Control strategy for a modular multilevel converter applied to HVDC transmission systems

Estratégia de controle para um conversor modular multinível aplicado a sistemas de transmissão HVDC

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Abstract
This article aims to propose a control technique that enables the simultaneous control of active and reactive power through a structure based on the dq transformation, which also facilitates power flow reversal. The ModularMultilevel Converter (MMC) has proven to be a promising alternative for High Voltage Direct Current (HVDC) transmission systems. In such applications, semiconductor devices must be connected in series due to their limited voltage ratings, and the MMC architecture addresses this requirement by employing multiple cascaded submodules. Additionally, the MMC is capable of synthesizing output waveforms with low harmonic distortion, eliminating the need for bulky and costly filters traditionally required in HVDC systems. Despite not using AC filters, the converter still requires arm inductors, which may increase overall system cost. The control strategy proposed in this work demonstrated excellent performance, producing low-distortion waveforms even with reduced switching frequency. This reduction decreases semiconductor stress and enhances converter efficiency. Furthermore, the implemented capacitor-voltage balancing algorithm operated effectively, maintaining stable capacitor voltages. However, the update period of this algorithm must be carefully selected, as shorter update intervals help minimize voltage imbalance but may increase the effective switching frequency.
Keywords: Modular Multilevel Converter (MMC); HVDC Transmission; Power Control; Capacitor Voltage Balancing.

Resumo
Este artigo tem como objetivo propor uma técnica de controle que permita o controle simultâneo de potência ativa e reativa por meio de uma estrutura baseada na transformada dq, que também facilita a inversão do fluxo de potência. O Conversor Modular Multinível (MMC) tem se mostrado uma alternativa promissora para sistemas de Transmissão em Corrente Contínua de Alta Tensão (HVDC). Nesses sistemas, é necessário conectar dispositivos semicondutores em série devido às suas limitações de tensão, e a arquitetura do MMC atende a essa necessidade ao utilizar múltiplos submódulos em cascata. Além disso, o MMC é capaz de sintetizar formas de onda com baixo conteúdo harmônico, eliminando a necessidade de filtros volumosos e de alto custo normalmente empregados em sistemas HVDC. Apesar de dispensar filtros de saída, o conversor ainda requer indutores nos braços, o que pode aumentar o custo total do sistema. A estratégia de controle proposta apresentou excelente desempenho, produzindo formas de onda com baixa distorção mesmo com frequência de chaveamento reduzida. Essa redução diminui o estresse sobre os dispositivos semicondutores e aumenta a eficiência do conversor. Ademais, o algoritmo implementado para o balanceamento da tensão dos capacitores flutuantes do MMC funcionou de forma eficaz, mantendo a estabilidade das tensões. No entanto, o período de atualização desse algoritmo deve ser cuidadosamente definido, pois intervalos menores reduzem o desbalanceamento de tensão, mas podem aumentar a frequência efetiva de chaveamento.
Palavras-chave: Conversor Modular Multinível (MMC); Transmissão HVDC; Controle de Potência; Balanceamento de Tensão dos Capacitores.

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Resumen
Este artículo tiene como objetivo proponer una técnica de control que permita el control simultáneo de la potencia activa y reactiva mediante una estructura basada en la transformación dq, la cual también facilita la inversión del flujo de potencia. El Convertidor Modular Multinivel (MMC) ha demostrado ser una alternativa prometedora para los sistemas de Transmisión en Corriente Continua de Alta Tensión (HVDC). En estas aplicaciones, es necesario conectar dispositivos semiconductores en serie debido a sus limitaciones de tensión, y la arquitectura del MMC responde a esta necesidad mediante el uso de múltiples submódulos en cascada. Además, el MMC puede sintetizar formas de onda con bajo contenido armónico, lo que elimina la necesidad de filtros voluminosos y costosos que normalmente se requieren en sistemas HVDC. Aunque no utiliza filtros de salida, el convertidor requiere inductores en los brazos, lo que puede incrementar el costo del sistema. La estrategia de control propuesta mostró un desempeño sobresaliente, generando formas de onda de baja distorsión incluso con una frecuencia de conmutación reducida. Esta reducción disminuye el estrés sobre los dispositivos semiconductores y mejora la eficiencia del convertidor. Asimismo, el algoritmo implementado para el balanceo de la tensión en los capacitores flotantes del MMC funcionó adecuadamente, manteniendo estables los niveles de tensión. No obstante, el período de actualización del algoritmo debe seleccionarse cuidadosamente, ya que intervalos más cortos reducen el desbalance de tensión, pero pueden aumentar la frecuencia efectiva de conmutación.
Palabras clave: Convertidor Modular Multinivel (MMC); Transmisión HVDC; Control de Potencia; Balanceo de Tensión de Capacitores.

