Control Strategy for Cascaded Medium – High Voltage STATCOM

Libing Chen, Liping Shi, Xiaodong Yang, and Zhenglong Xia

Abstract—**Control strategy is researched for cascaded medium high static synchronous compensator to provide synthetic compensation ability of reactive power, harmonics and asymmetric currents. Basing on selective harmonic compensation strategy, a reference current detection method utilizing the combination of synchronous reference frame transformation and discrete Fourier transformation is proposed. The tracking control of instruction current is implemented by multi-carrier pulse width modulation (PWM). In allusion to the multi-carrier PWM, the capacitor voltage balancing control at the dc side is realized by a type of software based on the energy balance principle of the inverter bridge. The proposed control strategy is convenient for engineering implementation given its low calculation burden and simplicity. The effectiveness of the proposed control strategy is proven by both simulation and experimental results.**

Index Terms—**control strategy, reference current detection, static synchronous compensator, tracking control of instruction current, voltage balance control at the dc side.**

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I. Introduction

STATIC synchronous compensator (STATCOM) is the most advanced equipment for reactive power and harmonic current compensation. Compared with other types of STATCOM, cascaded STATCOM, which is based on the series connection of the H-bridge cells, excels for its physical consistency, fewer components, better quality of output current and low difficulty in controller designing especially when the cascaded level becomes large [1]. Given its characteristics, cascaded STATCOM is suitable for high- or medium-voltage power systems.

When used in power systems that have harmonic distortion and asymmetry, the optimal goal of STATCOM is to compensate all reactive currents, harmonic currents, and unbalanced currents, so that the system will need only to provide the positive fundamental active current. To achieve this goal, an appropriate reference current detection method is needed.

The frequently used detection methods were divided into two types in [2]. The first type is the fundamental wave extraction methods (indirect extraction methods). An example of this type of method is the method based on synchronous reference frame transformation [3]. These methods extract the positive fundamental active current component (i_{lb}) from the load current (i_l); subsequently, the compensate currents (i_f) will be equal to ($i_l - i_{lb}$). These methods are usually used for full compensation. The second type of detection method is the harmonic direct extraction methods. These methods extract the reactive currents, harmonic currents and unbalanced currents directly from the load currents. Therefore, this type of method is usually used for selective harmonic elimination. The main function of STATCOM is reactive compensation. Thus, if we utilize fundamental wave extraction method for full compensation, then the installed capacity of STATCOM should be increased. Harmonic energy is mainly concentrated in low frequency band, and the bandwidth of STATCOM is limited because of limited control frequency. Therefore, the output compensating current probably cannot suppress the harmonic components of the load current in high frequency band. Accordingly, the harmonic direct extraction method will be a better choice. The discrete Fourier transformation (DFT) algorithm [4] is one example of the harmonic direct extraction method. However, the ordinary DFT algorithm is complex and needs large storage space. Another direct extraction method based on multiple synchronous rotating reference frames was presented in [5]. When we use this method, the harmonic component to be compensated should be calculated individually. Thus, more calculation work and more resources are needed with more selective harmonic currents to be compensated. This disadvantage can negatively influence the practical effect of the method.

Another problem of cascaded STATCOM is the imbalance of the dc capacitor voltages [6], [7]. The imbalance is caused by the following: different switching patterns for different

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H-bridges [8]; parameter variations of active and passive components inside H-bridges; and control resolution [9]. The voltage balance control at the dc side plays an important role in the output performance and reliability of STATCOM. The imbalance of dc capacitor voltages will degrade the quality of the voltage output; in severe cases, this imbalance could lead to the complete collapse of the power-conversion system [10]. This imbalance will also cause excessive voltages across devices and an imbalance of switching losses. Currently, the capacitor voltage control strategy used for cascade STATCOM mainly has two forms: additional hardware devices and software control algorithm. In normal cases, the software method is used to ensure capacitor voltage balance because hardware requires an increase in complex and expensive equipment. A software method using angular deviation control is proposed in [11]. However, the controllable angle range is very small, so the pulse generator must have high accuracy. By adding an active component, the balance of H-bridge capacitor voltages is realized in [12], but the controller is complex and the parameters are difficult to set.

Aiming at the above-mentioned problems, this paper focuses on the control strategy for cascaded STATCOM. The reference current detection method and voltage balance control strategy at the dc side are discussed as the main part. The validity of the proposed method is verified through simulation and experiment.

