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Reference Current Detection Algorithm for STATCOM

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Abstract

A reference current detection algorithm based on synchronous reference frame transformation and discrete Fourier transformation is presented for STATCOM (Static Synchronous Compensator) to provide synthetic compensation. The proposed algorithm can be used to extract reactive currents, unbalanced currents and characteristic harmonic currents from the load currents in real time. This algorithm allows the simultaneous compensation of two current harmonics with just one regulator, yielding a significant reduction of the computational effort compared with other methods. The results of simulation and experiment show the validity of this method.

Keywords*: reference current detection, static synchronous compensator, selective harmonic compensation, synchronous reference frame, discrete Fourier transformation*

1. Introduction

As the most advanced equipment for reactive power compensation, the static synchronous compensator (STATCOM) which based on power electronics converter has been widely researched. Although the main function of STATCOM is reactive power compensation, it can also be used to compensate harmonic currents or even unbalanced load currents, just like the active power filter (APF). With the evolution of power electronics and the increasing use of power semiconductors, the interest in synthetic compensation capability of STATCOM has grown considerably in recent years. When used in power systems which have the problem of harmonic distortion and asymmetry, the most optimal goal of compensation for STATCOM is to compensate all the reactive currents, harmonic currents, as well as unbalanced currents, so that the system will only need to provide the positive fundamental active current.To achieve this goal, a reference current detection method which can extract reactive currents, harmonic currents and unbalanced currents from the load currents in real time is needed.

As a key problem of the STATCOM, the reference current detection method has been deeply researched. The frequently used detection methods can usually be divided into two types, time-domain methods or frequency-domain methods [1], however, another classification method has been presented in [2] from a different point of view.

The first type of detection method presented in [2] is fundamental wave extraction method (indirect extraction method). For example, the frequency-domain method using band pass, band rejection filter or trap filter which realized with analogy circuit, the method based on instantaneous reactive power theory [3-5], the method based on synchronous reference frame (SRF) transformation [6]. These methods extract the positive fundamental active current component (i_{lb}) from the load current (i_l), then the compensate currents (i_f) will be equal to (i_l -i_{lb}). These methods are usually be used for full compensation.

The other type of detection method presented in [2] is harmonic direct extraction method. For example, the discrete Fourier transformation (DFT) algorithm based on frequency-domain analysis [7], the algorithm based on multiple synchronous rotating reference frames (MSRFs) [8]. These methods extract the reactive currents, harmonic currents and unbalanced currents directly from the load currents, so they are usually be used for selective harmonic elimination.

The main function of STATCOM is reactive power compensation, so if we using fundamental wave extraction method for full compensation, the installed capacity of STATCOM should be increased. Actually, the harmonic energy is mainly concentrated in low frequency

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band. On the other hand, the bandwidth of STATCOM is limited because of the power electronic devices, so the output compensating current probably can not suppress the harmonic components of the load current in high frequency band. According to that, we use harmonic direct extraction method for selective harmonic elimination.

The aim of this work is to propose a reference current detection method which is easy to be realized for STATCOM to provide synthetic compensation. The algorithm based on SRF transformation and MSRFs transformation are introduced and analysed, and then a new method based on SRF transformation and discrete Fourier transformation is presented. Finally, the validity of the proposed method is verified through simulation and experiment.

2. Detection Algorithm Based on SRF and MSRFs

Assume that the three-phase load currents are described as follows:

$$\begin{cases} i_{la} = \sum_{n=1}^{\infty}\left[i_{\ln+}\cos(n\omega t+\theta_{n+}) + i_{\ln-}\cos(n\omega t+\theta_{n-}) + i_{\ln 0}\cos(n\omega t+\theta_{n0})\right] \\ i_{lb} = \sum_{n=1}^{\infty}\left[i_{\ln+}\cos(n\omega t+\theta_{n+}-\frac{2\pi}{3}) + i_{\ln-}\cos(n\omega t+\theta_{n-}+\frac{2\pi}{3}) + i_{\ln 0}\cos(n\omega t+\theta_{n0})\right] \\ i_{lc} = \sum_{n=1}^{\infty}\left[i_{\ln+}\cos(n\omega t+\theta_{n+}+\frac{2\pi}{3}) + i_{\ln-}\cos(n\omega t+\theta_{n-}-\frac{2\pi}{3}) + i_{\ln 0}\cos(n\omega t+\theta_{n0})\right] \end{cases} \quad (1)$$

Where $i_{\ln+}$ stands for the amplitude ofpositivesequence component, $i_{\ln-}$ for the amplitude of negative sequence component, and $i_{\ln 0}$ for the zero sequence component.