1. Introduction

Population growth combined with industrial development—mainly in emerging countries—has generated an increasing demand for electrical energy. In many cases, the energy generation sites are located far from major consumer centers. For long-distance and subsea transmission, several studies have shown that High Voltage Direct Current (HVDC) systems are more economically and technically advantageous than High Voltage Alternating Current (HVAC) transmission (Wang & Aksoz, 2020).

In this context, the Modular Multilevel Converter (MMC) has emerged as a promising solution for HVDC systems since its original proposal (Lesnicar & Marquardt, 2003a; Lesnicar & Marquardt, 2003b; Marquardt & Lesnicar, 2004). The MMC topology is based on the cascaded interconnection of submodules, typically composed of half-bridge converters, which enables high modularity, scalability, and operation at voltage levels far beyond the limits of individual semiconductor devices. Moreover, MMCs are capable of synthesizing output waveforms with low harmonic content, significantly reducing or even eliminating the need for bulky and expensive filters traditionally required in HVDC applications (Barros et al., 2022).

Currently, numerous research groups and industries are investigating control, modulation, voltage-balancing strategies, and fault diagnosis techniques for MMC-based HVDC transmission (Chuco & Watanabe, 2010; Gnanarathna et al., 2011; Bergna et al., 2011; Soto-Sanchez & Green, 2011). This growing interest is largely due to the intrinsic challenges of the topology, including floating capacitor voltage balancing, internal circulating current suppression, and the need for accurate dynamic models for AC/DC system analysis (Xie et al., 2022; Ahmad et al., 2022).

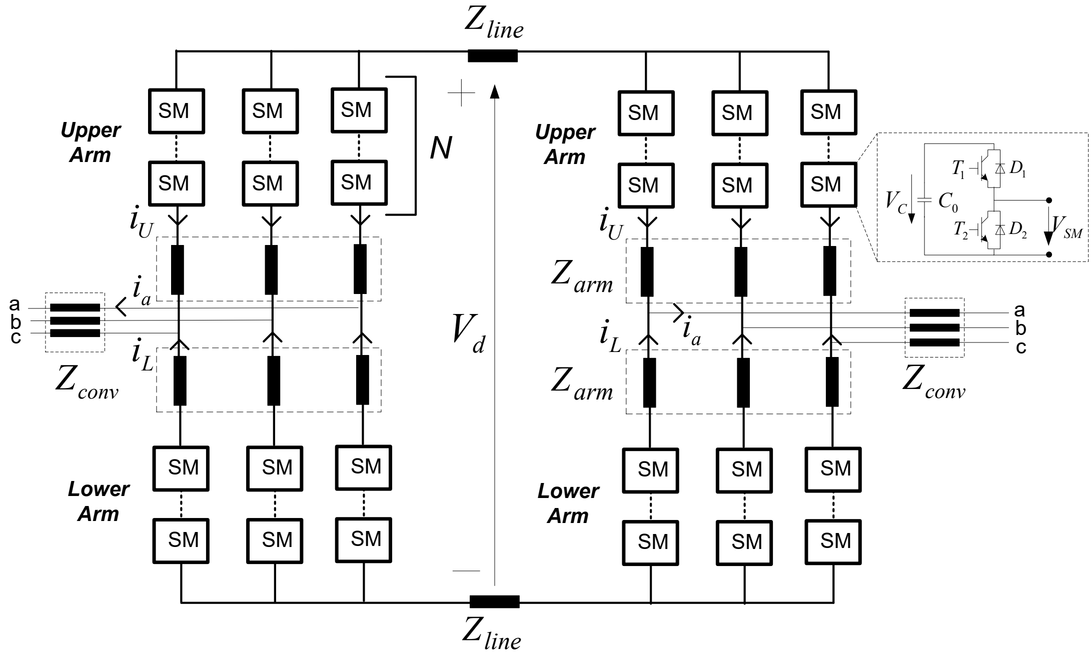
Beyond traditional dq-transform–based PI control, recent studies have explored advanced control techniques such as model predictive control (MPC), circulating-current minimization strategies, fault-tolerant operation, and machine-learning-based approaches for submodule fault diagnosis (Bhutto et al., 2024; Ke et al., 2024; Zhang et al., 2023). Additional investigations include hybrid MMC topologies, DC/DC variations, enhanced modulation schemes, and methods aimed at improving overall system efficiency and robustness (Challa et al., 2024; Tebaldi et al., 2024).

