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Finite Control Set Model Predictive Control for Complex Energy System with Large-Scale Wind Power

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Complex energy systems can effectively integrate renewable energy sources such as wind and solar power into the information network and coordinate the operation of renewable energy sources to ensure its reliability. In the voltage source converter-based high voltage direct current system, the traditional vector control strategy faces some challenges, such as difficulty in PI parameters tuning and multiobjective optimizations. To overcome these issues, a finite control set model predictive control-based advanced control strategy is proposed. Based on the discrete mathematical model of the grid-side voltage source converter, the proposed strategy optimizes a value function with errors of current magnitudes to predict switching status of the grid-side converter. Moreover, the abilities of the system in resisting disturbances and fault recovery are enhanced by compensating delay and introducing weight coefficients. The complex energy system in which the wind power is delivered by the voltage source converter-based high voltage direct current system is modeled by Simulink and simulation results show that the proposed strategy is superior to the tradition PI control strategy under various situations, such as wind power fluctuation and fault occurrences.

1. Introduction

To deal with energy shortage and environment pollution issues, the development of complex energy systems, which can effectively coordinate the operation with various renewable energy sources such as wind and solar power to ensure its reliability, has drawn much attention from many countries. The focus is on the wind farm due to its high efficiency of wind power utilization and no occupation of land resources [1–4]. With the increasing capacity of the wind farm and innovations of power electronic technologies, many researchers focus on applications of the voltage source converter-based high voltage direct current (VSC-HVDC) technique and require better operational performance of the converter of the VSC-HVDC system.

The model predictive control (MPC) [5–9] has been extensively applied in the control of modular multilevel inverters [10], uninterruptible power systems [11], and neutral-point clamped converters [12] due to its advantages such as control flexibility and being free of modulators. The MPC strategies used for the control of the converter can be classified as the continuous control set MPC and the finite control set (FCS) MPC. For the continuous control set MPC, a modulator generates switching states based on the continuous mathematical model of the grid-side voltage source converter, the proposed strategy optimizes a value function with errors of current magnitudes to predict switching status of the grid-side converter. Moreover, the abilities of the system in resisting disturbances and fault recovery are enhanced by compensating delay and introducing weight coefficients. The complex energy system in which the wind power is delivered by the voltage source converter-based high voltage direct current system is modeled by Simulink and simulation results show that the proposed strategy is superior to the tradition PI control strategy under various situations, such as wind power fluctuation and fault occurrences.
support the system voltage and improve the transient stability of the system. The simulation results show that the PV power plant is able to support the voltage with the proposed strategy in the low voltage situation.

In [14–17], the FCS MPC strategy was used to optimize the control of inverters. A mixed logical dynamical (MLD) model for inverters was proposed in [15]. By treating the MLD model as a predictive model, a FCS-MPC strategy for inverters was developed. The proposed strategy considers the discreteness of inverters and selects the switch state corresponding to the optimal objective value as the control signal for inverters to control the output voltage. The simulation and test results validate that the proposed FCS-MPC strategy can improve the output voltage quality of inverters. To improve the conventional FCS-MPC strategy, a multistep prediction FCS-MPC strategy for converters is introduced in [15], in which the optimal and suboptimal control actions are considered in one control cycle. The optimal control action is determined in a fashion that the control action is optimal in two control cycles. Simulation results show that the proposed multistep FCS-MPC scheme can improve the quality of the output voltage of the three-phase inverter and reduces the tracking error of the reference voltage as compared with the conventional FCS-MPC. In [16], the authors proposed a FCS-MPC strategy for a four-level converter to control output currents and voltages of flying capacitors. A discrete model of the converter is developed to obtain switching states. During each sampling period, the predicted variables are evaluated by an evaluation function and the optimal switching state with the minimum cost value is selected and applied to the converter. In [17], the authors proposed a simplified FCS-MPC with extended voltage vectors for two-level three-phase grid-connected converters. The proposed algorithm uses multiple voltage vectors for the prediction process to reduce the ripple in the grid current. Moreover, the proposed approach utilizes a preselection scheme along with a simplified MPC approach to reduce the number of voltage vectors used in the proposed strategy. Simulations show that the proposed strategy retains the effectiveness obtained in the case where all the voltage vectors are used, and at the same time the current ripple is not adversely affected and the control delay is effectively reduced.

