

Current Compensation and DC-Link Voltage Control for Current Quality Compensator

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Abstract—This paper presents a novel control method for a shunt current quality compensator, which combines the current quality compensation and dc-link voltage control together. The proposed control method can be applied in single-phase, three-phase three-wire and three-phase four-wire active power filter and hybrid active power filter. Compared with conventional methods, the proposed method has a great reduction of computation steps, and both current compensation and dc-link voltage control processes are simplified into controlling the gain of a controller. Representative simulation results in a three-phase four-wire hybrid active power filter are presented to show the effectiveness of the proposed control method.

I. INTRODUCTION

Most facilities employ a variety of devices such as multiple switch mode power supplies, motors, and other nonlinear loads. However, current/power quality pollution came together with these developments and its associated problems became worse as the percent of these nonlinear load increased rapidly [1], [2].

In order to diminish the current quality pollution, shunt current quality compensators (SCQCs) can be implemented. Passive Power Filter (PPF) has disadvantages about low dynamic performance, filtering characteristics easily be affected by small variations of the system parameter values, and resonance problems with the source impedance [3]. Compared with PPF, Active Power Filter (APF) and Hybrid Active Power Filter (HAPF) have a great improvement of compensation performance, which can be effectively applied to diminish the current harmonic and reactive power problems [4]–[7]. Moreover, both APF and HAPF contain Voltage Source Inverter (VSI), which is the active part of the power filter, and all control actions are processed within this part.

For detecting the reference compensating current, the instantaneous active and reactive power theory (p-q theory)

are widely used, which can provide an instantaneous and accurate reference compensating current [8], [9]. In addition, the dc-link voltage of the VSI can be controlled by adjusting the instantaneous active power component of the p-q theory. However, the reference current detecting method with dc-link voltage control by p-q theory requires a lot of computation steps, such as matrix transformation, digital filter (LPF or HPF), and PI control etc., which increase the difficulty of the controller design. Moreover, to implement the control method, a large number of programming resources is necessary, and so thus reducing the efficiency of the controller. In this paper, a novel simplified control method is proposed, which combines both detecting method and dc-link voltage control together in a gain controller.

This paper is organized as follows: 1. Section II describes the operating principle of the SCQC with conventional control methods, which includes detection of reference compensating current and dc-link voltage control; 2. A novel simplified control method is proposed and discussed in Section III; 3. Finally, simulation results of a three-phase four-wire SCQC for both current quality compensation and dc-link voltage control are presented in Section IV to verify the effectiveness of the proposed control method.

II. CONVENTIONAL REFERENCE COMPENSATING CURRENT DETECTING AND DC-LINK VOLTAGE CONTROL METHODS BY P-Q THEORY

The compensating principle of SCQC is shown in Fig. 1. The compensator generates a compensating current to the utility, so that it cancels with the load harmonic and reactive current and keeps a pure sinusoidal and unit power factor source current. In Fig. 1, the subscript 'x' denotes phase a, b, c . i_{sx} represents the phase source current, i_{Lx} represents the phase load current, and i_{Cx} represents the phase compensating current. The SCQC can be either an APF or a HAPF depending on the impedance of coupling passive part. (L for APF, and LC for HAPF).

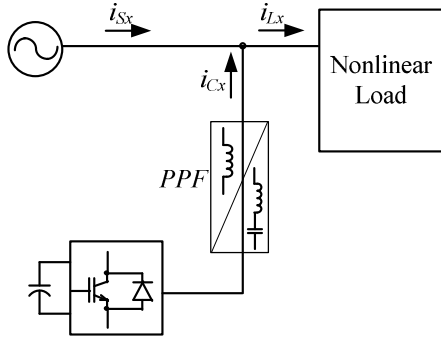


Fig. 1. Compensation principle of the SCQC.