Despite its numerous advantages, the MMC still presents relevant challenges. These include the additional cost associated with arm inductors, the inherent requirement to control the voltages of floating capacitors, and the need for strategies that reduce switching frequency without compromising waveform quality (Allebrod et al., 2008; Baroni et al., 2012).

This article aims to propose a control technique that enables simultaneous control of active and reactive power through a dq-transform–based structure, which also facilitates power-flow reversal. Furthermore, a capacitor voltage-balancing algorithm was implemented to ensure stable operation of the floating submodule capacitors. The proposed control method was validated through MATLAB/Simulink simulations on a representative HVDC transmission system, demonstrating good performance in terms of waveform quality, capacitor voltage stabilization, and reduced semiconductor stress (Konstantinou et al., 2011; Saeedifard & Iravani, 2011).

Accordingly, Section 2 presents the methodology used, Section 3 provides a brief description of the converter operation, Section 4 presents the modulation method used, Section 5 describes the energy-flow control technique, and Section 6 validates the control scheme through simulation. The results are discussed in Section 6.

Figure 1: Circuit configuration of the MMC.



Source: Author (2025).

2. Methodology

An experimental, laboratory-based research of a quantitative nature was carried out (Pereira et al., 2018) using simulations. In this study, all analyses were performed through detailed simulations developed in MATLAB/Simulink, with the objective of evaluating the performance of the proposed control strategy applied to a Modular Multilevel Converter (MMC) operating in an HVDC transmission system.

The methodological procedure was structured into four main stages. First, a representative MMC topology was modeled based on the configuration shown in Figure 1, incorporating twenty submodules per arm, arm inductors, floating capacitors, and the corresponding switching devices. The mathematical relationships governing arm currents, circulating currents, and the capacitor charging and discharging dynamics were implemented according to the classical MMC equations available in the literature.

In the second stage, two modulation strategies were developed—N+1 and 2N+1 level modulation—allowing the assessment of how different numbers of inserted submodules affect the synthesized waveform, the equivalent DC-bus capacitance, and the semiconductor switching behavior.

The third stage consisted of implementing the proposed dq-based control strategy. For the rectifier side (MMC-1), the active and reactive power references were compared with the measured values, and the resulting errors were processed by PI controllers to generate the modulation-index and phase-shift commands. For the inverter side (MMC-2), a PI controller was used to regulate the DC-bus voltage by adjusting the active power processed by the converter. This control structure enables simultaneous active/reactive power control and facilitates power-flow reversal.

Finally, in the fourth stage, the complete system—comprising both MMCs, the HVDC transmission line, the control loops, the modulation strategies, and the balancing algorithm—was simulated. A power-flow reversal was introduced at t = 15 s to evaluate the dynamic performance and robustness of the controller. The resulting waveforms for power, line current, DC voltage, converter voltage, capacitor voltages, and switching behavior were analyzed to assess oscillations, THD levels, voltage balancing, and switching effort.

3. Modular Multilevel Converter

As shown in Figure 1, a phase modulating the multilevel converter is formed by two arms: the upper arm is responsible for synthesizing a waveform in the positive semicycle and the lower arm is responsible for synthesizing a waveform in the negative semicycle. The possible voltage levels in a sub-module can be seen in Table 1. When T_2 is switched on, the voltage V_{SM} is equal to zero. On the other hand, if T_1 is switched on, the voltage V_{SM} is equal to the V_C. The switches T_1 and T_2 have a complementary command.