II. Reference Current Detection Method

The STATCOM equipment in this paper is mainly used for three three-phase three-wire systems. Thus, the zero sequence components of the three-phase load currents can be ignored, and the load currents can be described as follows:

$$\begin{cases} i_{\mathrm{la}} = \sum_{n=1}^{\infty}\left[i_{\mathrm{ln}+}\cos(n\omega t+\theta_{n+})+i_{\mathrm{ln}-}\cos(n\omega t+\theta_{n-})\right] \\ i_{\mathrm{lb}} = \sum_{n=1}^{\infty}\left[i_{\mathrm{ln}+}\cos(n\omega t+\theta_{n+}-2\pi/3)+i_{\mathrm{ln}-}\cos(n\omega t+\theta_{n-}+2\pi/3)\right] \\ i_{\mathrm{lc}} = \sum_{n=1}^{\infty}\left[i_{\mathrm{ln}+}\cos(n\omega t+\theta_{n+}+2\pi/3)+i_{\mathrm{ln}-}\cos(n\omega t+\theta_{n-}-2\pi/3)\right] \end{cases}, \quad (1)$$

where $i_{\mathrm{ln}+}$ and $\theta_{\mathrm{n}+}$ respectively stand for the amplitude and initial phase angle of the positive sequence component; $i_{\mathrm{ln}-}$ and $\theta_{\mathrm{n}-}$ respectively stand for the amplitude and initial phase angle of the negative sequence component; ω stands for the fundamental angular frequency; n stands for the harmonic order. The three-phase load currents can be transformed into dq vector forms by using abc–dq transformation.

$$\begin{bmatrix} i_{\mathrm{ld}} & i_{\mathrm{lq}} \end{bmatrix}^{\mathrm{T}} = \mathrm{T}_{\text{abc-dq}}\begin{bmatrix} i_{\mathrm{la}} & i_{\mathrm{lb}} & i_{\mathrm{lc}} \end{bmatrix}^{\mathrm{T}} \quad (2)$$

$$\mathrm{T}_{\text{abc-dq}} = \frac{2}{3}\begin{bmatrix} \cos\omega t & \cos(\omega t-2\pi/3) & \cos(\omega t+2\pi/3) \\ -\sin\omega t & -\sin(\omega t-2\pi/3) & -\sin(\omega t+2\pi/3) \end{bmatrix} \quad (3)$$

Substituting (1) into (2), we obtain (4) as follows:

$$\begin{cases} i_{\mathrm{ld}} = \sum_{n=1}^{\infty}\left\{i_{\mathrm{ln}+}\cos[(n-1)\omega t+\theta_{n+}]+i_{\mathrm{ln}-}\cos[(n+1)\omega t+\theta_{n-}]\right\} \\ i_{\mathrm{lq}} = \sum_{n=1}^{\infty}\left\{i_{\mathrm{ln}+}\sin[(n-1)\omega t+\theta_{n+}]-i_{\mathrm{ln}-}\sin[(n+1)\omega t+\theta_{n-}]\right\} \end{cases}. \quad (4)$$

The obtained d axis component i_{ld} and q axis component i_{lq} stand for the active component and reactive component of the load currents, respectively.

According to (4), the n-th positive sequence components in the abc frame become $(n-1)$-th components in the dq frame, and the n-th negative sequence components will become $(n+1)$-th components. Thus, the $(6k\pm1)$-th characteristic harmonic components in the abc frame will become the $6k$-th component in the dq frame (k=1,2,…). Taking advantage of these characteristics, we may firstly obtain the $6k$-th component of i_{ld} and i_{lq} which is gained through abc–dq transformation, then use a resonance regulator which is tuned at the frequency $6k\omega$ to track the $6k$-th component. By using this method, each couple of harmonics at $(6k\pm1)\omega$ can be compensated with only one regulator, thus allowing the required number of regulators to be halved. This approach is better compared with methods using a regulator for each harmonic, such as the method based on multiple synchronous rotating reference frames.

When using this method, the reference current can be obtained through the detection algorithm utilizing the combination of synchronous reference frame transformation with DFT. Firstly, the three-phase load currents in the abc frame become i_{ld} and i_{lq} in the dq frame through abc–dq transformation, then we can use the DFT algorithm in the dq frame to obtain the $6k$-th harmonic components of i_{ld} and i_{lq}.

Calculating the harmonic components in the dq frame by using the ordinary DFT algorithm, which is based on full period sampling, is complex and requires much time because all the sample values in one power cycle are needed to calculate the Fourier coefficients. To reduce the computational effort and to improve real-time performance, the recursive discrete Fourier transform (RDFT) algorithm can be used.

