OVERVOLTAGE SUPPRESSION OF MMC-HVDC OFFSHORE WIND FARM UNDER VALVE-SIDE SPG FAULT BASED ON MODEL PREDICTIVE CONTROL

KHỐNG CHẾ QUÁ ĐIỆN ÁP CHO HỆ THỐNG ĐIỆN GIÓ NGOÀI KHƠI SỬ DỤNG MMC-HVDC DƯỚI SỰ CỐ NGẮN MẠCH MỘT PHA CHẠM ĐẤT PHÍA VAN DỰA TRÊN ĐIỀU KHIỂN DỰ BÁO MÔ HÌNH

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Abstract:

In the midst of the world's rapidly accelerating energy transition, offshore wind power is one of the forefront technologies to be developed and implemented. With the advantage of having an extensive coastline, the potential for offshore wind power systems in Vietnam is enormous. To ensure a reliable and efficient power delivery system, modular multilevel converter high-voltage direct current (MMC-HVDC) transmission systems are being increasingly preferred. Considering onshore converter stations, occurrence of single-phase to ground (SPG) faults can cause DC line overvoltage, which triggers circuit breakers and interrupts the power transmission process. This paper proposes a method to suppress the overvoltage based on a model predictive control (MPC) controller for the onshore converter station. The simulated results are directly compared with a previously proposed zero-sequence voltage control method and show the superiority of the MPC model on controlling the DC line and the sub-modules' voltages. Simulations were performed using Simulink/MATLAB software.

Keywords:

Offshore wind farm, modular multilevel converter, high-voltage direct current, model predictive control

Tóm tắt:

Trong bối cảnh chuyển dịch năng lượng toàn cầu đang diễn ra nhanh chóng, điện gió ngoài khơi là một trong những công nghệ tiên phong được phát triển và triển khai. Với lợi thế sở hữu đường bờ biển dài, tiềm năng phát triển hệ thống điện gió ngoài khơi tại Việt Nam là vô cùng to lớn. Để đảm bảo hệ thống truyền tải điện năng ổn định và hiệu quả, hệ thống truyền tải điện một chiều điện áp cao sử dụng bộ chuyển đổi mô-đun đa cấp (MMC-HVDC) đang ngày càng được ưa chuộng. Xét đến các trạm chuyển đổi trên bờ, sự cố ngắn mạch một pha chạm đất (SPG) có thể gây ra hiện tượng quá điện áp trên đường dây DC, dẫn đến kích hoạt các máy cắt mạch và làm gián đoạn quá trình truyền tải điện. Bài báo này đề xuất một phương pháp khống chế quá điện áp dựa trên bộ điều khiển dự đoán mô hình (MPC) cho trạm chuyển đổi trên bờ. Các kết quả mô phỏng được so sánh trực tiếp với phương pháp điều khiển điện áp thứ tự không (zero-sequence voltage control) đã được đề xuất trước đó và cho thấy ưu điểm vượt trội của mô hình điều khiển MPC trong việc điều khiển điện áp đường dây DC và điện áp của các mô-đun con. Các mô phỏng được thực hiện bằng phần mềm Simulink/MATLAB.

Từ khóa:

Điện gió ngoài khơi, bộ chuyển đổi mô-đun đa cấp, hệ thống điện một chiều cao áp, điều khiển dự báo mô hình

1. INTRODUCTION

Modular Multilevel Converter-based High Voltage Direct Current (MMC-HVDC) system has become a key technology for connecting offshore wind farms to the power grid. With the increasing size and distance of offshore wind farms from the shore, HVDC transmission provides a more efficient and reliable means to transfer large amounts of power over long distances compared to traditional AC systems. The MMC's modular design, scalability, and high efficiency make it an ideal choice for HVDC applications. For such systems, onshore AC-side faults can cause disruptions in power transmission, voltage instability, and may lead to temporary disconnection of the wind farm from the grid. Various types of AC faults have been extensively reported in literatures in terms of their characteristics and unique impact on the components of MMC-HVDC systems.

