Postprint of Research on a Novel STATCOM Based on High-Frequency Isolated Direct AC-AC Converter

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Abstract

This paper first introduces a novel reactive power compensator based on a direct AC-AC converter. By eliminating the DC energy storage link, the compensator achieves enhanced reliability and reduced cost. Taking the push-pull forward AC converter as the research subject, the operating principle, compensation characteristics, and control strategy of the novel STATCOM are analyzed. For the first time, a high-frequency isolated converter is introduced into the research of the novel STATCOM, enabling electrical isolation between the grid side and the compensation capacitor and increasing the compensator' s capacity. A direct current control scheme based on a single-phase reactive current detection method is proposed. Compared with existing control methods based on orthogonal decomposition modules and dq coordinate transformation, this scheme features lower computational complexity, a simpler structure, and easier implementation. Finally, simulation experiments are conducted to verify the aforementioned theoretical analysis and the proposed direct current control scheme. The simulation results demonstrate that the novel STATCOM based on the push-pull forward AC converter can achieve real-time dynamic compensation of grid-side reactive current, exhibiting good system stability, fast closed-loop control response, and zero steady-state error.

Full Text

Preamble

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Abstract

This paper introduces a novel reactive power compensator based on an AC-AC direct converter that eliminates the DC energy storage link, thereby improving reliability and reducing cost. Using a push-pull forward AC converter as the research subject, the paper analyzes the operating principle, compensation characteristics, and control strategy of the novel STATCOM. For the first time, a high-frequency isolated converter is introduced into the novel STATCOM research, achieving electrical isolation between the grid side and compensation capacitor while increasing compensation capacity. A direct current control scheme based on single-phase reactive current detection is proposed. Compared with existing control methods based on orthogonal decomposition modules and dq coordinate transformation, this scheme requires less computation, features a simpler structure, and is easier to implement. Finally, simulation experiments verify the theoretical analysis and the proposed direct current control scheme. The results demonstrate that the novel STATCOM based on the push-pull forward AC-AC converter can achieve real-time dynamic compensation of grid-side reactive current with good system stability, fast closed-loop regulation, and zero steady-state error.

Keywords: AC-AC converter, push-pull forward, STATCOM, direct current control

1 Introduction

Reactive power is a crucial parameter in power systems. Most network components and loads consume reactive power, and it is clearly unreasonable—even impossible—for generators to provide this reactive power over long distances. The appropriate approach is to install reactive power compensation devices at locations where reactive power is consumed, allowing them to absorb or inject reactive power from/into the grid [1]. Early reactive compensation devices such as synchronous condensers and shunt capacitors suffered from large size, high cost, and limited dynamic compensation capability. Later, static reactive compensation devices emerged, with static var compensators (SVC) and static synchronous compensators (STATCOM) being typical representatives. While dynamically regulating fundamental reactive power, SVC must also address the elimination of harmonics generated by itself, and its reactive compensation capability decreases when system voltage is low. STATCOM refers to a dynamic compensation device that absorbs or emits reactive power using self-commutated power semiconductor bridge converters, capable of dynamically compensating rapidly changing instantaneous reactive power with flexible control and fast regulation [2]. However, mainstream STATCOM power circuits currently adopt a

DC/AC voltage-source inverter structure. The DC side of the voltage-source inverter uses large-capacity electrolytic capacitor banks as energy storage elements, which introduce several problems: First, electrolytic capacitors have short lifespans and are prone to failure, resulting in poor STATCOM reliability; second, energy storage capacitors are bulky and expensive, significantly limiting STATCOM' s market prospects. Consequently, traditional STATCOMs have not been widely applied in industrial production.