Supposing a periodic signal $X(t)$ with angular frequency ω and period T exists, after discrete sampling with a sampling period τ, we obtain N sample points in one power cycle. The signal $X(t)$ can be described as follows with the DFT formula:

$$X_n(k\tau) = A_n\cos(n\omega k\tau)+B_n\sin(n\omega k\tau), k = 0,1,2,...,N-1 \quad (5)$$

$$A_n = \frac{2}{N}\sum_{m=0}^{N-1}[X(m\tau)\cos(n\omega m\tau)] \quad (6)$$

$$B_n = \frac{2}{N}\sum_{m=0}^{N-1}[X(m\tau)\sin(n\omega m\tau)]. \quad (7)$$

When we use the RDFT algorithm, only the latest sample values, the sample values before one power cycle and the calculated results of the last cycle are needed [13]. The Fourier coefficients of each harmonic component can be calculated according to the following formula:

$$A_n(i) = A_n(i-1)+\frac{2}{N}\{X(i\tau)-X[(i-N)\tau]\}\cos(n\omega i\tau) \quad (8)$$

$$B_n(i) = B_n(i-1)+\frac{2}{N}\{X(i\tau)-X[(i-N)\tau]\}\sin(n\omega i\tau). \quad (9)$$

By using the recursive algorithm, we obtain a significant reduction of the computational effort.

The RDFT algorithm is based on the sampling period, so the calculation result will be refreshed once each sampling cycle. By using high-performance digital signal processor and high speed AD sampling, the sampling frequency can be higher than 10 kHz. Thus, the refresh speed of the calculation result is very fast. When the system is in steady state, i.e., $X(i\tau)=X[(i-N)\ \tau]$, the calculation result will remain unchanged. When the load currents change, the calculation results can show an error. If the fundamental current changes, the correct calculation results will be obtained after a delay time of one power frequency cycle. If only the harmonic component changes, then the delay time will be shorter. Therefore, this method can work correctly even for the fast variable load.

Fig. 1 shows the schematic of the reference current detection algorithm based on synchronous reference frame transformation and DFT. In Fig. 1, i_{ldnr}, i_{ldni} and i_{lqnr}, i_{lqni} stand for the Fourier coefficient of the real part and imaginary part of i_{ld} and i_{lq}, respectively; i_{ld0} and i_{lq0} stand for the dc component of i_{ld} and i_{lq}; i_{ldn} and i_{lqn} (n=2,6,…,24) stand for the n-th component of i_{ld} and i_{lq}; u_{dc} stands for the average voltage value of all the capacitors at the dc side; U_{dc}^* stands for the reference value of the capacitor voltage; u_e stands for the error between U_{dc}^* and u_{dc}; i_{dcd} stands for the reference value of fundamental active current.

Only the characteristic harmonic components below the 25-th component are taken into account in Fig. 1. The three-phase load currents are processed with the proposed detection algorithm, and the reference currents (i_{Fd}^*, i_{Fq}^*) in the dq frame are finally obtained.

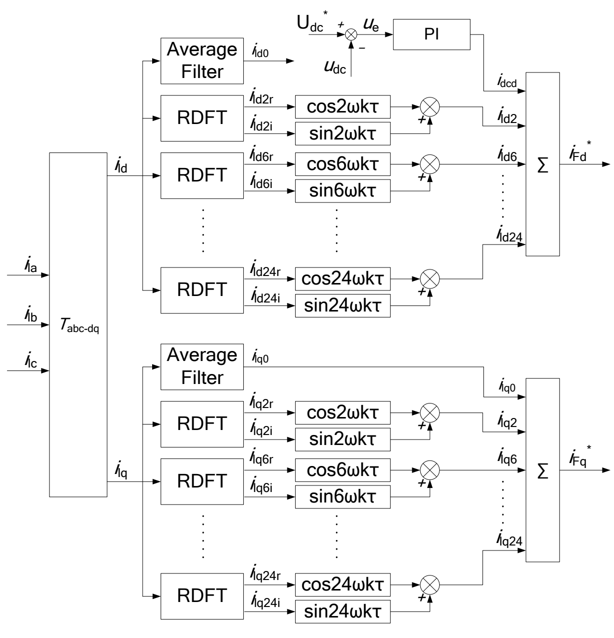

Fig. 1. Proposed reference current detection algorithm.

If the three-phase load currents are unbalanced, a fundamental negative sequence current will occur, which will become a 2-th harmonic component in the dq frame. Therefore, the 2-th component is also calculated in Fig. 1, except for the 6k-th harmonic components. When the load currents only have the characteristic harmonic components below 25-th, the system will need only to provide the positive fundamental active current if we consider the 2-th harmonic component.

By using this reference current detection method, the STATCOM will be able to provide more flexible compensation. Selective compensation can be easily realized by choosing the compensate components in Fig. 1 according to the actual need. The amplitude of reference currents can also be easily limited to avoid exceeding the power rating, and the amplitude of different compensate components can be limited to different values according to the importance degree.

The detection method presented in this paper is based on synchronous sampling. Thus, a voltage-phase synchronizer based on software phase-locked loop technology is necessary. By using this technology, the sample points in one power frequency cycle will remain constant.