Table 1: State of the Sub-Modules.

T_1	T_2	Efects on the C_0 capacitor	V_{SM}
1	0	Charging when $i_{arm} > 0$ Discharging when $i_{arm} < 0$	V_C
0	1	None	0

Source: Author (2025).

The peak value of the waveform synthesized by the MMC converter is limited by the sum of the voltages at the output of each submodule according to (1). The DC bus voltage is given by (2) (Lesnicar & Marquardt, 2003a). The effective capacitance of each arm of the converter is given by the capacitance of a sub-module divided by the number of sub-modules placed on that arm N inserted, according to (3).

$$\left|\hat{V}_a\right| \leq N \cdot V_{SB} \tag{1}$$

$$V_d(t) = N \cdot V_{SB} \tag{2}$$

$$C_{arm} = \frac{N}{N_{inserted}} \tag{3}$$

According to Figure 1, the current in each arm of the converter is half the current over the network plus the current circulating between the arms (4), (5), and the current network is the sum of the currents in the arms (6). Thus, the current circulating between the arms, i_{circ}, is given in (7).

$$i_U = \frac{i_a}{2} + i_{circ} \tag{4}$$

$$i_L = \frac{i_a}{2} - i_{circ} \quad (5)$$

$$i_a = i_U + i_L \quad (6)$$

$$i_{circ} = \frac{i_U - i_L}{2} \quad (7)$$

4. Modulator

4.1 Voltage balance in floating capacitors

It is necessary to implement an algorithm to ensure voltage balance in the floating capacitors of the MMC converter, since the conduction time between these capacitors differs. Consequently, they charge and discharge irregularly, which can generate voltage unbalance. The voltage-balancing method selects the submodule to be inserted according to the direction of the current and the capacitor voltages in each arm of the submodule. If the current circulating in the converter arms is charging the arm capacitors, the submodules with the lowest capacitor voltage are inserted in ascending order. If the arm current is discharging the capacitors, the submodules with the highest capacitor voltage are inserted in descending order (Saeedifard & Iravani, 2011; Konstantinou, Ciobotaru, & Agelidis, 2011). The update period of the algorithm directly influences the switching frequency, since state changes affect the switching commands of the submodules. However, the shorter the update period, the lower the voltage imbalance among the capacitors.

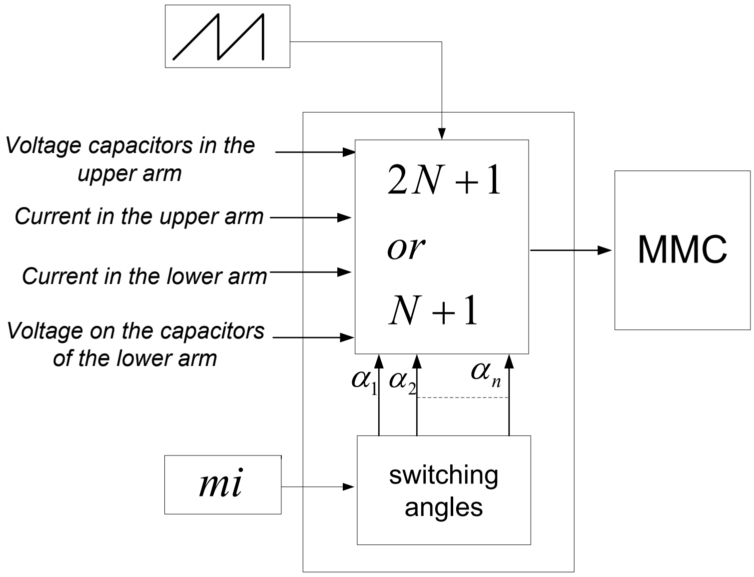
4.2 Pulse width modulation

It is possible to implement the MMC modulator in two different ways in a converter with the same number of sub-modules modifying only the switching commands.

