

Postprint: Research on the Application of High-Voltage High-Power Nonlinear Current-Source STATCOM in Transmission Networks

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Abstract

High-power STATCOM can provide substantial reactive power for grid power transmission; however, its control system exhibits strong nonlinearity. To achieve linear control of STATCOM reactive power output, this paper proposes a current-source STATCOM based on multilevel current reinjection current-source converter (MLCR-CSC), elaborates on the topology of MLCR-CSC and the operating principle of the novel STATCOM, and designs a direct current control system. Simulation results demonstrate that the harmonic content of MLCR-CSC is below 4%, and there are six zero-current instants within the fundamental period to achieve large-current zero-crossing turn-off. The direct current control method not only satisfies the reactive power requirements of the transmission grid but also responds rapidly to asymmetric faults.

Full Text

Preamble

High-Voltage High-Power Nonlinear Current-Source STATCOM Applied in Power Transmission System

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Abstract

High-power STATCOM can provide substantial reactive power for power transmission, yet its control system exhibits strong nonlinearity. To achieve linear control of STATCOM reactive power output, this paper proposes a current-source STATCOM based on Multi-Level Current Reinjection Current Source Converter (MLCR-CSC). The topology of MLCR-CSC and the operating principle of the novel STATCOM are elaborated, and a direct current control system is designed. Simulation results demonstrate that the harmonic content of MLCR-CSC is below 4%, with six zero-current instances within the fundamental period enabling large-current zero-crossing turn-off. The direct current control method not only satisfies reactive power demands in transmission networks but also responds rapidly to asymmetric faults.

Keywords: Current-source STATCOM, MLCR-CSC, nonlinear control model, direct current control, zero current switching

1 Introduction

Rapid industrial development consumes enormous amounts of electrical energy, with generation centers typically located far from load centers, necessitating efficient and stable power transmission. In high-voltage AC transmission networks, line impedance and ground admittance are proportional to line length. Frequent connection and disconnection of nonlinear loads increase reactive power demand in transmission networks, directly affecting transmission efficiency and increasing line losses [1]. In high-voltage DC transmission networks, three-phase AC distribution networks also require substantial reactive power [2].

2 Current-Source STATCOM Topology and Operation

In transmission networks, STATCOM can maintain or control node voltage, enhance line transmission capacity, damp power oscillations, and improve both steady-state and transient stability, thereby increasing system operational flexibility. During grid faults or sudden load increases, STATCOM can dynamically provide voltage support, enhance system security and stability, reduce low-voltage load shedding, prevent large-scale blackouts caused by transient voltage collapse, and additionally function to damp system oscillations, suppress voltage flicker, and improve power quality.

Existing STATCOM topologies are based on Voltage Source Converters (VSC),

which achieve excellent theoretical results through cascaded 2H-bridge units using IGBT (or IGCT, IEGT) devices combined with multilevel modulation techniques. Practical equipment has been widely applied in distribution networks below 35kV, wind power, and photovoltaic industries [3-4]. For instance, the ± 200 Mvar chain STATCOM device operating at 35kV in the Southern Power Grid represents the highest voltage-level reactive compensation equipment in operation, providing valuable experience for VSC applications in high-voltage high-power scenarios. Further improvements in capacitor voltage balancing control strategies, optimization of control objectives, and reduction of equipment losses can enhance operational efficiency [5-6].

However, with increasing grid transmission power, few STATCOM installations operate at voltage levels of 500kV and above. For single-group VSC reactive compensation capacity exceeding 200Mvar, series-parallel connection of power devices presents significant technical challenges, with voltage balancing issues and safety concerns during equipment failures becoming more prominent [7-9].

High-voltage DC transmission technology based on Line Commutated Converters (LCC) is mature, with extensive experience in thyristor series connection. Traditional 12-pulse converter topologies exhibit high stability and rapid fault response [10-11]. References [12-14] introduced the concept of DC ripple and elaborated on the development of DC ripple injection technology in converters. By incorporating VSC multilevel techniques, a Multi-Level Current Reinjection Current Source Converter (MLCR-CSC) was developed, which adds a new current reinjection circuit to the traditional 12-pulse converter. This topology offers several advantages: the main circuit uses thyristors with a switching frequency of 50Hz, reducing device losses; the reinjection circuit operates at 450Hz; there are six zero-current instances per fundamental period enabling zero-current turn-off at any moment; AC-side current harmonic content is below 4%; direct current control ensures rapid fault response; voltage commutation does not rely on natural commutation points, enabling unity power factor operation; and there is no capacitor voltage balancing issue.

This paper designs a dual-group MLCR-CSC topology and verifies its response to reactive power demands in transmission networks above 100Mvar.

2.1 Topology Structure

In 220kV and below transmission and distribution networks, VSC-based STATCOM technology is mature with successful operational projects, while Current Source Converter (CSC) topologies offer no advantages in such applications. However, in high-voltage high-power scenarios, VSC is constrained by device characteristics and safety issues, making it difficult to surpass the safety and stability advantages of CSC, where direct current control can ensure grid stability and equipment safety. Technically, VSC voltage boosting and capacity expansion are challenging, whereas CSC can more easily achieve transmission network applications by leveraging LCC. Economically, VSC chain structures

can improve power quality in distribution networks, while CSC topologies can more readily enhance power quality in high-voltage and ultra-high-voltage applications with shorter development cycles and lower costs.