Improved MPC strategies were proposed for the STATCOM and multilevel converters in [18, 19]. A novel control delay elimination for the MPC strategy was proposed in [18] for the control of the cascaded STATCOM. The MPC based optimization problem was proposed and simplified for the possible switching states. Based on the further recursion of the simplified MPC based model, the effect of control delay on the control performance is reduced. The simulation results show that the proposed delay elimination for the MPC strategy can improve current tracking control of the cascaded STATCOM and the system has strong robustness. In [19], the discrete mathematic model of the modular multilevel converter-based HVDC (MMC-HVDC) system is developed, and an improved MPC strategy is proposed for the five-level MMC. Moreover, the improved MPC strategy is combined with the voltage-sequencing algorithm to reduce computational burdens and realize the transmission power control in the MMC-HVDC system and circulating current elimination.

In [20–23], the MPC strategies were applied to the control of electric motors. In [20], the authors proposed a MPC strategy combined with a disturbance observer (DOB) for regulating the torque of a permanent magnet synchronous motor (PMSM) without the steady state error. In the proposed strategy, the online optimal solutions can be obtained without relying on a numeric algorithm based on the property of the input matrix of the PMSM. The results show that the proposed MPC strategy ensures satisfactory torque control performance. A quasideadbeat MPC strategy for induction motors was proposed in [21]. By building a rolling optimization problem, the optimal switching state corresponding to the optimal voltage vector was selected as the output of the inverter. The simulations and experimental results show that the proposed strategy can reduce computational time and ensure satisfactory static and dynamic performance for torque.

However, the above researches mainly focus on the steady state and have not studied operational performance of inverters under renewable energy integration and system disturbances. To deal with the above issues, a FCS-MPC based control strategy for the VSC-HVDC system is proposed. The control strategy generates the reference value through the outer loop and compares the reference value with the predicted value obtained under a given voltage vector. Then, the switching status corresponding to the value function with the smallest difference is obtained and used in the next sampling period, which can achieve the fast tracking of the reference value. Moreover, abilities of the system in resisting disturbances and fault recovery are enhanced by compensating delay and introducing weight coefficients. The VSC-HVDC connected OWF system is modeled in the MATLAB/Simulink and simulation results validate that the proposed FCS-MPC strategy is superior to the tradition PI control strategy under various situations, such as wind power fluctuation and fault occurrences.

The contributions of this paper are summarized as follows: (1) A FCS-MPC based control strategy for the complex energy system is proposed considering the renewable energy integration and system disturbances; (2) A MPC based delay compensation technique is proposed. Compared with the conventional PI control strategy, the proposed FCS-MPC has the following advantages: (1) it is easy to tune control parameters; (2) it can realize multiobjective optimization and incorporate constraints; (3) there is no need to implement the decoupling process; (4) no PMW modulators are required.

2. Control Strategies for Wind Farm-Side VSC and Direct Driven Permanent Magnet Synchronous Generator

Figure 1 shows the typical configuration of the OWF connected to an external AC grid through the complex energy system. The complex energy system consists of the wind farm-side VSC (WF-VSC), the grid-side VSC (GS-VSC), and the DC transmission system. To ensure utilization of the
OWP and secure operation of the complex energy system, the GS-VSC should maintain the steady DC voltage of the DC transmission system.

2.1. Control Strategy for the WF-VSC. The mathematical model of the WF-VSC in the synchronized rotating d-q frame is formulated as below.

\[
\begin{align*}
L_d \frac{d i_{sd}}{dt} &= u_{sd} - i_{sd} R + \omega_s L i_{sq} - v_{sd} \\
L_q \frac{d i_{sq}}{dt} &= u_{sq} - i_{sq} R - \omega_s L i_{sd} - v_{sq} \\
C \frac{d i_{dc}}{dt} &= \frac{3}{2} (S_{sd} i_{gd} + S_{sq} i_{gs}) - i_{dc}
\end{align*}
\]

where \(u_{sd}\) and \(u_{sq}\) are the d-axis and q-axis components of the three-phase voltage, respectively; \(i_{sd}\) and \(i_{sq}\) are the d-axis and q-axis components of the three-phase current, respectively; \(v_{sd}\) and \(v_{sq}\) are the d-axis and q-axis components of the voltage at the converter side, respectively; \(S_{sd}\) and \(S_{sq}\) are the d-axis and q-axis components of the switching function, respectively; \(\omega_s\) is synchronized angular velocity. The direct control strategy is applied to maintain the voltage magnitude and frequency at the WF side.