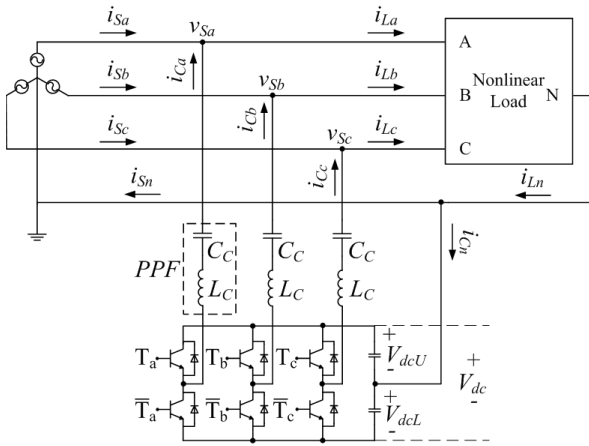


Fig. 2. Circuit configuration of the SCQC .

Due to the HAPF can provide a cost-effective solution to the current quality problems [6], [7]. In this paper, a three-phase four-wire center-split HAPF circuit topology is adopted as the SCQC.

The overall circuit configuration of the SCQC is shown in Fig. 2, where v_{Sx} represents the phase source voltage, which is assumed balanced without any distortion in this paper. i_{Sn} , i_{Ln} and i_{Cn} represent the source, load, and compensating neutral currents. L_C and C_C are the coupling inductor and capacitor. C_{dc} , V_{dcU} and V_{dcL} are the dc-link capacitor, upper and lower dc-link capacitor voltages, and V_{dc} is sum of them.

A. Reference Compensating Current Detecting Method

The reference compensating current is achieved by the well-known instantaneous active and reactive power theory (p-q theory) proposed by H. Akagi [8], [9]. By injecting the ideal compensating current into the system, the source current keeps pure sinusoidal and in phase with the source voltage.

The p-q theory is based on a set of instantaneous powers defined in time domain. No restrictions are imposed on the

voltage or current waveforms, and it can be applied in three-phase systems, with or without neutral wire. The theory firstly transforms voltages and currents from $a-b-c$ to $\alpha-\beta-0$ coordinates, which are transformed by Clarke transformation

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/\sqrt{2} & -1/\sqrt{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/\sqrt{2} & -1/\sqrt{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (2)$$

For a three-phase four-wire system, the $p-q$ theory defines two instantaneous active power p_0 and $p_{\alpha\beta}$ and one instantaneous reactive power $q_{\alpha\beta}$ in the three-phase four-wire system as

$$\begin{bmatrix} p_0 \\ p_{\alpha\beta} \\ q_{\alpha\beta} \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

In (3), $p_0 = v_0 i_0$ implies the instantaneous active power in the zero-sequence circuit, and $p_{\alpha\beta}$ is the instantaneous active power in the α and β -phase circuits. Conversely, $q_{\alpha\beta}$ is the instantaneous reactive power.

$p_{\alpha\beta}$ and $q_{\alpha\beta}$ can be expressed as (4)

$$\begin{bmatrix} p_{\alpha\beta} \\ q_{\alpha\beta} \end{bmatrix} = \begin{bmatrix} \bar{p}_{\alpha\beta} + \tilde{p}_{\alpha\beta} \\ \bar{q}_{\alpha\beta} + \tilde{q}_{\alpha\beta} \end{bmatrix} \quad (4)$$

where $\bar{p}_{\alpha\beta}$ and $\bar{q}_{\alpha\beta}$ are the instantaneous active and reactive power originating from the symmetrical fundamental component of the load current, $\tilde{p}_{\alpha\beta}$ and $\tilde{q}_{\alpha\beta}$ are the instantaneous active and reactive power originating from harmonic and the asymmetrical fundamental component of the load current.

[9] gives that the compensating current in 0 coordinate exist $i_{C0} = i_{L0}$ when $v_0 = 0$. And the reference compensating current in $\alpha-\beta$ coordinates $i_{C\alpha}$, $i_{C\beta}$ can be computed as

$$\begin{bmatrix} i_{C\alpha} \\ i_{C\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p}_{\alpha\beta} \\ \bar{q}_{\alpha\beta} + \tilde{q}_{\alpha\beta} \end{bmatrix} \quad (5)$$

B. DC-Link Voltage Control

The dc-link voltage control of the SCQC is a critical issue. The dc-link capacitor voltage is charged from the

power supply. During operation, the VSI may absorb an amount of active power into, or release it from, the dc-link capacitor. To keep satisfactory operation of the SCQC, dc-link capacitor voltage control should be applied, so that the active power supplied from the source will be equal to the active power demand of the load in steady-state.