This paper selects two groups of MLCR-CSC in series to both increase the voltage level based on traditional grid-commutated converters and to verify the feasibility of applying MLCR-CSC as a STATCOM converter in 500kV and above grids. The high-voltage high-power STATCOM composed of dual-group MLCR-CSC is shown in [Figure 1: see original paper].

Each MLCR-CSC group consists of a traditional 12-pulse converter and a reinjection circuit. The connecting transformer of the 12-pulse converter comprises a primary side and two secondary sides with turn ratios of $K_n:1$ (Y-connection) and $K_n:\sqrt{3}$ (D-connection). For analysis convenience, this paper selects 5 injection current levels. The reinjection circuit consists of 5 groups of anti-parallel self-turn-off devices and 2 reinjection transformers. VTY1-VTY6 are the main bridge thyristor switches for the Y-bridge group; VTD1-VTD6 are the main bridge thyristor switches for the D-bridge group; I_aY is the A-phase winding current of the main transformer secondary Y-bridge; I_aD is the A-phase winding current of the main transformer secondary D-bridge; IA, IB, IC are the three-phase currents of Grid 1; VTpj1-VThj4 distribute DC current to the multi-tap reinjection transformer; I_{inj} is the injection current; Ci and Cj are DC blocking capacitors; I_{dc} is the DC current; and Lm is the smoothing reactor.

2.2 Reactive Power Compensation Principle

In practical applications, MLCR-CSC controls active and reactive power or the active and reactive components of AC output current as control variables. Since the main circuit uses thyristors, the only control variable is the power angle θ . To enable four-quadrant operation, the power angle must vary within $\pm 180^\circ$, making MLCR-CSC a strongly nonlinear system. When MLCR-CSC operates as STATCOM, the active and reactive power control is illustrated in [Figure 2: see original paper].

In [Figure 2: see original paper], k_u and k_i are AC/DC voltage and current conversion coefficients; U_{sRMS} and I_{sRMS} are the RMS values of transformer primary-side phase voltage and current; R is the DC equivalent resistance. The DC-side current I_{dc} is controlled using a power angle of $\pm 90^\circ \pm \Delta$, where Δ varies within a small range and approximates linear variation at the operating point. Thus, reactive power variation is determined by Δ , and the $\pm 90^\circ$ control angle forces MLCR-CSC to operate in inductive or capacitive states.

However, the amplitude variation of single-phase DC current is determined not only by the power angle variation Δ but also by the polarity of the power angle. Near $+90^\circ$:

$$dU_{dc} = d[k_u U_{sRMS} \cos(90^\circ + \Delta\theta)] = -k_u U_{sRMS} (\sin \Delta\theta) \approx -k_u U_{sRMS} d\Delta\theta$$

Near -90° :

$$dU_{dc} = d[k_u U_{sRMS} \cos(-90^\circ + \Delta\theta)] = k_u U_{sRMS} (\sin \Delta\theta) \approx k_u U_{sRMS} d\Delta\theta$$

3 Direct Current Control Design

[Figure 3: see original paper] shows the STATCOM logic control schematic, which takes the reactive power required by the AC system as the initial input, converts it to the reactive component of AC-side current as the reference command, and determines the reactive demand characteristics. The reactive component of AC-side current serves as the direct control command for the closed-loop control system, ensuring direct current control of MLCR-CSC. The trigger pulse sequence of MLCR-CSC is synchronized with AC grid voltage signals, thereby guaranteeing synchronization between the MLCR-CSC stepped current and AC current [15-17].

By measuring three-phase AC voltage and current, the actual reactive component of AC-side current is calculated. The difference between this value and the reference reactive component passes through a PI controller to generate the required phase angle control command. By judging the reactive component of AC-side current, the grid's required inductive or capacitive reactive power is obtained, enabling control of DC-side current and output voltage to achieve the desired reactive power value. When asymmetric grid faults are detected, STATCOM operates at full power. When DC-side current I_{dc} operates outside the normal range, after a delay, the trigger synchronization signal is blocked and the reinjection pulse trigger sequence is locked, advancing or lagging by 30° to make the converter operate under zero-current conditions, thereby exiting reactive power compensation.

4 Simulation Verification

Using 11-level current as the research object, current-source STATCOM simulations are conducted. The main work includes: verification of zero-current turn-off; THD content of grid-side output current waveforms, and the influence of different zero-current pulse widths on harmonics and amplitude; and STATCOM response under symmetrical disturbances and asymmetrical faults in the power grid.

4.1 Zero-Current Generation and Harmonic Elimination

To control DC current, the power angle increment Δ near $\pm 90^\circ$ must coordinate with the converter operating state to produce the correct polarity of Δ variation, thereby controlling reactive power generation and absorption and satisfying the active power flow required for equipment losses.