The three-phase load currents are transformed into dqz vector forms using abc-dq0 transformation.

$$\begin{bmatrix} i_{ld} & i_{lq} & i_{l0} \end{bmatrix}^T = T_{abc-dq0}\begin{bmatrix} i_{la} & i_{lb} & i_{lc} \end{bmatrix}^T \quad (2)$$

$$T_{abc-dq0} = \frac{2}{3}\begin{bmatrix} \cos\omega t & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin\omega t & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (3)$$

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

$$\begin{cases} i_{ld} = \sum_{n=1}^{\infty}\{i_{\ln+}\cos[(n-1)\omega t+\theta_{n+}] + i_{\ln-}\cos[(n+1)\omega t+\theta_{n-}]\} \\ i_{lq} = \sum_{n=1}^{\infty}\{i_{\ln+}\sin[(n-1)\omega t+\theta_{n+}] - i_{\ln-}\sin[(n+1)\omega t+\theta_{n-}]\} \\ i_{l0} = \sum_{n=1}^{\infty}\left[i_{\ln 0}\sin(n\omega t+\theta_{n0})\right] \end{cases} \quad (4)$$

According to (4), the n-th positivesequence components in abc frame become (n-1)-th components in dqz frame, so the positivesequence fundamental components in abc frame becomes a dc term. The n-th negitivesequence components in abc frame, in contrast, will become (n+1)-th components in dqz frame. Another conclusion is that the zero sequence components have no effect oni_{ld} and i_{lq}. The STATCOM equipments in this paper are mainly used for three three-phase three-wire system, so the zero sequence components can be ignored and the abc-dq0 transform matrix $T_{abc-dq0}$ can be simplified to T_{abc-dq}. Figure 1 shows the control block diagram of the SRF-based reference current generator.

As mentioned above, the positivesequence fundamental components in abc frame becomes a dc term, so they are relatively easy to be filtered out with the LPFs approach. In order to compensate reactive power current, the switch S in Figure 1 should be set to open. Then, the instantaneous waveforms of the active power currents (i_{lab},i_{lbb},i_{lcb}) can be produced by applying the dq-abc transformation to the filtered dc terms. Subtracting (i_{lab},i_{lbb},i_{lcb}) from i_{labc}, the instantaneous reference currents (i_{Fa}^*,i_{Fb}^*,i_{Fc}^*) are then obtained.

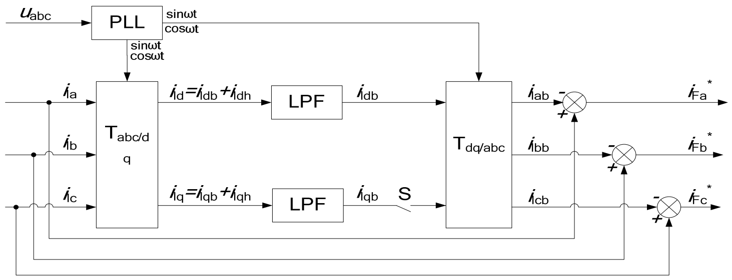

Figure 1. SRF-based Reference Current Generator

The detection method based on SRF is a kind of fundamental wave extraction method and is not suitable for selective harmonic elimination. The detection method based on MSRFs, which isevolved from the SRF based method, is a kind of harmonic direct extraction method, so it can be used for selective harmonic elimination. When using this method, four transform matrixes are needed:

$$T_{abc-dq}^{P}=\frac{2}{3}\begin{bmatrix}\cos n\omega t & \cos(n\omega t-2\pi/3) & \cos(n\omega t+2\pi/3)\\ -\sin n\omega t & -\sin(n\omega t-2\pi/3) & -\sin(n\omega t+2\pi/3)\end{bmatrix} \tag{5}$$

$$T_{abc-dq}^{N}=\frac{2}{3}\begin{bmatrix}\cos n\omega t & \cos(n\omega t+2\pi/3) & \cos(n\omega t-2\pi/3)\\ -\sin n\omega t & -\sin(n\omega t+2\pi/3) & -\sin(n\omega t-2\pi/3)\end{bmatrix} \tag{6}$$

$$T_{dqn-dq1}^{P}=\begin{bmatrix}\cos((n-1)\omega t) & \sin((n-1)\omega t)\\ -\sin((n-1)\omega t) & \cos((n-1)\omega t)\end{bmatrix} \tag{7}$$

$$T_{dqn-dq1}^{N}=\begin{bmatrix}\cos((n+1)\omega t) & -\sin((n+1)\omega t)\\ -\sin((n+1)\omega t) & -\cos((n+1)\omega t)\end{bmatrix} \tag{8}$$