The control structure of the WF-VSC is shown in Figure 2. It can be seen that the voltage magnitude and phase at the WF side are controlled through commands in d-q axis and the synchronized angular velocity of the WF-VSC. To reduce control complexity, the initial voltage angle at the WS side is set as zero and voltage magnitude components in d-q axis are used for feedback control. The differences between the reference values and real-time values of voltage magnitude are used to obtain the modulation ratio and generate the trigger pulse.

2.2. Control Strategy for Direct Driven Permanent Magnet Synchronous Generator. The typical configuration of the direct driven permanent magnet synchronous generator (PMSG) is shown in Figure 3. The direct driven PMSG system consists of the wind turbine, PMSG, generator-side converters, and grid-side converters.

The double closed loop control strategy, namely, the outer loop of angular velocity and inner loop of current, is applied to the generator-side converter to achieve the MPPT. The grid-side converter controls the DC voltage to ensure wind power integration. In this paper, the PMSG-based wind farm is represented by an equivalent single-machine model. Since the dynamic response speed of the grid-side converter is faster than the ones of the wind turbine and generator-side converters, the wind turbine, the PMSG, and generator-side converters are simplified as an equivalent voltage resource, as shown in Figure 3. Different levels of wind power output are simulated by controlling power output of the grid-side converter.

The control strategy for the grid-side converter is shown in Figure 4. In this paper, input wind power variation is simulated by controlling the grid-side converter of the PMSG because this study focuses on the verification of the abilities of the system with the proposed control strategy in resisting disturbances and fault recovery under different situations, such as wind speed variation and fault occurrence. As shown in Figure 4, the actual wind speed is simulated by the wind power generator, which generates the varying input wind power and obtains the d-axis component of the reference
3. FCS-MPC Based Control Strategy for GS-VSC

The FCS-MPC based control strategy for the GS-VSC is shown in Figure 5. As shown in Figure 5, the proposed control strategy is applied to the DC voltage control of the GS-VSC. The DC voltage reference value $u^{*}_{dc}$ is compared to the actual value $u_{dc}$, and the difference between them is used to generate the current reference value through the PI units. Then, the measurement unit collects three-phase grid voltage ($e$) and grid current ($i$), and these values are used to obtain the predicted values in the $ab$ coordinate system by using the proposed predicted models. Finally, a value function is used to evaluate the difference between the predicted value and the reference value. The value function is optimized over a rolling horizon to obtain the optimal switching combination corresponding to the value function with the smallest value. Finally, the optimal switching combination is applied to control the GS-VSC.

As the most important blocks of the FCS-MPC based control strategy, the predicted model of the GS-VSC and the value function are described in detail in the following subsections. In addition, the method of delay compensation is also illustrated.

3.1. Discrete Predicted Model of the GS-VSC. The discrete predicted model of the GS-VSC is formulated and described in this subsection. The structure of the GS-VSC is shown in Figure 6. The GS-VSC consists of six IGBT and six antiparallel diodes. $u_{a}$, $u_{b}$, and $u_{c}$ represent the three-phase output voltage value of the three-phase AC current. The reference value of the three-phase AC voltage is compared with the measure value to obtain the q-axis component of the reference value of the three-phase current through the PI unit. Then, the d-q axis components of the three-phase current are adjusted by PI units and transformed using Park inverse transformation to control the converter.
of the converter; $i_a$, $i_b$, and $i_c$ represent the three-phase grid current; $e_a$, $e_b$, and $e_c$ represent the three-phase grid voltage; $u_a$, $u_b$, and $u_c$ represent the three-phase output voltage of the converter. $L$ is the reactance, $R$ is the resistance, and $C$ is the capacitance. $u_{dc}$, $i_{dc}$, and $i_L$ are the DC voltage, DC input current, and DC output current, respectively. More details on the structure of the GS-VSC can be found in [24–27].