III. TRACKING CONTROL STRATEGY OF INSTRUCTION CURRENTS

Fig. 2 shows a control system that uses the proposed detection method. The variables i_{Fa}, i_{Fb}, i_{Fc} stand for the three-phase output currents of the STATCOM; i_{Fd}, i_{Fq} are the output currents in the dq frame; i_{ed}, i_{eq} are the tracking errors in the dq frame; k_{in} (n=2,6,…,24) are the amplitude gain of the resonance controller; ω_c is the cut-off frequency of the resonance controller; $\omega_n=n\omega$, u_{Fdn}^*, u_{Fqn}^* are the n order reference voltage in the dq frame; u_{Fdsum}^*, u_{Fqsum}^* are the sum of the reference voltage in the dq frame; u_{sa}, u_{sb}, u_{sc} are the three-phase grid voltage; L stands for the connected air-core reactor inductance.

The control system contains a dc link voltage control loop (see Fig. 1), two fundament current control loops and two sets of selective harmonic control loops. The traditional proportion-integral (PI) controller is used in the dc link voltage control loop, which gives the fundamental active reference current. The two fundamental current control loops also use the PI controller. The selective harmonic control loops use resonance controller instead. Given the grid voltage disturbance and current coupling, the grid voltage feed-forward and output current decoupling control strategies are adopted in the control system.

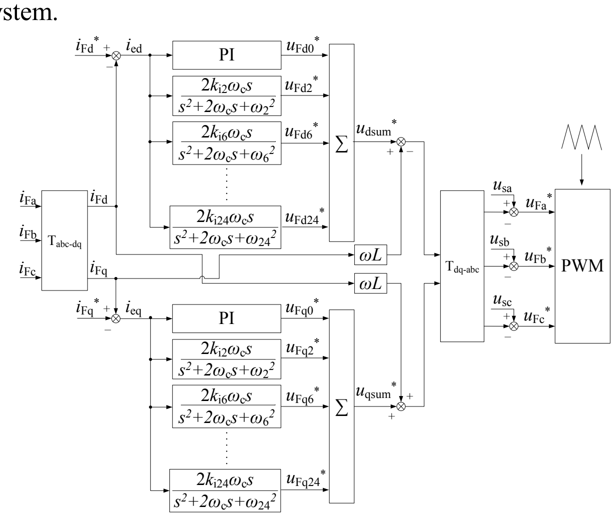

Fig. 2. Control strategy based on the proposed detection algorithm.

The obtained u_{Fa}^*,u_{Fb}^* and u_{Fc}^* in Fig. 2 are the voltage commands, i.e., the final modulation waves in the abc frame. The three-phase modulation waves are applied to a digital PWM block on the basis of the sine-triangle comparison modulation technique to generate the switching pulse for the STATCOM inverter. The multi-carrier PWM method, which is widely used in multi-level converters, can be used here for the cascaded STATCOM. Taking the single-phase three H-bridges as an example, the principle of the multi-carrier PWM method is shown in Fig. 3. The main modulation wave must be split into sections, then each section should be assigned to a different power unit.

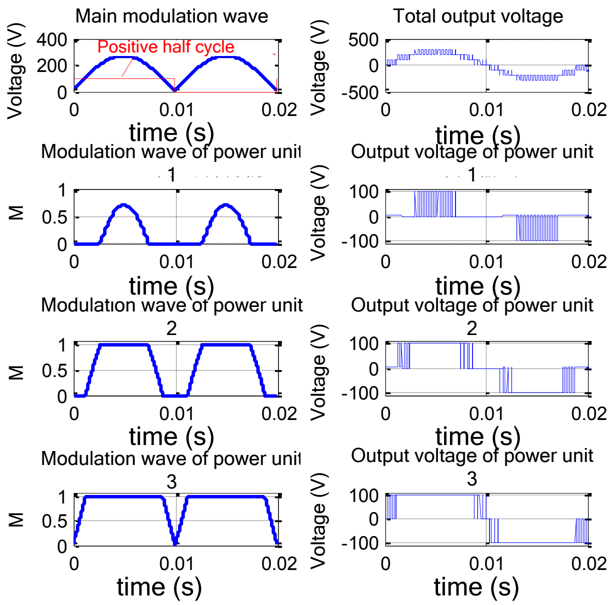

Fig. 3. Multi-carrier PWM.

IV. DC Voltage Balance Control Strategy

The dc link voltage control loop in Fig. 1 is used to control the total real power into the STATCOM to regulate the total dc voltage of all H-bridge units. However, this approach is not enough. Clustered balancing control (to balance the phase leg voltages) and individual balancing control (to balance the capacitors in each phase leg) are also needed. Clustered balancing control can be realized through zero sequence injection [14] or negative sequence injection [15]. Limited by space, this paper provides a discussion only on individual balancing control.

In allusion to the multi-carrier PWM used in this paper, a software individual balancing control strategy is proposed. The software strategy is based on the energy balance principle of the inverter bridge, as shown in Fig. 4.