The reliability of MMC-HVDC systems heavily depends on their fault tolerance, making it a key focus in research. Several studies, such as those in [1] – [3], have explored DC fault behavior and strategies for fault management. Other researches have also addressed the impact of grid-side unbalanced AC faults. According to studies [4], [5], [6], a single-phase to ground fault on the valve side in the MMC system will lead to DC line overvoltage and a current that does not pass through the grid neutral point and overvoltage of the capacitors in the upper branches of the converter. The AC-side circuit breaker (ACCB) may face difficulties in interrupting fault currents that do not pass through the neutral point. Overvoltage in the upper branches can cause damage to the SM capacitors and threaten the insulation of the converter. Reference [7] provides a theoretical analysis of SPG faults on the valve side of MMC, but it focuses on system structures typically applied to overhead transmission lines with asymmetric monopolar or symmetric bipolar structures. In this document, they also propose the use of an MMC system that relies on full-bridge sub-modules (FB-SM). Adding FB-SM to the converter will, on one hand, increase the number of IGBTs in the converter and, on the other hand, require a larger area of converter stations for equipment installation. This will significantly increase the project cost. Reference [8] has provided the author with comprehensive theoretical knowledge about the characteristics of single-phase to ground faults at the onshore converter station for each specific location: onshore, HVDC transmission line, and offshore. At the same time, the document also presents a zero-sequence voltage control method in order to suppress the DC overvoltage. However, the more intense the suppression

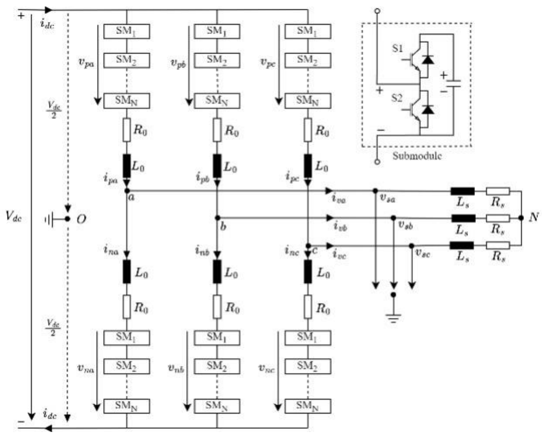

Figure 1: MMC topology

control is, the more the capacitor voltage of sub-modules lose stability due to the mechanism of the proposed method.

This paper proposes a Model Predictive Control based method to subdue the DC line overvoltage of a MMC-HVDC offshore wind farm in the event of a valve-side SPG fault. The proposed controller will directly evaluate the switching states of the grid-side MMC and decide the upcoming optimal switching signals in order to mitigate the overvoltage of the DC line as well as the sub-modules capacitor voltage. The simulated results are compared with the zero-sequence voltage control method in [8] to show the superiority of the proposed controller. The rest of the paper is organized as follows: Section 2 provides the topology and modelling of a half-bridge MMC as well as overview of the Model Predictive Control technique. Section 3 describes the design of the MPC controller for the MMC. Section 4 presents the simulation results and the conclusions are drawn in section 5.

2. MMC MODELLING AND MPC TECHNIQUE

2.1. MMC Modelling

In general, MMC has three legs, each leg contains two arms (upper and lower arm), each arm is constructed with *N* cascaded SMs (sub-modules) and an arm inductor. *O* is the virtual midpoint of the dc link and *N* is the neutral point of the AC side. $\boldsymbol{i_{pa}}, \boldsymbol{i_{na}}, \boldsymbol{i_{pb}}, \boldsymbol{i_{nb}}, \boldsymbol{i_{pc}}, \boldsymbol{i_{nc}}$ are the currents flowing through the upper and lower arms in three phases, respectively. $\boldsymbol{v_{pa}}, \boldsymbol{v_{na}}, \boldsymbol{v_{pb}}, \boldsymbol{v_{nb}}, \boldsymbol{v_{pc}}, \boldsymbol{v_{nc}}$ represent the voltages produced by the upper and lower arms in three phases. $\boldsymbol{v_{sa}}, \boldsymbol{v_{sb}}, \boldsymbol{v_{sc}}$ are the equivalent AC-side output voltages of the MMC. $\boldsymbol{V_{dc}}$ and $\boldsymbol{i_{dc}}$ are the DC-link voltage and current. The voltage and current are produced by the upper and lower arm based on the switching states of SMs, which are categorized:

- Inserted: S1 is turned on and S2 is turned off, which provides the voltage $\boldsymbol{v_c}$ on the terminal of the SM.
- Bypassed: S1 is turned off and S2 is turned on, which causes the voltage of the capacitor to remain constant regardless of the arm current and the SM voltage is 0.
- Blocked: Both S1 and S2 are turned off. This state is often used for protection processes.