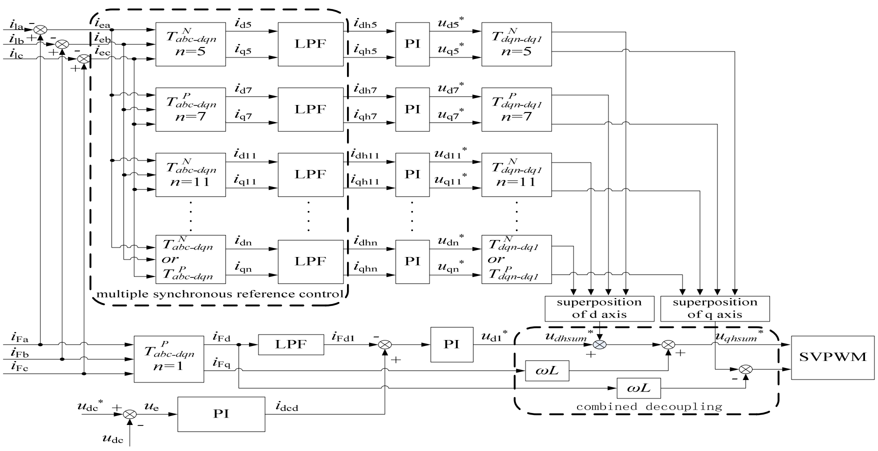

Figure 2. Control Strategy Based on MSRFs

Equation (5) is the n-th positive harmonic transform matrix and (6) is the n-th negative harmonic transform matrix from abc frame to the corresponding harmonic positive or negative synchronous rotating frame. To the positive sequence harmonic, the transform matrix from the harmonic frame to the fundamental frame is shown as (7). To the negative sequence harmonic, the corresponding transform matrix is shown as (8).

A control system which using the detection method based on MSRFs was presented in [8] as shown in Figure 2. The control system contains a dc link voltage control loop, a fundamental current control loop and a set of selective harmonic current control loops. Selective n-th harmonic current can be detected by the n-th harmonic synchronous transform as (5) or (6) which makes the AC component to the corresponding DC component. The DC component can be extracted by the low pass filter as in Figure 2. As we all know, PI control can achieve the tracking to the DC component without steady-state error, so PI control in harmonic frame is adopted in Figure 2. The complete harmonic current controller is achieved as the super position of all individual harmonic controllers.

3. Detection Algorithm Based On SRF And DFT

The harmonic component to be compensated should be calculated individually when we use the detection method based on MSRFs, so the more calculation work and more resources areneeded with the more selective harmonic currents to be compensated. This disadvantage can severely impact the practical effect of the method.

As mentioned above, the n-th positivesequence components in abc frame become (n-1)-th components in dq frame, and the n-th negitivesequence components will become (n+1)-th components, so the (6k±1)-th characteristic harmonic components in abc frame will become 6k-th component in dq frame (k=1,2,…). Take advantage ofthis characteristics, we may firstly get the 6k-th component of i_{ld} and i_{lq} which gained through abc-dq transformation, then use a resonance regulator which tuned at the frequency $6k\omega_1$ to track the 6k-th component(ω_1 is the fundamental frequency). Using this method, each couple of harmonics at $(6k\pm1)\omega_1$ can be compensated with just one regulator, it allows to halve the number of regulators needed, compared with the solution using a regulator for each harmonic.