From (4), $\bar{p}_{\alpha\beta}$ represents the active power consumed by the load. To realize the dc-link voltage control, a dc control signal $\Delta\bar{p}_{\alpha\beta}$ is added into reference compensating current thus controlling the active power between the source and the compensator. By combing the dc-link voltage control, the reference compensating current in (5) can be rewritten as

$$\begin{bmatrix} i_{C\alpha} \\ i_{C\beta} \end{bmatrix} = \frac{1}{v_{\alpha}^2 + v_{\beta}^2} \begin{bmatrix} v_{\alpha} & -v_{\beta} \\ v_{\beta} & v_{\alpha} \end{bmatrix} \begin{bmatrix} \bar{p}_{\alpha\beta} + \Delta\bar{p}_{\alpha\beta} \\ \bar{q}_{\alpha\beta} + \tilde{q}_{\alpha\beta} \end{bmatrix} \quad (6)$$

Finally, the reference compensating currents i_{Cx}^* in $a-b-c$ coordinate can be obtained by inversed matrix of Clarke transformation in $\alpha-\beta-0$ coordinate

$$\begin{bmatrix} i_{Ca}^* \\ i_{Cb}^* \\ i_{Cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{C0} \\ i_{C\alpha} \\ i_{C\beta} \end{bmatrix} \quad (7)$$

C. Control Block

Fig. 3 shows the whole control block diagram of reference compensating current detecting and dc-link voltage control. The three-phase reference compensating currents for the loading harmonic and reactive currents are calculated by (5). And the dc-link voltage control signal $\Delta\bar{p}_{\alpha\beta}$ is obtained from the voltage regulator as shown in Fig. 3. The sum of V_{dcU} and V_{dcL} is compared to a dc-link voltage reference V_{dc}^* , a low pass filter (LPF) is inserted in the voltage regulator to filter out high frequency noise. Finally, i_{Cx}^* together with compensating current i_{Cx} will be sent to the

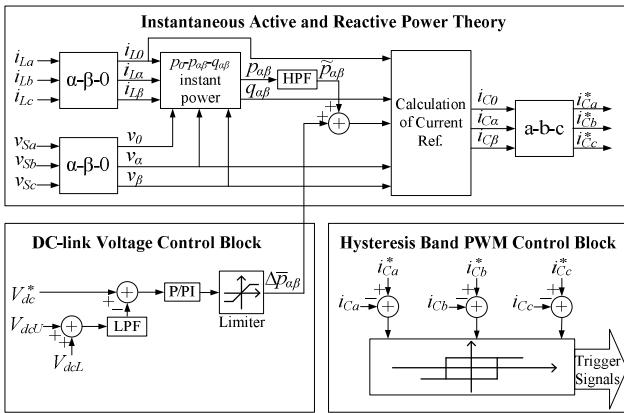


Fig. 3. Control block diagram of reference compensating current detecting, dc-link voltage control, and hysteresis band PWM control.

current hysteresis band PWM controller for generating corresponding PWM trigger signals[10]. From Fig. 3, it is obviously shown that a large number of computation steps are necessary to obtain the reference compensating current and control the dc-link voltage. To implement the current quality compensation and dc-link voltage control with p-q theory, the controller would be designed in a complex and low efficient way.

III. PROPOSED DETECTING AND DC-LINK VOLTAGE CONTROL METHOD

Based on the p-q theory, the load current i_{Lx} is composed of fundamental active, fundamental reactive, harmonic active and harmonic reactive components as

$$i_{Lx} = \bar{i}_{Lpx} + \bar{i}_{Lqx} + \tilde{i}_{Lpx} + \tilde{i}_{Lqx} \quad (8)$$

where

\bar{i}_{Lpx} : instantaneous fundamental active current, which is related to $\bar{p}_{\alpha\beta}$;

\bar{i}_{Lqx} : instantaneous fundamental reactive current, which is related to $\bar{q}_{\alpha\beta}$;

\tilde{i}_{Lpx} : instantaneous harmonic active current, which is related to $\tilde{p}_{\alpha\beta}$;

\tilde{i}_{Lqx} : instantaneous harmonic reactive current, which is related to $\tilde{q}_{\alpha\beta}$.