In 2008, American scholars Deepak Divan and Jyoti Sastry proposed the concept of Inverter-less STATCOMs [3], connecting traditional compensation capacitors to the grid through an AC chopper in parallel. By controlling the AC chopper, the compensation capacitor exhibits "dynamic capacitor" characteristics, enabling continuous dynamic compensation of reactive power with high regulation speed. However, their paper only introduced the basic principle of this compensation method without in-depth research on the characteristics and control strategies of this new technology. Based on this concept, domestic and international scholars have conducted corresponding research on the system structure, characteristics, and control strategies of inverter-less STATCOMs, attempting to extend this method from single-phase to three-phase systems. However, all these studies have been based on basic Buck-type and Boost-type AC choppers, which offer limited compensation capacity and feature complex yet monolithic closed-loop control strategies. Therefore, this new technology remains in a developmental stage, requiring further research on the introduction of novel AC-AC converter topologies, increased compensation capacity, and the design and simplification of new closed-loop control schemes [4-7].

2 Reactive Power Compensation Principle Based on AC-AC Converter

The structure of the reactive power compensation system based on an AC-AC converter is shown in Figure 1a [Figure 1: see original paper]. The AC-AC converter is directly connected in parallel with the grid, with traditional reactive power compensation capacitors as its load. Thus, the AC-AC converter can "absorb" a capacitive current i_c that leads the grid voltage by 90°.

In Figure 1b, U_s represents the voltage vector and I_L represents the load current vector. Since power system loads are generally inductive, the current lags the grid voltage. When STATCOM is connected to the system, the capacitive current I_c compensates for the inductive reactive power, and the grid-side current becomes $I_s = I_L + I_c$. Clearly, by controlling the magnitude of the capacitive current I_c "absorbed" by the AC-AC converter, the phase of I_s can be made identical to the grid-side voltage, achieving dynamic reactive power compensation.

The novel STATCOM device mainly consists of two parts: an AC-AC converter and reactive power compensation capacitors. This paper employs a high-frequency isolated push-pull forward AC-AC direct converter, whose topology is shown in Figure 2 [Figure 2: see original paper].

Figure 2 [Figure 2: see original paper] High-frequency isolated push-pull forward AC-AC direct converter

The push-pull forward topology achieves recovery of leakage inductance energy from the high-frequency transformer and suppresses voltage spikes in primary-side switching devices by adding a clamping capacitor C_s. The push-pull forward topology can be divided into five parts: the high-frequency transformer, the push-pull forward chopper 1 on the primary side of the transformer, the full-wave rectifier chopper 2 on the secondary side, the input filter, and the output filter.

The high-frequency transformer has four windings: primary windings T_{p1}, T_{p2} and secondary windings T_{s1}, T_{p2}. The turn numbers satisfy $N_{p1} = N_{p2}$ and $N_{s1} = N_{p2}$, with the voltage ratio defined as $N = N_{s1}/N_{p1}$. The input filter inductor L_i and input capacitor C_i filter harmonic components—primarily switching frequency components—from the converter input current. The output filter removes switching frequency components from the output voltage.

The AC-AC converter operates in two modes depending on the input: Mode 1 when $u_i > 0$ and Mode 2 when $u_i < 0$. Each switching cycle is divided into four operating stages based on the relationship between the polarity of u_{Np} and u_s: a forward stage (when u_{Np} and u_s have the same polarity), a reverse stage (when they have opposite polarity), and two zero stages (when u_{Np} is zero). The main operating waveforms are shown in Figure 3 [Figure 3: see original paper]. Each switching cycle in Figure 3 contains two triangular waves, generating two turn-on pulses. The duty ratio is redefined as follows: the duty ratio D equals the proportion of the output voltage u_{AB} from the secondary-side rectifier circuit within one switching period T.

As shown in Figure 3, the voltage u_{AB} at the front end of the output filter is a unipolar pulse wave with sinusoidally varying amplitude, and its pulse period is twice the switching period. When the load is capacitive, the input-output characteristics of the high-frequency isolated push-pull forward AC-AC direct converter are:

$$u_o = NDu_s i_o = C\frac{du_o}{dt} i_c = NDi_o$$

where the grid-side voltage $u_s = U_m \sin \omega t$, C is the compensation capacitance, N is the transformer voltage ratio, D is the duty ratio, i_o is the load current, and i_c is the grid-side injected current.