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

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

Suppose there is a periodic signal X(t), with angular frequency ω, period T. After discrete sampling with a sampling period τ, we get N sample points in one power cycle, then the signal X(t) can be described as follows with DFT formula:

$$X_n(k\tau) = A_n\cos(n\omega k\tau) + B_n\sin(n\omega k\tau), k = 0,1,2,...,N-1 \tag{9}$$

$$A_n = \frac{2}{N}\sum_{m=0}^{N-1}[X(m\tau)\cos(n\omega m\tau)] \tag{10}$$

$$B_n = \frac{2}{N}\sum_{m=0}^{N-1}[X(m\tau)\sin(n\omega m\tau)] \tag{11}$$

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 time are needed [9-11]. The Fourier coefficients of each harmonic component can be calculated according to the following formula:

$$A_n(i) = A_n(i-1) + \frac{2}{N}\{X(i\tau) - X[(i-N)\tau]\}\cos(n\omega i\tau) \tag{11}$$

$$B_n(i) = B_n(i-1) + \frac{2}{N}\{X(i\tau) - X[(i-N)\tau]\}\sin(n\omega i\tau) \tag{12}$$

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

The RDFT algorithm is based on the sampling period, so the calculated result will be refreshed once each sampling cycle.

Figure 3 Shows the schematic diagram of reference current detection algorithm based on SRF and DFT. Only the characteristic harmonic components which below 25-th are taken into account in Figure 3. The three-phase load currents are processed with the detection algorithm based on SRF and DFT, and the instantaneous reference currents (i_{Fd}^*、i_{Fq}^*) in dq frame are finally obtained.

If the three-phase load currents are unbalanced, there will be fundamental negative sequence current which become 2-th harmonic component in dq frame, so the 2-th component is also calculated in Figure 3 except the 6k-th harmonic components. When the load currents only have the characteristic harmonic components which below 25-th, the system will only need to provide the positive fundamental active current if we take the 2-th harmonic component into account. One thing to note here is that the amplitude of reference currents should be limited to avoid exceeding of the power rating. The amplitude of different compensate components can be limited to different values according to the importance degree.

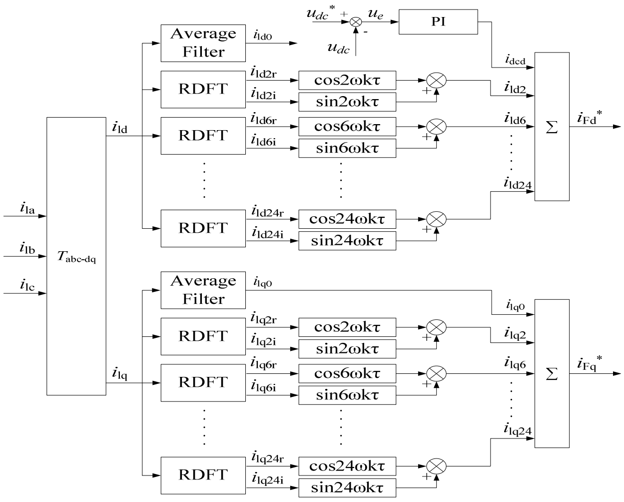

Figure 3. Reference Current Detection Algorithm Based on SRF and DFT

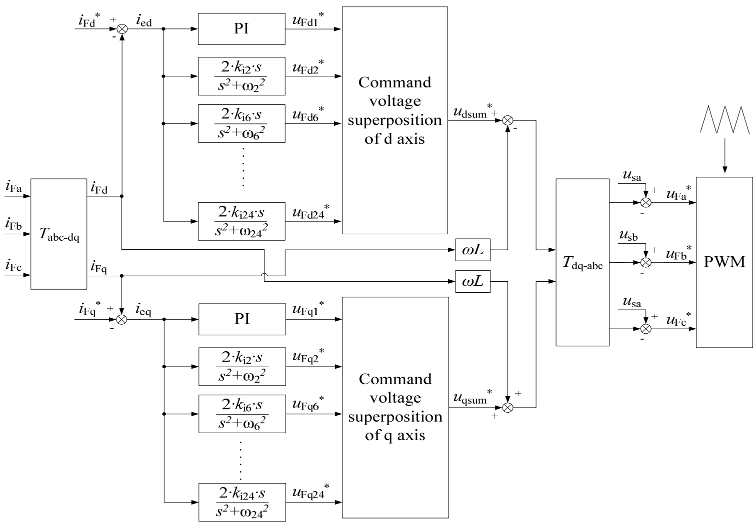

Figure 4. Control Strategy Based on SRF and DFT

A control system which using the detection method based on SRF and DFT is shown in Figure 4. The control system contains a dc link voltage control loop, two fundament current control loops and two sets of selective harmonic control loops. Traditional 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 PI controller. The selective harmonic control loops use resonance controller instead.

u_{Fa}^*,u_{Fb}^* and u_{Fc}^*in Figure 4 are the final voltage commands in abc frame. The three-phase command voltages are applied to a digital PWM block based on the sine-triangle comparison modulation technique to generate the switching pulse for the STATCOM inverter.