From Fig. 1, the relationship between i_{Sx} , i_{Lx} , and i_{Cx} can be formulated as

$$i_{Cx} = i_{Lx} - i_{Sx} \quad (9)$$

Substituting (8) into (9) yields,

$$i_{Cx} = \bar{i}_{Lpx} + \bar{i}_{Lqx} + \tilde{i}_{Lpx} + \tilde{i}_{Lqx} - i_{Sx} \quad (10)$$

In ideal case, the source current contains the fundamental active component of the load current only after SCQC is being operated. As a result, the ideal reference compensating current $i_{Cx_{ideal}}$ contains the reactive ($\tilde{i}_{Lqx} + \bar{i}_{Lqx}$) and harmonic active (\tilde{i}_{Lpx}) components of the load current.

$$i_{Cx_{ideal}} = \bar{i}_{Lqx} + \tilde{i}_{Lpx} + \tilde{i}_{Lqx} \quad (11)$$

Compare (10) and (11), the compensating current $i_{Cx} = i_{Cx_{ideal}}$ can be achieved if and only if

$$i_{Sx} = \bar{i}_{Spx} = \bar{i}_{Lpx} \quad (12)$$

where \bar{i}_{Spx} represents fundamental active source current

For the dc-link voltage control, the charging/discharging current of the VSI relates to the fundamental active component different between the source and load currents,

thus the dc-link voltage can be controlled by adjusting the difference between $\bar{i}_{Lpx} - \bar{i}_{SpX}$. When the dc-link voltage is controlled as its reference value, no charging/discharging current is required, i.e. $\bar{i}_{Lpx} = \bar{i}_{SpX}$, which meets the condition for achieving the ideal compensating current in (12). Moreover, \bar{i}_{Lpx} is dependent on the characteristic of the current load, thus both current quality compensation and dc-link voltage can be achieved by only varying the instantaneous value of \bar{i}_{SpX} .

When v_{Sx} is assumed as perfect sinusoidal without any distortion, the fundamental active component of the source current \bar{i}_{SpX} is in phase with v_{Sx} . Thus, the proposed control scheme can be simplified as

$$\bar{i}_{SpX}^* = k \cdot v_{Sx} \quad (13)$$

where \bar{i}_{SpX}^* is the reference source current, and k is the adjustable gain. Therefore, both current quality compensation and dc-link voltage control can be simplified as controlling the value of gain k .

Fig. 4 shows the control block diagram of the proposed method. The control action of proposed method can be expressed as

$$k_{n+1} = k_n + \Delta k_n \quad (14)$$

$$\Delta k_n = G \cdot (V_{dc}^* - V_{dc}) \quad (15)$$

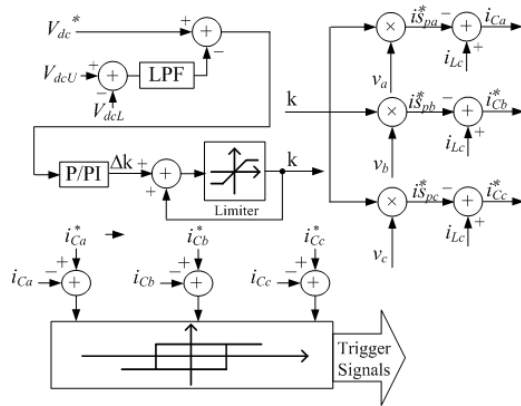


Fig. 4. Control block diagram of the proposed method.