From these equations, we derive:

$$i_c = N^2 D^2 C U_m \cos \omega t$$

This equation shows that under normal conditions, the grid voltage amplitude U_m, transformer voltage ratio N, and compensation capacitance C are all constant. Therefore, the compensation current i_c depends only on the duty ratio D, enabling real-time reactive power compensation through dynamic control of D. The novel STATCOM based on the high-frequency isolated push-pull forward topology can be regarded as a variable capacitor with adjustable capacitance value, where the current i_c leads the grid-side voltage by 90°.

Compared with STATCOM based on AC choppers, the magnitude of i_c in this novel approach is directly related to the transformer voltage ratio N. Therefore, under identical external conditions, the injection current magnitude—and thus the compensation capacity—of the novel STATCOM can be significantly larger than that of AC chopper-based STATCOMs, as shown in Figure 4 [Figure 4: see original paper]. Figure 4a shows the relationship between compensation current, grid voltage level U_m, and duty ratio D for the novel STATCOM when $N = 2$, while Figure 4b shows the corresponding relationship for Buck AC chopper-based STATCOM [8]. Under the same voltage level, duty ratio, and other parameters, the former' s compensation capacity is four times that of the latter.

Figure 4 [Figure 4: see original paper] Comparison of compensation capacity

3 Direct Current Control Strategy

3.1 Single-Phase Reactive Current Detection

Currently, the most common method for single-phase reactive current detection derives from three-phase methods using dq coordinate transformation. This approach requires orthogonal decomposition of the sampled current i_s, followed by dq transformation of the two orthogonal components to obtain the i_q component representing reactive current. This detection method is relatively complex and demands high precision in the orthogonal component generation module. Another single-phase detection method constructs three-phase currents from the single-phase current before applying three-phase detection methods, which suffers from computational complexity and additional delays that affect detection efficiency. This paper employs a direct single-phase reactive current detection method [9].

The detection principle is as follows: First, the grid-side current i_s can be decomposed into two components:

$$i_s = i_p(t) + i_q(t)$$

where $i_p(t)$ represents the active component and $i_q(t)$ represents the reactive component. Assuming the grid-side voltage is $u_s = U_m \sin \omega t$, this can be expressed as:

$$i_s = I_p \sin \omega t + I_q \cos \omega t$$

Multiplying equation (4) by a cosine signal synchronized with the grid voltage yields:

$$i_s \cos \omega t = I_p \sin \omega t \cos \omega t + I_q \cos^2 \omega t = \frac{I_p}{2} \sin 2\omega t + \frac{I_q}{2}(1 + \cos 2\omega t)$$

This result shows that the reactive component $I_q \cos \omega t$ in the grid-side current can be represented by $I_q/2$. In other words, the AC reactive power is transformed into a DC component. By extracting this DC component through appropriate means, the reactive current content can be detected. For example, passing the product of the grid-side current and a cosine signal synchronized with the grid voltage through a low-pass filter (LPF) yields a DC quantity representing the reactive power magnitude. This detection method requires minimal computation, is easy to implement, and offers high detection efficiency.

3.2 Direct Current Control

Based on the single-phase reactive current detection method described in Section 3.1, this paper proposes a direct current control scheme suitable for the novel STATCOM, with the principle shown in Figure 5 [Figure 5: see original paper]. Direct current control employs tracking PWM control technology to perform feedback control of the instantaneous grid-side reactive current. Tracking PWM techniques include triangular wave comparison and hysteresis comparison methods; this paper adopts the triangular wave comparison approach to generate PWM control signals.

Figure 5 [Figure 5: see original paper] Direct current control schematic

The control principle is as follows: First, the grid-side voltage and current are sampled. The sampled voltage u_s passes through a phase-locked loop (PLL) to generate a unit cosine signal $\cos \omega t$ in phase with the voltage. The sampled current i_s is multiplied by the cosine signal $\cos \omega t$, converting the AC reactive component into a DC component. A low-pass filter (LPF) extracts the DC component representing reactive current i_q^*, which is then compared with the reference value 0. The error signal passes through a PI regulator to obtain the duty ratio D, which is compared with a carrier wave to generate PWM trigger signals for the AC-AC converter switches, ultimately achieving dynamic compensation of grid-side reactive current. The PI regulator in this control method enables current tracking control with zero steady-state error.