As a final note, the detection method presented in this paper are all based on synchronoussampling, so a voltage-phase synchronizer based on PLL technology is necessary.

4. Results and Analysis

4.1. Simulation Verification

For verify of the proposed reference current detection algorithm, simulation model is built in MATLAB. The STATCOM used in the model is a cascaded H bridge STATCOM. Compared with other kinds of STATCOM, cascaded STATCOM excels for its physical consistency, less use of components, better quality of output current and lower difficulty in controller designing especially when the cascaded level gets large [12], so it's very suitable for high or medium voltage power system.

The system voltage is 6kV, the fundamental frequency is 50Hz. The number of the cascaded H bridges of each phase is 8, and star connection method is adopted. The inductance value of the connection reactor is 2.6mH. The dc link capacitor of each power unit is 3000μF. The sample frequency is 10.8kHz.

To verify the synthetic compensation abilityfor STATCOM when using the algorithm proposed in this paper, the load current is designed to contain 150A active currents, 100A reactive currents, 20A harmonic currents, and 10A unbalanced currents. Figure5 shows the reference current of d axis and q axis which gained through the algorithm presented in this paper. The d axis and q axis component of output currents and the tracking err are also shown in this figure. According to Figure5, the tracking err in normal operation stage is very small.

The results of simulation are shown as Figure6 to Figure9. From these figures, 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 running properly. The system power factor values are improved from below 0.9 to 1. The current THD are also greatly restricted, take phase A for example, the system current THD is about 10.8% before the STATCOM running properly and is only about 1.44% in normal operation stage. From these data, we can see that the STATCOM really has the synthetic compensation ability, so the algorithm presented in this paper is accurate.