In Fig. 4, when the capacitor voltage u_c and the current i_{dc} are in the same direction, the capacitor is charged and the voltage increases. When the capacitor voltage u_c and the current i_{dc} are in the reverse direction, the capacitor is discharged and the voltage drops. Shadows A and B stand for the energy absorbed and released by the capacitor, respectively. Given the differences in losses, the capacitance parameters and pulse width of each H-bridge, the energy absorbed and released by the capacitor is not equal in each cycle, so the capacitor voltage of each H-bridge will be imbalanced. The above-mentioned charge and discharge process can be adjusted by the software method, thus solving the voltage imbalance problem.

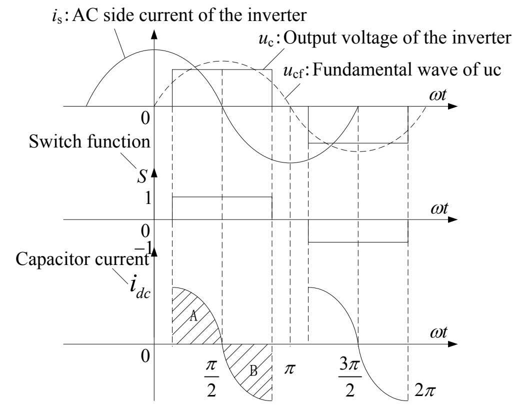

Fig. 4. Energy balance principle of the inverter bridge.

In this paper, the multi-carrier PWM method is adopted to realize the tracking control of instruction currents. As shown in Fig. 3, the modulation wave of each power unit is different, so the charging and discharging time of each dc capacitor will likewise be different. Given these characteristics, the imbalance problem of the dc-link capacitor voltage is even more serious. To solve this problem, a simple and practical software method is presented in this paper. Take phase A for example, when the main modulation signal u_{Fa}^* and the output current i_{Fa} are in the same direction, the dc capacitors of phase A will be charged, but their charging time are different because of their different modulation waves. When u_{Fa}^* and i_{Fa} are in the reverse directions, the dc capacitors of phase A will be discharged, but their discharging time will be different. Thus, we can control the charging and discharging time by changing the distributive rule of modulation signal according to the capacitor voltages. The individual capacitor balance algorithm is made up of a sequence of steps, which are executed every control cycle (see Figs. 5 and 6). In Figs. 5 and 6, x=a, b or c; *temp*0 and *temp*1 are two temporary variables; n is the number of cascaded power units in each phase; the capacitor voltages of each power unit are stored in array $u_{cx}[n]$; the modulation signal for each power unit is stored in array $pwmo_x[n]$; the serial number of each power unit is stored in array $id_x[n]$ according to the order of capacitor voltages.

By using this method, the capacitor with lower voltage will have longer charging time or shorter discharging time, and the capacitor with higher voltage will have shorter charging time or longer discharging time. Thus, the voltages of all the capacitors will become balanced.

The distributive rule of the modulation signal will be changed immediately when the charging and discharging state changes or when the order of capacitor voltages changes. This method is based on the sample time and has a good dynamic response. Furthermore, this method does not require other controllers and will never be out of control.

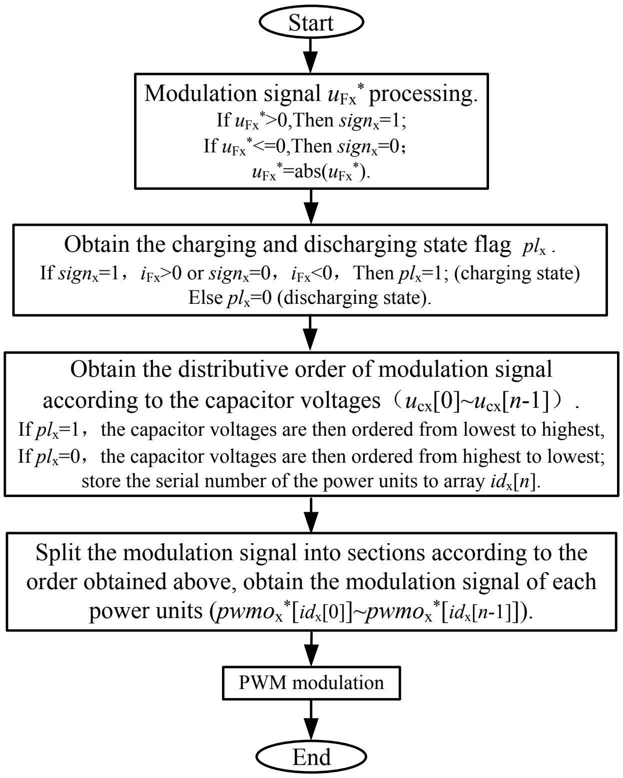

Fig. 5. Flow diagram of proposed individual balancing control strategy.