It can be seen that by selecting the appropriate number of SMs to insert in the arm, the desired arm output voltage can be generated, which is the total voltage of the inserted SMs.

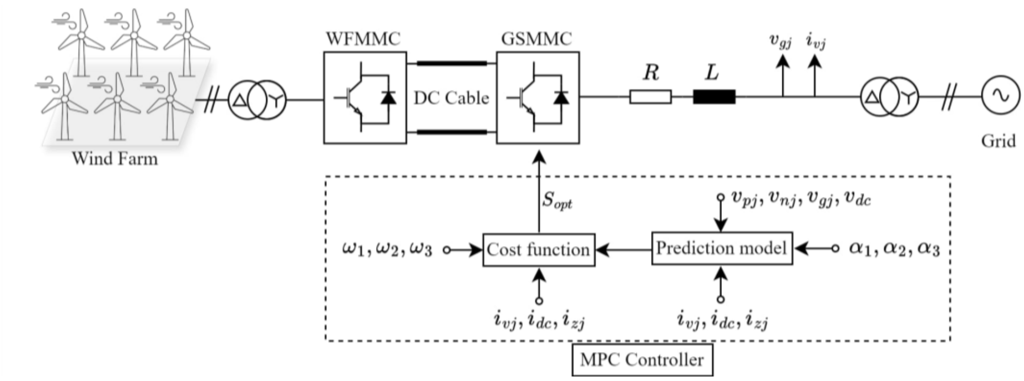

Figure 2: Proposed control scheme

To ensure the stable operation of the MMC, the capacitor voltage of each sub-module needs to be maintained at the reference value $\boldsymbol{V_c^*}$:

$$\boldsymbol{V_c^*} = \frac{\boldsymbol{V_{dc}}}{\boldsymbol{N}} \quad (1)$$

where N is the number of sub-modules. Applying Kirchhoff's law, the output current of the MMC i_{vj} and the DC current i_{dc} are formulated as follows:

$$\begin{cases} \boldsymbol{i_{vj}} = \boldsymbol{i_{pj}} - \boldsymbol{i_{nj}} \\ \boldsymbol{i_{dc}} = \boldsymbol{i_{pa}} + \boldsymbol{i_{na}} + \boldsymbol{i_{pb}} + \boldsymbol{i_{nb}} + \boldsymbol{i_{pc}} + \boldsymbol{i_{nc}} \end{cases} \quad (2)$$

To describe the energy flow within the branches of the MMC, the circulating current is calculated as follows:

$$\boldsymbol{i_{zj}} = \frac{\boldsymbol{i_{pj}} + \boldsymbol{i_{nj}}}{2} - \frac{\boldsymbol{i_{dc}}}{3} \quad (3)$$

The DC voltage is formulated as:

$$\begin{cases} \frac{V_{dc}}{2} = v_{pj} + L_o\frac{di_{pj}}{dt} + R_s i_{vj} + L_s\frac{di_{vj}}{dt} + U_{vj} + v_{NO} \\ \frac{V_{dc}}{2} = v_{nj} + L_o\frac{di_{nj}}{dt} - R_s i_{vj} - L_s\frac{di_{vj}}{dt} - U_{vj} - v_{NO} \end{cases} \quad (4)$$

in which $\boldsymbol{v_{NO}} = \frac{1}{6}(\boldsymbol{v_{na}} - \boldsymbol{v_{pa}} + \boldsymbol{v_{nb}} - \boldsymbol{v_{pb}} + \boldsymbol{v_{nc}} - \boldsymbol{v_{pc}})$, L_s and R_s are the inductance and resistance on the AC side. From (2)-(4), the mathematical modelling of i_{vj}, i_{dc}, i_{zj} are formed as below:

$$\begin{cases} \frac{di_{vj}}{dt} = \frac{1}{2L_s + L_o}(v_{pj} - v_{nj} - 2R_s i_{vj} - 2v_{gj} - 2v_{NO}) \\ \frac{di_{dc}}{dt} = \frac{3}{2L_o}(V_{dc} - v_{sum}) \\ \frac{di_{zj}}{dt} = \frac{1}{2L_o}(V_{sum} - v_{nj} - v_{pj}) \end{cases} \quad (5)$$

with $\boldsymbol{v_{sum}} = \frac{1}{3}(\boldsymbol{v_{na}} + \boldsymbol{v_{pa}} + \boldsymbol{v_{nb}} + \boldsymbol{v_{pb}} + \boldsymbol{v_{nc}} + \boldsymbol{v_{pc}})$.

2.2. Model Predictive Control

Model Predictive Control technique deals with the past, present, and future values of the variable. The controller predicts future errors and takes preventive control actions such that the system will not be subjected to huge errors, thereby making the overall system robust. The operation of MPC is mainly based on the discrete-time model of the system, where the future values of the state variables and control inputs are predicted for a specific forward interval by using the model measurements at the present instant. The predicted values are then evaluated by a cost function that defines the desired control objectives or behavior. A typical cost function is a nonlinear function of reference, predicted, and input variables. The control sequence, which minimizes the cost function, is selected as the optimal input.

3. ZERO-SEQUENCE VOLTAGE CONTROL METHOD AND MPC CONTROLLER DESIGN

3.1. Zero-sequence Voltage Control Method

The proposed method in [8] is based on the analysis of the AC-side sequence equivalent circuit when the fault occurs. The study shows that the DC-side oscillation component causing the overvoltage is equal to the zero-sequence voltage of the faulted phase. Therefore, by identifying the zero-sequence voltage, the oscillation component on the DC-side can be determined. From there, by using the zero-sequence voltage to modulate the sub-modules inputs, overvoltage can be suppressed. However, one drawback lies in the selection of parameter *k* in the scheme; choosing more suppression with larger *k* will lead to overmodulation and cause the sub-modules' capacitor voltage to be unstable. With the proposed MPC controller, the suppression can be achieved without compromising the capacitor voltage component.

3.2. State Matrix of MMC

The simulation model of the MMC converter is implemented using aggregate models to represent the power models of each arm. By selecting the appropriate number of SMs to insert in the branch as the input control signal, the desired arm output voltage can be generated, which is the total voltage of the inserted SMs. Since the number of SMs switched on in one phase during the PWM process is always 36, it is only necessary to examine the

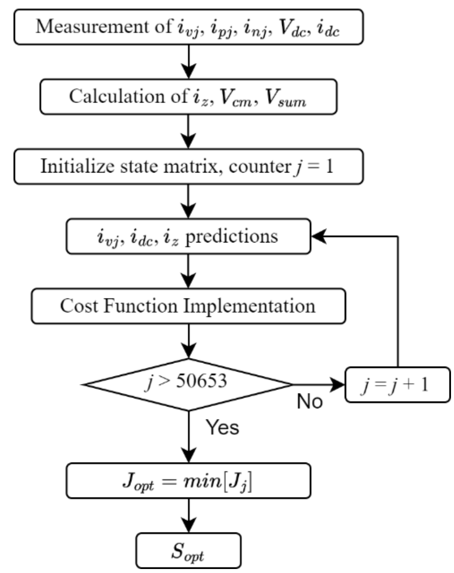

Figure 3: MPC control algorithm

states of the upper branch models, and from there the lower branch states will be deduced accordingly. Each aggregate model consists of 36 SMs, so the state of the model will range from 0 to 36. As the upper branches of the three-phase MMC has three aggregate models, the total number of possible states in the upper branches is 37^3 = 50,653 states. The number of states will increase as the number of SMs in each arm increases, and vice versa. With the proposed scheme, the MPC algorithm will examine all possible states of the converter within a pre-defined sampling period. To achieve this, a matrix containing all the states of the converter needs to be created:

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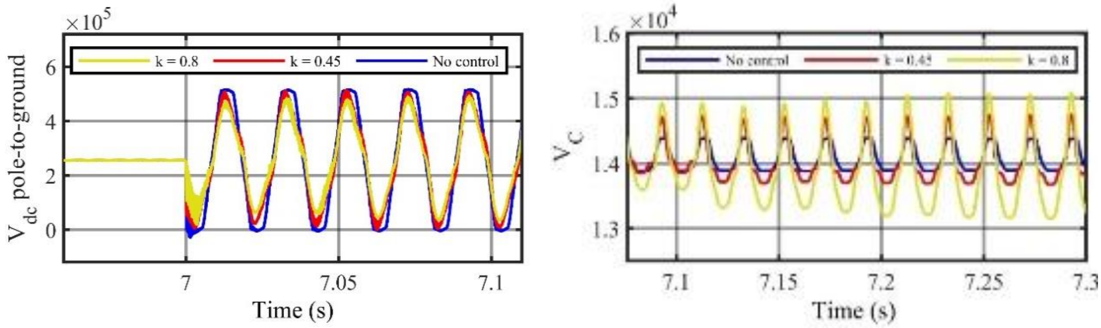
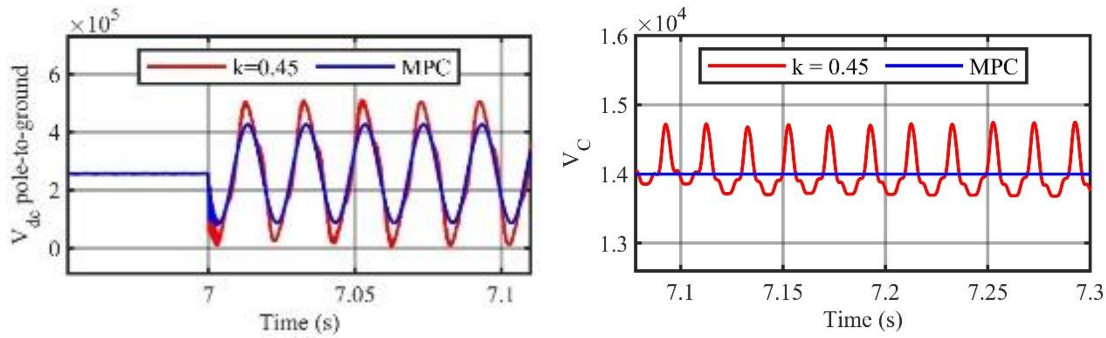
$$\boldsymbol{S} = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} \\ \mathbf{0} & \mathbf{1} & \mathbf{0} \\ \vdots & \vdots & \vdots \\ \mathbf{36} & \mathbf{36} & \mathbf{36} \end{bmatrix} \quad (6)$$

3.3. Predictions



a) b)

Figure 4: Zero-sequence voltage control method



a) b)

Figure 5: Comparison between zero-sequence method and MPC-based method

As mentioned in the previous section, the predictions are formulated based on the discrete time model of the equations. In this paper, the Euler approximation method is used to discretize the expressions, which will represent the future values based on the present samples. Combining (4) and (5) then discretizing, the expressions of $\boldsymbol{i_{vj}}, \boldsymbol{i_{dc}}, \boldsymbol{i_{zj}}$ in instance $\boldsymbol{k+1}$ are as follows:

$$\begin{cases} \boldsymbol{i_{sj}(k+1) = \alpha_1 i_{vj}(k) + \alpha_2\left(v_{nj}(k) - v_{pj}(k) - 2v_{gj}(k) - 2v_{NO}(k)\right)} \\ \boldsymbol{i_{dc}(k+1) = i_{dc}(k) + 3\alpha_3\left(V_{dc} - v_{sum}(k)\right)} \\ \boldsymbol{i_{zj}(k+1) = i_{zj}(k) + \alpha_3\left(v_{sum}(k) - v_{nj}(k) - v_{pj}(k)\right)} \end{cases} \quad (7)$$

in which $\boldsymbol{\alpha_1 = 1 - \frac{2R_sT_s}{2L_s+L_o}}, \boldsymbol{\alpha_2 = \frac{T_s}{2L_s+L_o}}$ and $\boldsymbol{\alpha_3 = \frac{T_s}{2L_o}}$.