Modulation *N+1*: This modulation method synthesizes a waveform on the output of the converter with *N+1* levels. In this case, the number of sub-modules that are connected is always equal to the number of sub-modules in each arm of the converter, *N*. The rest of the sub-modules are by passed. The number of sub-modules to be inserted in the upper arm and lower arm is given by the voltage level to be synthesized. In this modulation technique the capacitance of the DC bus is constant, since the number of sub-modules (capacitors) inserted is constant.

Modulation *2N+1*: The second modulation method results in a waveform at the output of a converter with *2N+1* levels. In this modulation method, the number of sub-modules connected varies between *N-1*, *N* and *N+1*. When the number of sub-modules connected is equal to *N* the voltage level in the output coincides with the first method, *N+1*. In the same way as the first modulation method, the voltage level to be sinthesized is what defines the number of sub-modules in the lower and upper arm to be inserted. At the *2N+1* modulation the capacitance of the DC bus varies with the number of sub-modules (capacitors) inserted. The Figure 2 illustrates in a simplified manner the MMC modulator used in this study.

Figure 2: Modulator structure.



Source: Author (2025).

5. Control Implemented

In Baroni, Mendes, and Cortizo (2012), two control techniques are proposed based on controlling the RMS current either by adjusting the modulation index or by using the phase difference between the AC network and the power converter. In contrast, this paper proposes a new control technique that allows both variables to be controlled simultaneously. This characteristic enables independent control of real and reactive power. Furthermore, the control technique proposed in this work facilitates power-flow reversal, as it uses the dq0 transform, which enables determining the direction of power flow.

The proposed control technique is based on controlling the power flow in the AC network, and its topology is shown in Figure 3. The control of the converter operating as a rectifier (MMC-1) compares the active and reactive power references with AC network measurements, and the resulting errors are used as inputs to a set of PI controllers. The output of the PI controller regulating active power corresponds to the phase shift (θ) between the AC network and the power converter, whereas the output of the PI controller regulating reactive power corresponds to the converter modulation index (mi). On the DC transmission side, the converter operating as an inverter (MMC-2) is controlled by defining a reference for the DC bus voltage (Vd), which is compared with the average measured DC bus voltage. The resulting error is processed by a PI controller, and its output is subtracted from the measured AC-side active power.

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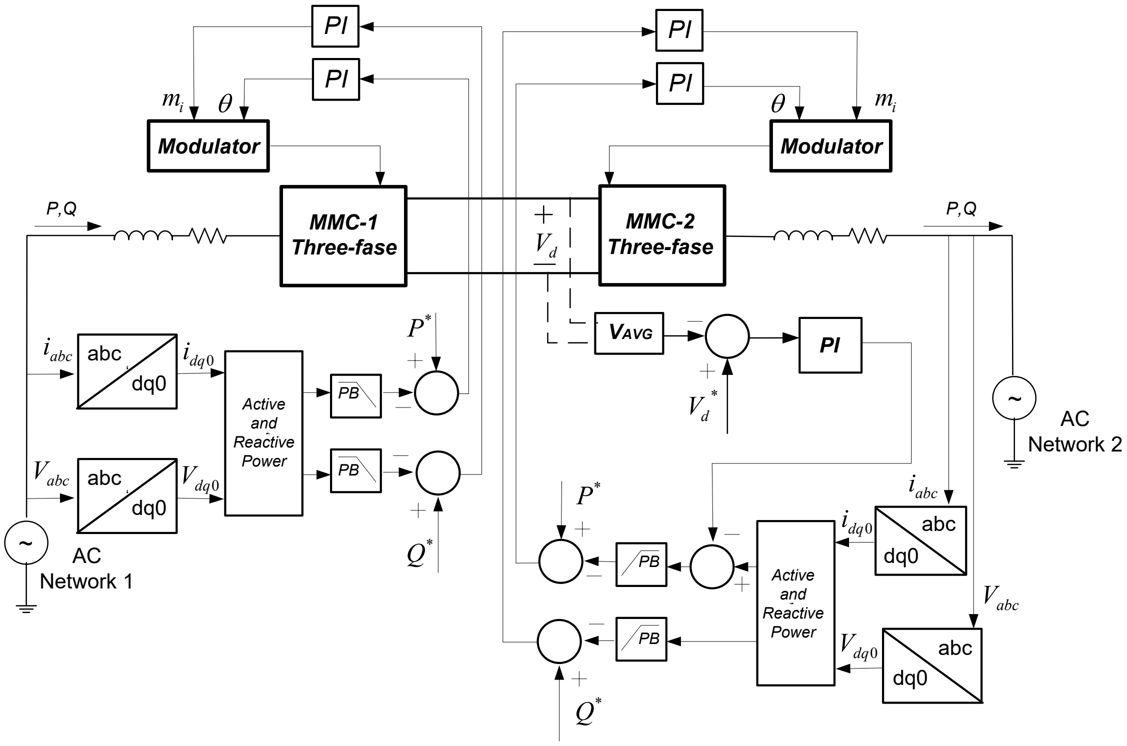
Figure 3: Controller implementation.