TABLE I. COMPARISON BETWEEN CONVENTIONAL METHOD BASED ON P-Q THEORY AND THE PROPOSED CONTROL METHOD

Method	Number of operation					
	+	×	÷	Digital filter	PI	Total
p-q theory	28	70	4	2	1	105
Proposed method	9	3	0	1	1	14
% of reduction	86.7%					

where k is the controlled variable for current quality compensation and dc-link voltage control, and Δk is output of the PI controller, which reflects the error difference between the V_{dc}^* and V_{dc} , subscripts 'n' and 'n+1' represent the number of iterations; G represents the gain of PI controller. Once the dc-link voltage is controlled as its reference value in steady-state, the feedback value Δk closes to zero, and the controlled variable k reaches its optimum value, which let the source remain a pure sinusoidal active current.

Compared to the conventional control method as shown in Fig. 3, the proposed one combines the current quality compensation and dc-link voltage control together in a gain controller. Table I summaries the number of operations by using conventional based on p-q theory and the proposed method; it is shown that the proposed control method has a great reduction of the computation steps (almost 90% of reduction). Therefore, the proposed method not only simplifies the control process, but also saving lots of resources in the controller.

IV. SIMULATION VERIFICATION

To verify the effectiveness of the proposed control method, simulation studies are carried out by using PSCAD/EMTDC. Table II lists the simulated parameters for the SCQC system.

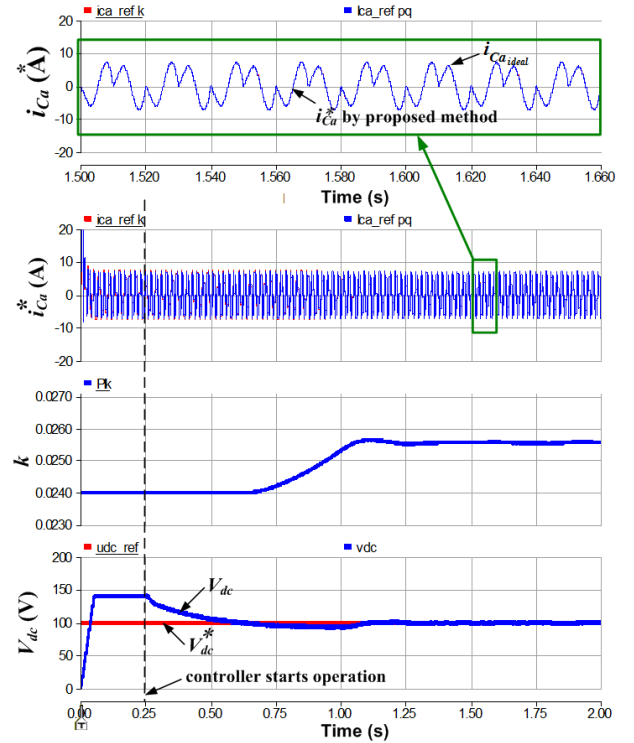


Fig. 5 Control process of the proposed method in phase a.

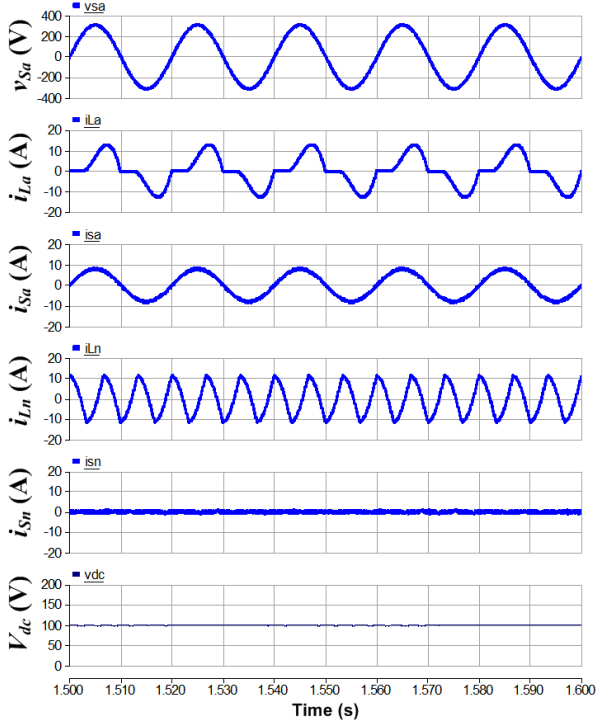


Fig. 6 Compensating performance of the SCQC with conventional method.