[Figure 4: see original paper] shows simulation waveforms when the main circuit trigger angle is 0° . At 0.17s, IBY amplitude reaches maximum while converter IBD amplitude is zero, providing Zero Current Switching (ZCS) conditions for D-bridge commutation. At 0.175s, IBD amplitude reaches maximum while upper converter IBY amplitude is zero, providing ZCS conditions for Y-bridge commutation.

The reinjection current frequency is six times the grid fundamental frequency, providing six current zero-crossing points per fundamental period. The DC current IBY output from the main transformer Y-connected converter exhibits 11 levels, and the DC current IBD output from the D-connected converter also exhibits 11 levels. The A-phase AC output current I_{aY} from the main transformer secondary Y-connected converter conducts for 120° , and the A-phase AC output current I_{aD} from the secondary D-connected converter conducts for 120° . After coupling through the main transformer, the multi-level current in the transformer primary-side A-phase approximates a sinusoidal waveform.

4.2 Optimal Zero-Current Pulse Width

In the simulation model, the reinjection current waveform is modulated using a triangular wave with linear rise and fall. The switching pulse width of reinjection circuit gate controllable devices uses equal height and width as the baseline, providing six current zero-crossing points within the fundamental frequency period. Since the reinjection circuit switching is independent of grid-side voltage synchronization signals, the 11-level reinjection zero-current pulse width baseline is set as $(1/11, 3/11, 5/11, 7/11, 9/11)$. Setting the zero-current pulse width to 0.850-1.200 times the baseline value yields the relationship between harmonic content, current amplitude, and zero-current pulse width ratio shown in [Figure 5: see original paper] and [Figure 6: see original paper].

4.3 Reactive Power Compensation Characteristics Under Grid Voltage Disturbances

[Figure 7: see original paper] and [Figure 8: see original paper] show STATCOM reactive power control simulations under significant grid voltage fluctuations. At $t=0.1s$, grid voltage is 0.95pu; STATCOM detects the voltage drop and outputs 0.48pu reactive current with current phase leading voltage, while the grid connection point absorbs 51.4Mvar reactive power from STATCOM. At $t=0.15s$, grid voltage is 0.74pu; STATCOM outputs 1pu reactive current with current phase leading voltage, while the grid connection point absorbs 105.4Mvar reactive power. At $t=0.2s$, grid voltage is 1.02pu; the current-source STATCOM detects the voltage rise and absorbs 0.78pu reactive current with current lagging voltage, while the grid connection point delivers 86.7Mvar reactive power to STATCOM. At $t=0.25s$, grid voltage is 1.18pu; STATCOM absorbs 1pu reactive current with current lagging voltage, while the grid connection point delivers 130.2Mvar reactive power. Throughout this process, the DC-side current of

the current-source STATCOM remains constant, absorbing or returning a small amount of active power from the grid to satisfy its own losses.

4.4 Reactive Power Compensation Characteristics Under Asymmetric Voltage Faults

[Figure 9: see original paper] shows the simulation for a single-phase grounding fault. At $t=0.15s$, Phase A is grounded. STATCOM detects the fault and operates at full power through direct current control strategy, providing Phase A compensation current slightly larger than the other two phases. The DC-side current fluctuates significantly. At $t=0.25s$, the Phase A ground fault is cleared and STATCOM quickly returns to standby status.

[Figure 10: see original paper] shows simulation curves for a three-phase grounding fault. At $t=0.15s$, the three-phase ground fault occurs. STATCOM detects the fault and operates at full power, providing three-phase compensation current. The DC-side current shows a clear downward trend with amplitude below the set value, and STATCOM enters zero-current turn-off conditions to directly exit operation. At $t=0.25s$, the Phase A ground fault is cleared and STATCOM quickly resumes standby status.

5 Conclusion

- (1) The 11-level MLCR-CSC main circuit thyristor switching frequency is 50Hz, while the reinjection circuit gate turn-off power switch frequency is 450Hz, reducing power device losses. It achieves flexible turn-off characteristics for thyristors with zero-current turn-off within the fundamental period, harmonic elimination without variation with trigger angle, and high power factor operation, simplifying the overall equipment structure.
- (2) Zero-current pulse width can be arbitrarily adjusted between 0.85-1.2 times the standard pulse width with THD < 4%. At 1.1 times the standard pulse width, the minimum THD is 1.83%, providing effective theoretical data for physical platform construction.
- (3) STATCOM can adjust voltage levels in real-time during transmission network voltage disturbances. When grid voltage drops, it supports voltage to the rated level; when grid voltage rises, it reduces voltage to the rated level. During asymmetric faults, it provides full-power compensation with rapid voltage support response.
- (4) The current-source STATCOM topology is simple, uncoupled, and easily expandable. In large-capacity transmission networks, simple parallel connection can meet reactive power demands of high-voltage or ultra-high-voltage transmission systems.

Future research should focus on two aspects: independent control of active and reactive power for current-source STATCOM systems, and the planned

development of a 1MVA MLCR-CSC experimental platform to verify topology and control strategy feasibility.

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