Source: Author (2025).

6. Results

In order to test the proposed control technique, a 40kV HDVC transmission line with two three-phase MMC converters generating a 21 level voltage waveform is simulated by means of MATLAB/Simulink. The simulation parameters are shown in Table 2.

In order to show the control performance, the power flux was inverted at t=15s. The simulation results are shown in Figure 4 a Figure 7. Figure 4 shows the active and reactive power in the converters. As can be seen when the transient behavior ends, the active and reactive power show a low oscillation (about 10%). Furthermore the Figure 4 shows the current in the HVDC line this signal shows a smooth behavior; also when the steady state is reached, it presents an average value equal to 500A_{RMS} and its oscillation is about 10%. Figure 5 shows the DC voltage of the HVDC line has a ripple of about 12% and voltage of the flying capacitors. As can be seen, a balance voltage distribution was achieved by means of the voltage balancing algorithm. Figure 6 shows the converter voltage and the AC network current. Those signals have low THD values, which are shown in each figure. The average number of key switching per cycle is low, approximately eight switches in the interval of 1/60 seconds, as can be seen in Figure 7 This reduces the switching losses.

Table 2: Simulation Parameters.

Rated Power	20 MW	Arm resistor (R_{arm})	0.1 Ω
Number of sub-modules (phase-leg *2N*)	20	Commutations per cycle averaged	8
Number of levels	21	V*ac* (rms line-neutral)	10 KV
DC-link voltage	40 KV	L_{conv}	2.0 mH
Sub-module capacitance (C_0)	4.5 mF	R_{conv}	0.1 Ω
Sub-module voltage (V_{SM})	4.0 KV	R_{line}	0.1 Ω
Arm inductor (L_{arm})	4.4 mH	L_{line}	0.1 H

Source: Author (2025).