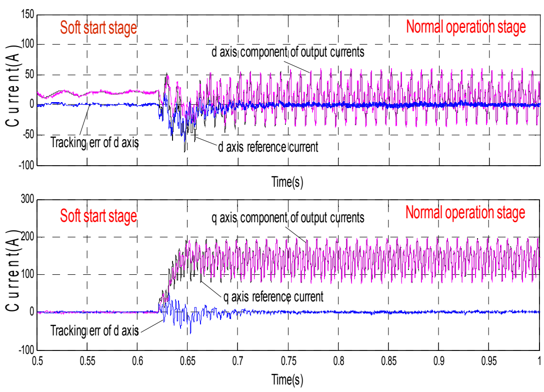

Figure 5. Reference Current, Output Current and Tracking err

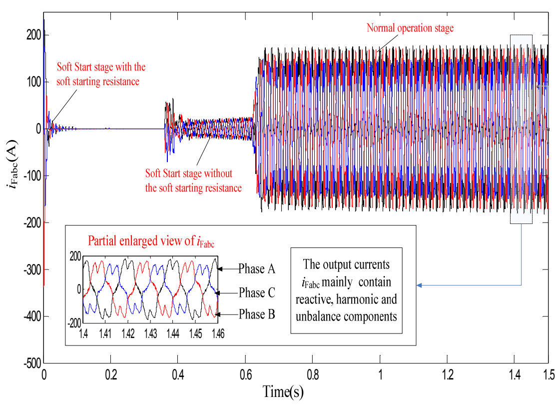

Figure 6. Waveforms of Three Phase Output Currents

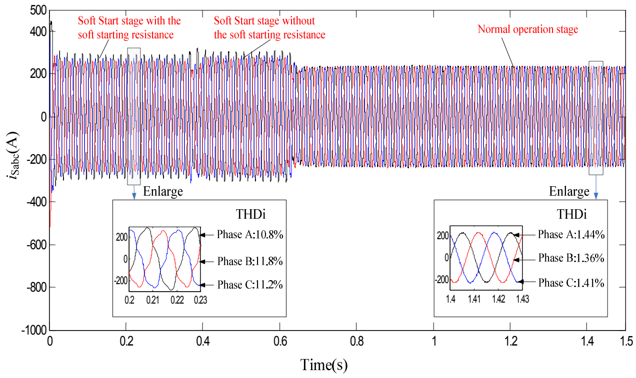

Figure 7. Waveforms of Three Phase System Currents

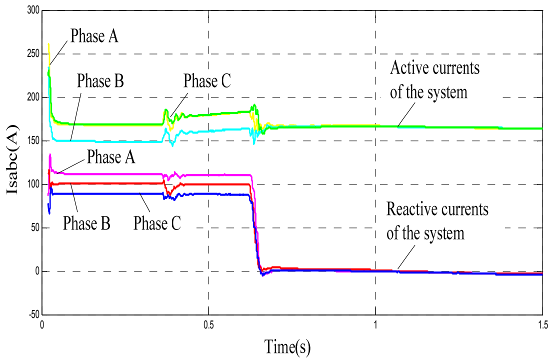

Figure 8. System Active and Reactive Currents

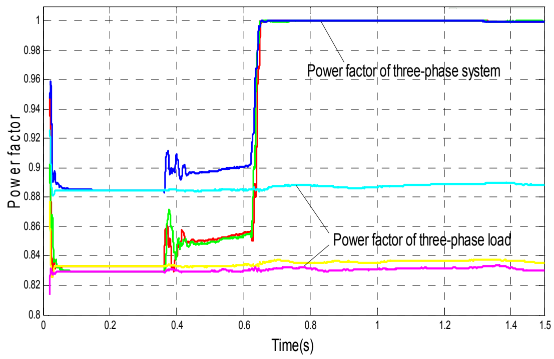

Figure 9. Power Factor

4.2. Experiment Verification

Verify is carried out in the laboratory platform. Take account of the difficult to set 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 (PCC) of 6kV power system. One of them works as a load machine, and the other works as a compensating machine. The load machine can send out various currents flexibly so as to imitate the real load. The currents mainly contain two components, fundamental reactive current (may be inductive, may be capacitive) and harmonic currents (may contain a variety ofcharacteristic harmonic currents). The compensating machine will detect the current of the load machine in real time, then will compensate it by using the method proposed in this paper.

Waveforms were observed through the use of storage oscillograph and corresponding data were recorded. The current waves are shown as Figure 10. We can see that the current waves of the two STATCOMs are almost the same in steady state, so the output current of the load machine is compensated by the compensating machine fairly well.

By processing the recorded data of steady state in matlab, We can get the magnitude spectrogram of the two output currents as shown in Figure 11. From Figure 11, we can see that the two magnitude spectrograms are almost the same which demonstrates the good compensation effect once again.

In order to verify the dynamic performance, we designed a step change for the output current of the load machine at set intervals (as shown in Figure 10). The Figure shows that only need about one power cycle after the change, the good compensation effect will be achieved again.

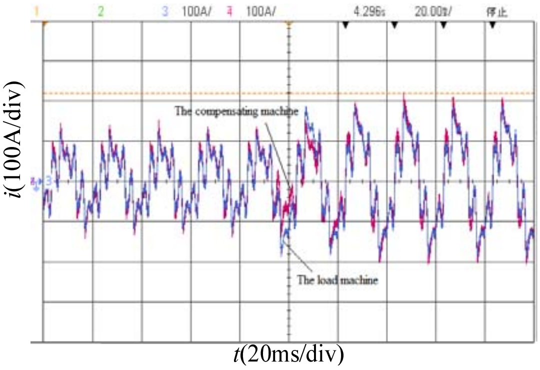

Figure 10. Waveforms of Output Current

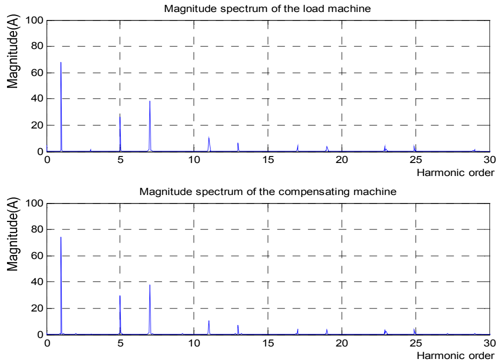

Figure 11. Magnitude Spectrum of Output Currents

5. Conclusion

A reference current detection algorithm based on SRF and DFT is presented for STATCOM. By using this method, the STATCOM will be able to compensate the reactive currents, unbalanced currents and characteristic harmonic currents of the load currents. Theoreticalanalysis and experiment research show that the proposed method is characterized by its simple structure, small calculating amount and good dynamic performance. In conclusion, the proposed method is suitable for the practical application of engineering and has a wide application prospects.

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