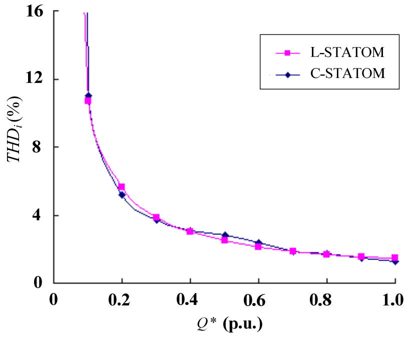


Figure 11. The comparison of THD_i between L-STATCOM and C-STATCOM

V. CONCLUSIONS

In the proposed topology of STATCOM, it can effectively reduce the demand for the dc voltage amplitude, which is general about 25% and makes the selected device has a greater safety margin, or made it possible to choose switching device having low voltage stress. At the same time, its performance index, such as starting current and THD_i, exceed the traditional topology of STATCOM, and its THD_i is similar with hybrid reactive compensation system. Next, we will do the experiment to verify the theoretical analysis.

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