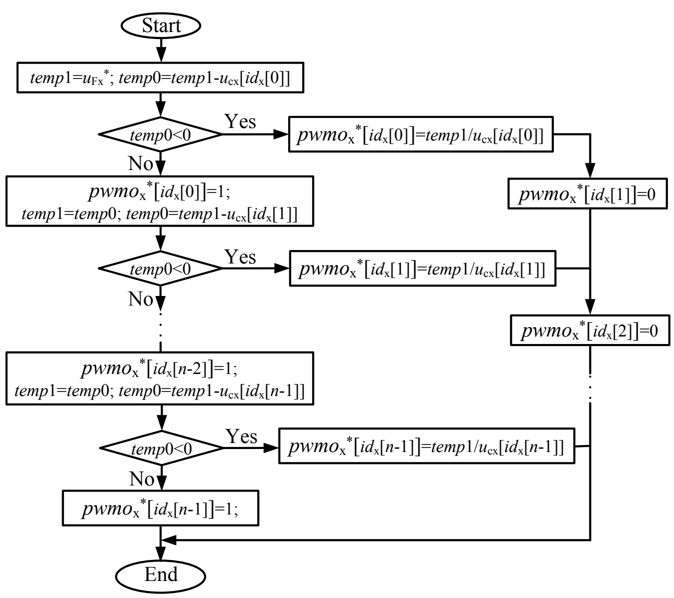

Fig. 6. Flow diagram of the modulation signal distribution process.

V. Results and Analysis

A. Simulation Verification

A simulation model is built in MATLAB. The system voltage is 6 kV, and the fundamental frequency is 50 Hz. The number of cascaded H bridges of each phase is 8, and the star connection method is adopted. The dc link capacitor of each power unit is 3000 μF. The reference voltage of the dc link capacitor is 750 V, and the sampling frequency is 10.8 kHz. To verify the synthetic compensation ability for STATCOM when using the control strategy proposed in this paper, the load current is designed to contain 150 A active currents, 100 A reactive currents, 20 A harmonic currents and 10 A unbalanced currents. Simulation results are shown in Figs. 7 to 11.

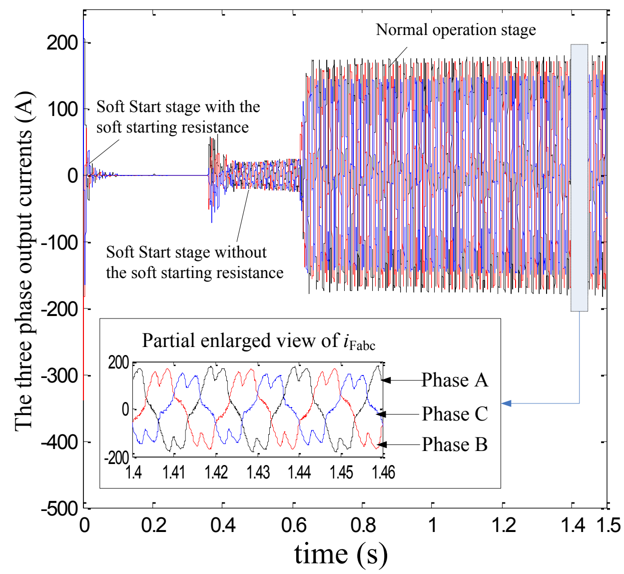

Fig. 7. Waveforms of three-phase output currents.

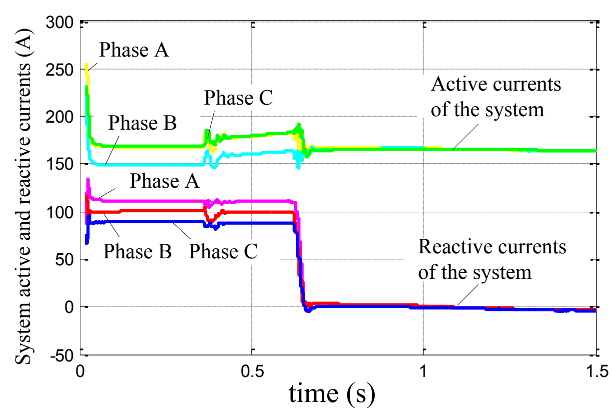

Fig. 8. System active and reactive currents.

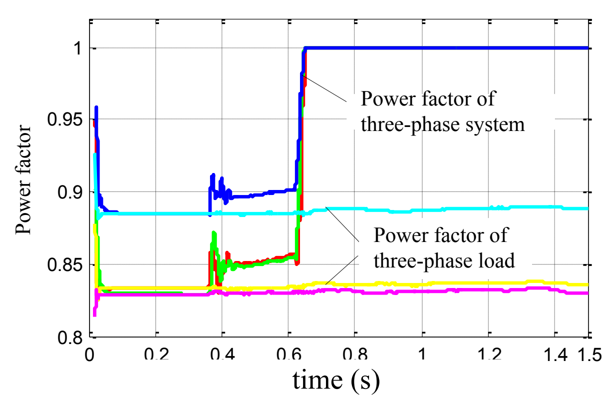

Fig. 9. System power factor.