3.4. Cost Function

After obtaining the predicted values, a cost function evaluating the references and predictions is implemented to complete the optimization. As the capacitor voltage of the sub-modules is affected by the circulating current and the DC current, effectively controlling the current signals will also ensure the stabililty of the capacitor voltages. Therefore, the final cost function considers the three current signals $\boldsymbol{i_{vj}}, \boldsymbol{i_{dc}}, \boldsymbol{i_{zj}}$ and will be formulated as follows:

$$J = \omega_1 \sum_{j=a,b,c} \left\| i_{vj}^* - i_{vj}(k+1) \right\|^2 + \omega_2 \sum_{j=a,b,c} \left\| i_{zj}^* - i_{zj}(k+1) \right\|^2 + \omega_3 \left\| i_{dc}^* - i_{dc}(k+1) \right\|^2 \quad (8)$$

where $\boldsymbol{\omega_1}, \boldsymbol{\omega_2}, \boldsymbol{\omega_3}$ are weighting factors, $\boldsymbol{i_{vj}^*}, \boldsymbol{i_{zj}^*}, \boldsymbol{i_{dc}^*}$ are the corresponding reference signals. Figure 3 shows the MPC control algorithm. Through iterative loops, the MPC controller will evaluate all switching states in the state matrix, determine the state that produces the minimum value of J and select it as the next switching state for the MMC.

4. SIMULATION RESULTS

4.1. Zero-sequence Method

In this section, authors simulated the zero-sequence voltage control method from [8] using Simulink/MATLAB software. The simulation examined the pole-to-ground voltage on the DC line, the SM capacitor voltage, and the number of active SMs during an SPG fault at the GSMMC converter station. The SPG fault occurred in phase A, with the fault duration from 7s to 7.5s. To observe the impact of the zero-sequence voltage control method, three cases are simulated: No control, k = 0.45, and k = 0.8.

As analyzed above, the SPG fault causes the pole-to-ground voltage on the DC line to oscillate. The results in Figure 4(a) show that this signal oscillates sinusoidally with an amplitude of about 550 kV during the fault when no method is applied. After applying the method, the voltage decreases to 490 kV and 470 kV corresponding to k = 0.45 and k = 0.8, respectively. This method has resolved the issue, and it can also be observed that the larger the value of k, the greater the voltage reduction.

However, by altering the number of open SMs, the drawback of this method is highlighted when examining the SM capacitor voltage. Figure 4(b) shows that when no method is applied, the SPG fault does not cause overvoltage in the DC capacitor within the SM. With the zero-sequence voltage control method, this signal increases during the fault. The larger the value of k, the more the voltage oscillates, leading to overvoltage. For this reason, k = 0.45 is selected and the result is compared with the proposed method in this paper.

4.2. MPC-based Method

This section presents the results of the MPC method and compare them with the zero-sequence voltage control method. Figure 5(a) shows that with the use of MPC, the pole-to-ground voltage on the DC line during a fault oscillates less compared to the zero-sequence voltage control method. Therefore, the MPC controller helps the MMC-HVDC system prevent overvoltage.

For the capacitor voltage on the SM, Figure 5(b) shows that the zero-sequence voltage control method causes this signal to oscillate more during a fault. In contrast, the MPC method helps to stabilize this signal, both during and after a fault. This prevents overvoltage in the capacitor, unlike the zero-sequence voltage control method. The reason that the capacitor voltage on the SM does not oscillate even when there is no fault using the MPC method is that the MPC algorithm effectively finds the minimum optimal function, ensuring that the circulating and DC current signals, $\boldsymbol{i_{zj}}$ and $\boldsymbol{i_{dc}}$, follow the reference signals correctly, thereby adjusting the capacitor voltage of the SM.

5. CONCLUSION

This paper presents a MPC algorithm model aimed at optimizing the switching signal of the MMC, thereby reducing the DC pole-to-ground overvoltage during a single-phase ground fault at the onshore converter station. Compared with a previously proposed zero-sequence voltage control method, the simulation results show that the MPC method not only reduces the pole-to-ground voltage oscillations on the DC line but also does not affect the SM capacitor voltage during faults. Future works may include: the application of MPC control for MMC-HVDC transmission systems for Type 4 wind farms, not only in SPG fault scenarios but also in other potential fault situations, to enhance the offshore wind power transmission capability to the grid.

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