3.3 Cosine Wave Generator Based on PLL

The direct current control method proposed in Figure 5 requires a cosine signal synchronized in frequency and phase with the grid-side voltage. The accuracy and speed of this cosine signal directly affect the control system performance. The design principle of the grid-voltage-synchronized cosine signal generator based on a phase-locked loop (PLL) is shown in Figure 6 [Figure 6: see original paper].

Figure 6 [**Figure 6: see original paper**] Principle of synchronization cosine signal generator based on PLL

The basic principle is: The sampled grid-side voltage u_s passes through a zero comparator to generate a square wave that serves as one input to the PLL. The phase detector, low-pass filter, and function signal generator constitute a PLL circuit. The function signal generator produces two synchronized sine and square wave signals whose frequency is controlled by a control voltage. The square wave signal serves as a feedback signal connected to the other input of the phase detector for comparison with the square wave of u_s. The resulting error signal passes through the LPF to obtain a control signal that quickly adjusts the frequency and phase of the sine signal generated by the signal generator until it synchronizes with u_s. The obtained sine signal is then phase-shifted by 90° through a phase-shifting circuit to produce the required cosine signal.

4 Simulation Analysis

To verify the theoretical analysis and the correctness of the direct current control strategy, as well as the system dynamic characteristics, simulation experiments were conducted using simulation software.

System simulation parameters: Grid-side voltage amplitude is 220 V, frequency is 50 Hz, switching frequency is 20 kHz, grid-side filter inductance $L_i = 6$ mH, filter capacitance $C_i = 4$ F, reactive power compensation capacitor $C = 110$ F, and the maximum compensation capacity is approximately 1.1 kvar under ideal conditions.

Figure 7 [**Figure 7: see original paper**] shows the system compensation current magnitude at different duty ratios. For observation convenience, the current waveforms in the figure are the detected values multiplied by 20. As shown, the injection current i_c leads the grid voltage u_s by approximately 90°, and its amplitude varies with the duty ratio D.

Closed-loop simulation waveforms for an inductive load ($R = 30\ \Omega$, $L = 80$ mH) are shown in Figure 8 [Figure 8: see original paper]. Figure 8a shows that before STATCOM connection, a phase difference exists between grid-side voltage u_s and grid-side current i_s, indicating reactive power presence. Figure 8b shows that the compensation current i_c leads the grid-side voltage by 90°, representing a capacitive current. Figure 8c demonstrates that after compensation, the grid-side voltage u_s and grid-side current i_s are in phase, indicating complete reactive power compensation by STATCOM. Figure 8d illustrates the PI regulator' s adjustment process, reflecting the system' s dynamic regulation and steady-state performance. The input signal is the grid-side reactive power error signal, which after a period of regulation eventually stabilizes at 0, indicating complete reactive power compensation. The PI regulator' s output signal serves as the control signal for the control signal generator, representing the duty ratio magnitude, which finally stabilizes at a constant value. This demonstrates good dynamic regulation performance with fast adjustment speed and no steady-state error.

Figure 7 [**Figure 7: see original paper**] Compensation current at different duty cycles

Figure 8 [**Figure 8: see original paper**] Simulation waveforms

5 Conclusion

(1) This paper theoretically analyzes the compensation characteristics of the novel STATCOM based on the push-pull forward high-frequency isolated AC-AC converter. The proposed scheme achieves electrical isolation between the grid side and compensation capacitor side, improving device reliability. Compared with AC chopper-based STATCOM under identical conditions, the novel STATCOM can provide significantly larger compensation capacity.

(2) A direct current control scheme based on single-phase reactive current detection is proposed. Compared with control methods based on orthogonal decomposition modules and dq coordinate transformation, this scheme features simple computation, easy implementation, and high detection efficiency.

(3) Simulation experiments verify the theoretical analysis and demonstrate the feasibility of the novel STATCOM scheme and the proposed direct current control, confirming that the scheme can achieve real-time dynamic reactive power compensation on the grid side.

(4) This scheme eliminates the need for DC energy storage units, reducing reactive compensation device cost while featuring simple system structure, easy control implementation, high reliability, and promising industrial application prospects.

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