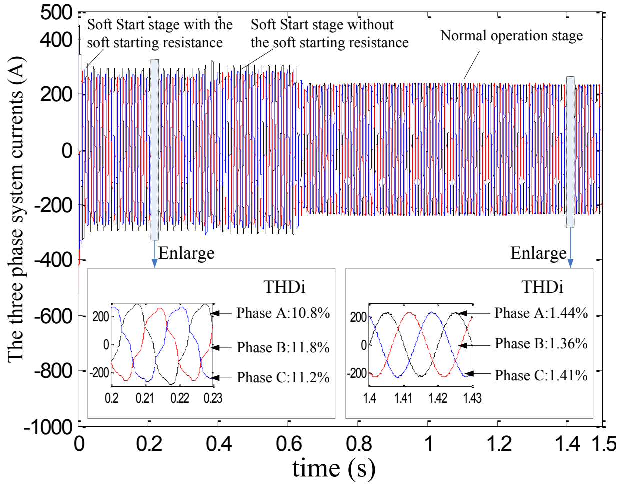

Fig. 10. Waveforms of three-phase system currents.

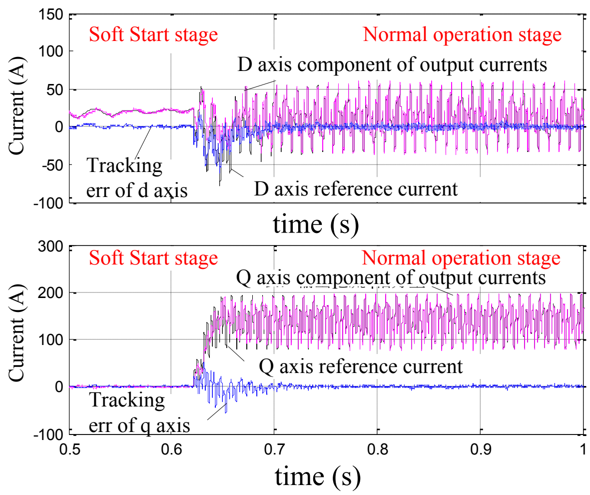

Fig. 11. Reference current, output current, and err.

From Figs. 8 to 10, we can see that the three-phase active currents and reactive currents provided by the system are changed from unbalanced to balanced, and the reactive currents are restricted to almost zero after the STATCOM runs properly (see Fig. 8). The system power factor values are improved from below 0.9 to 1(see Fig. 9). The total harmonic distortion (THD) values of the system currents are also significantly restricted (see Fig. 10). From these data, we can denote that the STATCOM has synthetic compensation ability. Thus, the proposed reference current detection algorithm is accurate.

Fig. 11 shows the reference current of the *d* axis and *q* axis, the *d* axis and *q* axis component of the output currents and the tracking err. According to Fig. 11, the tracking err in the normal operation stage is very small. Thus, the performance of the tracking control strategy used in this paper is very good.

The dc voltage balance control strategy is also verified in the simulation process. The modulation waves of each power unit in phase A, which is obtained by using the balance method presented in this paper, are shown in Fig. 12. All the dc capacitor voltages fluctuate slightly around the reference voltage, as shown in Fig. 13, which shows that the control strategy is very effective.

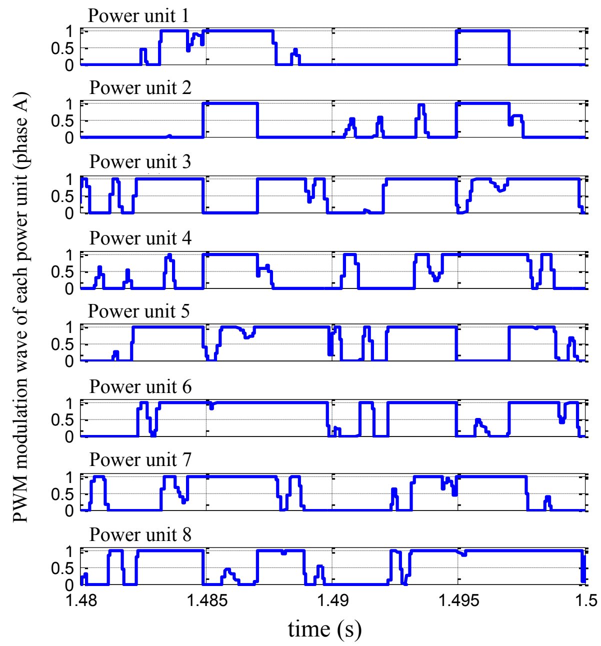

Fig. 12. PWM modulation wave for each power module.