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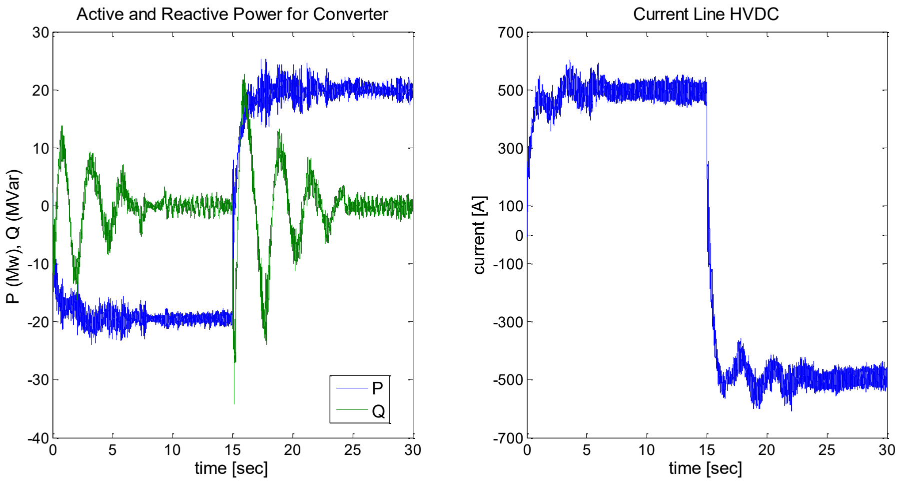
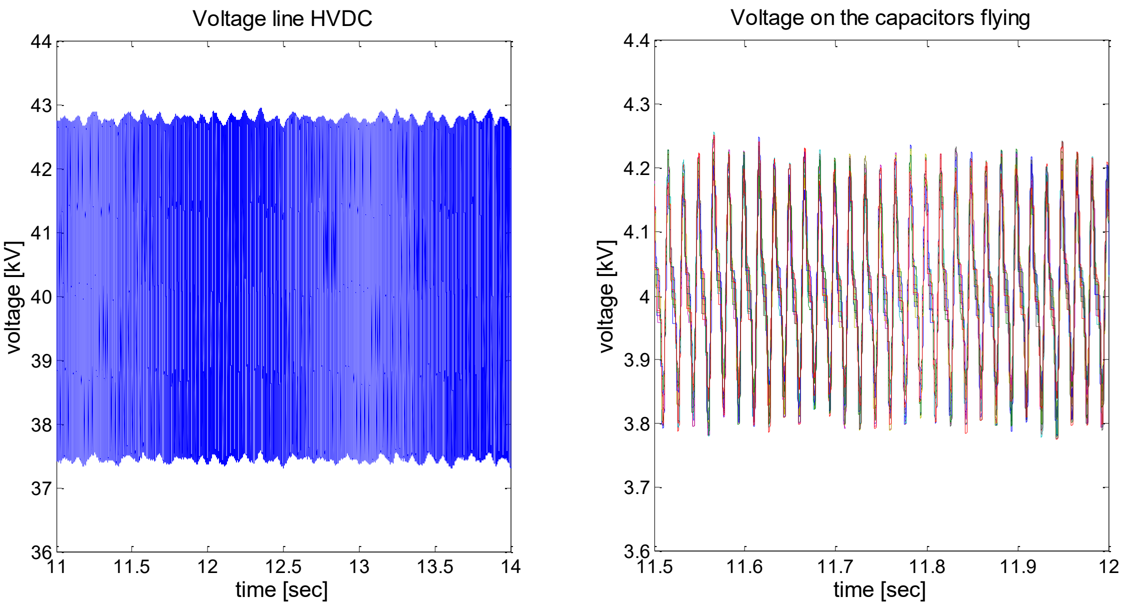
Figure 4: Active and reactive power and current of line HVDC.



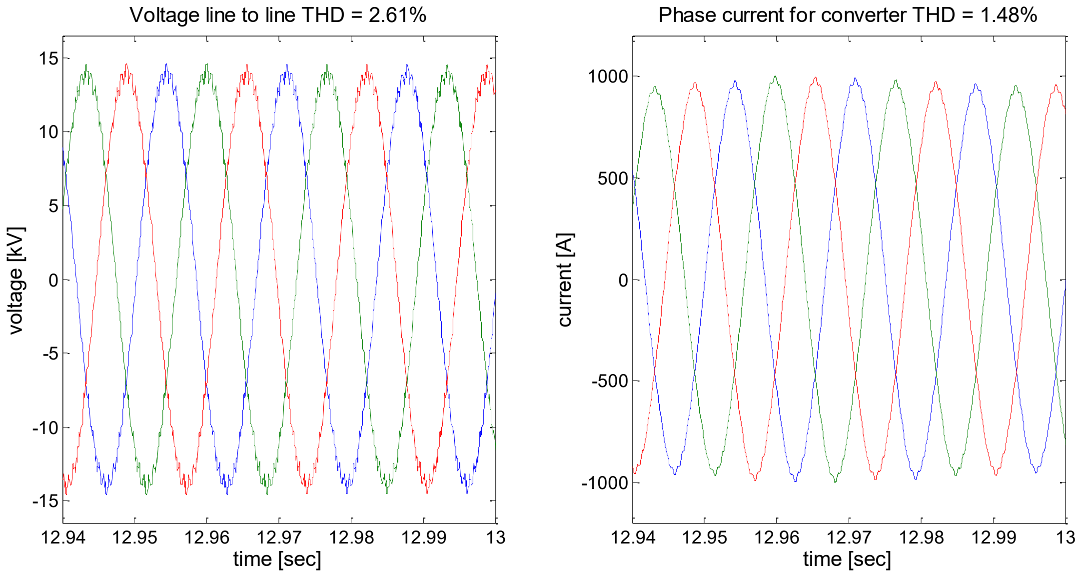
Source: Research data (2025).