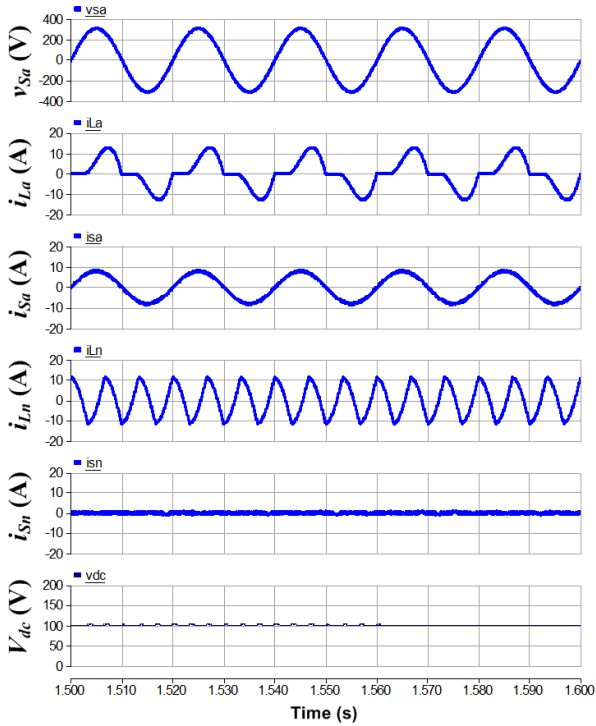


Fig. 7 Compensating performance of the SCQC with proposed method.

TABLE II. SYSTEM PARAMETERS IN THE SIMULATION

System parameters		Physical values
Source	V_{Sx}	220Vrms
SCQC	L_C	8mH
	C_C	53uF
	V_{dc}^*	100V

TABLE III. COMPENSATING PERFORMANCE OF SCQC WITH CONVENTIONAL AND PROPOSED CONTROL METHODS

Different Cases:	DPF	$THD_{i_{Sx}}$ (%)	i_{Sx} (A _{rms})	i_{Sn} (A _{rms})
Before Compensation	0.83	38.22	7.23	7.54
With p-q theory method				
After Compensation	0.99	1.6	5.60	0.42
With proposed method				
After Compensation	0.99	1.43	5.60	0.34

In order to simplify the verification, the system is being balanced. Fig. 5 shows the overall process of the proposed control method in phase a, the dc-link voltage is firstly supplied by an external power supply with $V_{dc} = 140V$ until $t = 0.25s$. From Fig. 5, it is shown that the reference compensating current i_{Ca}^* by using the proposed control method is equivalent to the ideal reference compensating current $i_{Cx_{ideal}}$ once the dc-link voltage is controlled as its reference value by controlling the gain k of the controller, which verifies the previous analysis. .

The compensating performance of the SCQC with both p-q theory and proposed control method are summarized in Table III, and the corresponding waveforms are illustrated in Fig. 6 and Fig. 7. In steady-state, both control methods can achieve: the phase and neutral source current i_{Sa} and i_{Sn} are reduced; i_{Sa} keeps pure sinusoidal and in-phase with the phase source voltage v_{Sa} ; the dc-link voltage of VSI is controlled as the reference one $V_{dc} = V_{dc}^* = 100V$.

Finally, the simulation results show that, with the proposed control method, both current compensation and dc-link voltage can be controlled simultaneously by a gain controller, which verifies the effectiveness of the proposed control method.

V. CONCLUSION

In this paper, a novel control method for the SCQC is proposed, through simply controlling the gain of the controller, both current compensation and dc-link voltage control can be achieved simultaneously. Simulation results show that the SCQC with proposed method can obtain the same compensation performance as that with conventional

one. In addition, the proposed method not only provides a great simplification of the control process, but also saving lots of programming resources of the controller.

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