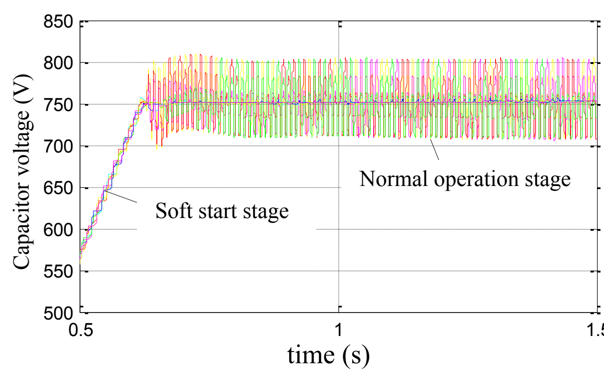

Fig. 13. Capacitor voltage of each power module (phase A).

B. Experiment Verification

Verification is carried out in the laboratory platform. Taking account of the difficulty of setting up a real load in medium- or high-voltage environment, we use two same capacity (3MVar) STATCOMs in the experiment. The two STATCOMs are connected to the point of common coupling of a 6 kV power system. One STATCOM works as a load, and the other works as a compensator. The STATCOM working as a load can send out various currents flexibly in open loop state, thus imitating the real load. The currents mainly contain two components, namely, fundamental reactive current (may be inductive, may be capacitive) and harmonic currents (may contain a variety of characteristic harmonic currents). The STATCOM working as a compensator will detect the load currents in real time and will then compensate the load currents by using the method proposed in this paper.

We made a performance test for reactive compensation. One STATCOM worked as a load and sent out inductive reactive currents, which changed between 70 A (light load) and 250 A (heavy load) every 5 s. Fig. 14 shows the current waves of the two STATCOMs (measured from the same phase but with an opposite direction). After the reactive compensation test, we made a performance test for harmonic compensation. This time, the load currents also sent out 30 A harmonic currents (contained a variety of characteristic harmonic currents), except for the inductive reactive currents, which changed between 50 A and 100 A every 5 s. Fig. 15 shows the current waves of the two STATCOMs.

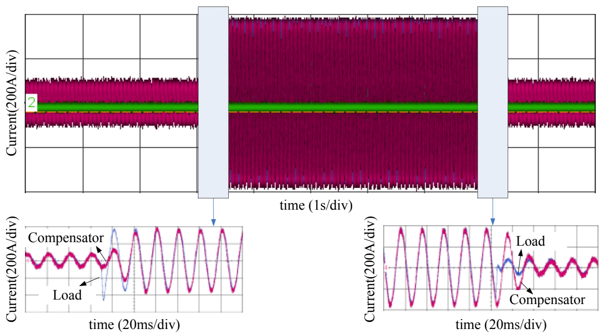

Fig. 14. Performance test for reactive compensation.

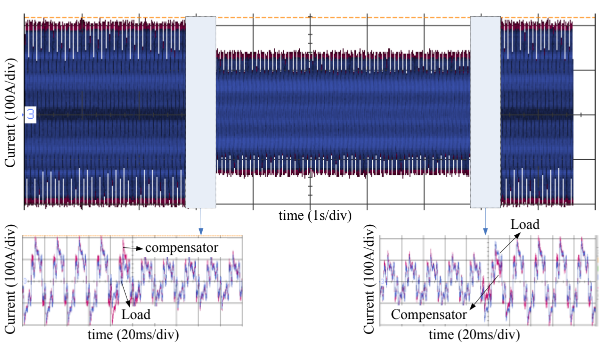

Fig. 15. Performance test for harmonic compensation.

From Figs. 14 and 15, we can see that the current waves of the two STATCOMs are almost the same in steady state. Therefore, the reactive and harmonic load currents are compensated by the STATCOM, which worked as a compensator fairly well. Figs. 14 and 15 also show that only about one power cycle is needed after the step change of the load currents, good compensation effect will be achieved again. Thus, we can denote that the dynamic performance of the STATCOM in this paper is good.

VI. Conclusion

The main contribution of this paper is the development of a new reference current detection algorithm based on selective compensation strategy for STATCOM. This algorithm allows the simultaneous compensation of two characteristic harmonics with only one regulator, yielding a significant reduction of computational effort compared with other methods. By using this method, the STATCOM can provide synthetic compensation ability, and the compensation will be very flexible.

This paper also proposed a software method to realize the individual balancing control of capacitor voltages at the dc side. Compared with other methods, the proposed method does not require other controllers and will never be out of control.

Theoretical analysis and experimental research show that the proposed control strategy is characterized by its simple structure, small calculation time and good dynamic performance. In conclusion, the proposed strategy is suitable for practical application of engineering and has wide application prospects.

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