Figure 5: Voltage line HVDC and on the capacitors flying.



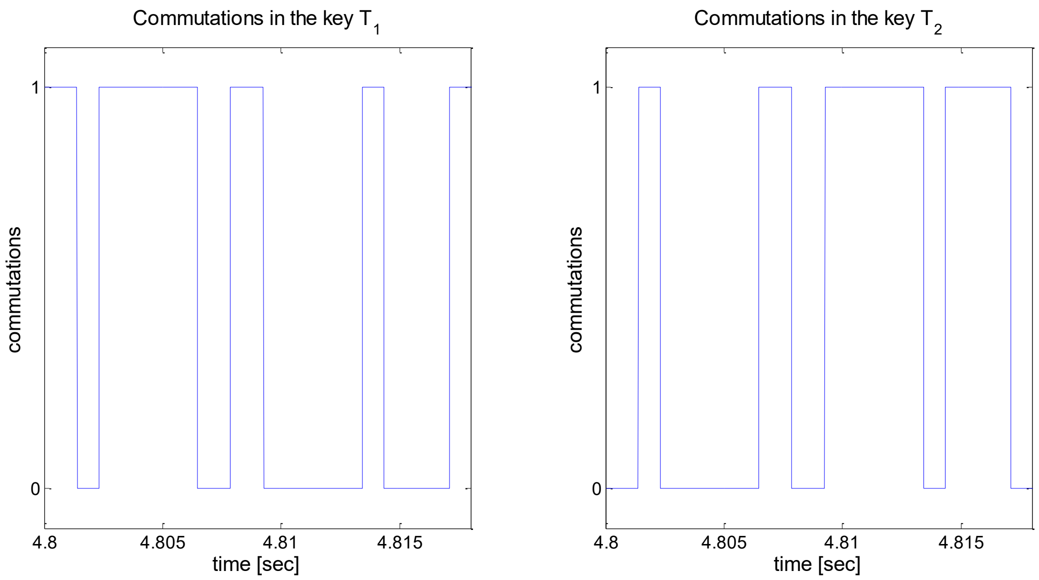
Source: Research data (2025).

Figure 6: Voltage of the converter and AC network current.



Source: Research data (2025).

Figure 7: Commutations in the keys of a sub-module.



Source: Research data (2025).

7. Final Considerations

The Modular Multilevel Converter (MMC) has demonstrated to be a highly suitable and effective solution for HVDC transmission systems. Its modular structure enables the series connection of semiconductor devices, overcoming individual device voltage limitations and allowing operation at very high voltage levels. Additionally, the MMC is capable of producing output waveforms with low harmonic distortion, significantly reducing the dependence on bulky and costly AC filters traditionally required in HVDC applications. Although the converter still requires arm inductors—resulting in additional cost—the overall benefits of modularity, scalability, and superior waveform quality reinforce the relevance of this topology for modern transmission systems.

The control strategy proposed in this work showed excellent performance in regulating both active and reactive power while maintaining high-quality output voltages and currents. The reduction in switching frequency, achieved without compromising waveform quality, contributes to lowering semiconductor stress and improving the overall efficiency of the converter. Furthermore, the capacitor voltage-balancing algorithm implemented for the floating submodules operated effectively, ensuring stable voltage distribution and proper converter behavior. It was observed that the algorithm's update period has a direct impact on the effective switching frequency: shorter update intervals improve capacitor voltage balancing, but may increase the frequency of switching events. Therefore, selecting an appropriate update interval is essential to achieving the desired compromise between voltage stability and switching performance.

Overall, the results obtained through MATLAB/Simulink simulations confirm that the proposed control strategy, combined with an efficient voltage-balancing method, enhances the dynamic performance, reliability, and efficiency of MMC-based HVDC transmission systems. These findings reinforce the MMC's potential as a key technology for future high-voltage power conversion and transmission applications.

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