To derive the predicted model of the grid current, the GS-VSC should be modeled. The dynamic equation of the grid current in the three-phase stationary reference frame is as follows:

$$L \frac{di}{dt} = u - e - Ri$$  

where $i$ is the vector of current; $u$ is the vector of output voltage of converter; $e$ is the vector of the grid voltage. Vectors $i$, $u$, and $e$ can be expressed as

$$\begin{bmatrix} 1 \\ i \\ u \\ e \end{bmatrix} = \frac{2}{3} \begin{bmatrix} i_a & i_b & i_c \\ u_{aN} & u_{bN} & u_{cN} \\ e_a & e_b & e_c \end{bmatrix} \begin{bmatrix} 1 \\ a \\ a^2 \end{bmatrix}$$  

where $a = e^{j(2\pi/3)}$; $u_{aN}$, $u_{bN}$, and $u_{cN}$ represent the three-phase output voltage of the converter to the neutral point and can be obtained using the following equation:

$$u_{xN} = S_x u_{dc}, \quad (x = a, b, c)$$  

where $S_x$ is the switching function representing the switching status of each bridge arm of the converter; $u_{dc}$ is the DC voltage. The $S_x$ can be expressed as follows [28]:

$$S_x = \begin{cases} 0 & \text{upper arm is open, lower arm is closed} \\ 1 & \text{upper arm is closed, lower arm is open} \end{cases}$$  

Suppose that the sampling period is $T_s$; the derivative of the grid current can be discretized using the forward Euler approximation method as below:

$$\frac{di}{dt} \approx \frac{i(k + 1) - i(k)}{T_s}$$  

FIGURE 5: FCS-MPC based control strategy for the GS-VSC considering delay compensation.

FIGURE 6: The structure of the GS-VSC.
where \( i(k+1) \) and \( i(k) \) are sampling current values in \( k+1 \)th and \( k \)-th sampling periods, respectively. Substitute (6) into (2); the predicted current can be expressed as

\[
i(k+1) = \frac{T_s}{L} (u(k) - e(k)) + \left(1 - \frac{R}{L} \right) i(k)
\]

(7)

The expression of (7) in the \( \alpha \beta \) coordinate system can be obtained using Clarke transformation as below:

\[
\begin{bmatrix} i_\alpha (k+1) \\ i_\beta (k+1) \end{bmatrix} = \frac{T_s}{L} \begin{bmatrix} u_\alpha (k) - e_\alpha (k) \\ u_\beta (k) - e_\beta (k) \end{bmatrix}
+ \left(1 - \frac{R}{L} \right) \begin{bmatrix} i_\alpha (k) \\ i_\beta (k) \end{bmatrix}
\]

(8)

where \( i_\alpha (k+1) \) and \( i_\beta (k+1) \) are \( \alpha \)-axis and \( \beta \)-axis components of the current in \( k+1 \)th period, respectively; \( u_\alpha (k) \) and \( u_\beta (k) \) are \( \alpha \)-axis and \( \beta \)-axis components of the output voltage of converter in \( k \)-th period, respectively; \( e_\alpha (k) \) and \( e_\beta (k) \) are \( \alpha \)-axis and \( \beta \)-axis components of the grid voltage in \( k \)-th period, respectively. As shown in (8), the current of the GS-VSC in \( k+1 \)th period can be accurately predicted according to the current measurement of the GS-VSC in \( k \)-th period, which can achieve the fast tracking and control of the GS-VSC current and enhance the ability of the GS-VSC in resisting system disturbances.

### 3.2. Value Function

The main goal of the GS-VSC is to ensure power balance of the VSC-HVDC transmission system and achieve wind power integration. The control strategy of the GS-VSC is described as follows. According to the desired reference output and the current input of the GS-VSC, the output voltage vector (U) of the GS-VSC can be obtained by determining the switching function value, namely, switching status, of each bridge arm of the converter. Then, based on the output voltage vector (U), grid voltage vector (E), and equivalent reactance \( Z_e \), the magnitude and angle controllable threephase current \( (i_\alpha, i_\beta, i) \) can be obtained to control the input and output power of the GS-VSC. Therefore, it is important to determine the optimal output voltage vector (U) of the GS-VSC.

It can be seen from (4) and (5) that the output voltage vector (U) is determined by the switching functions of three bridge arms, namely, \( S_a \), \( S_b \), and \( S_c \). In the study, it is assumed that the GS-VSC is a three-phase two-level converter. Considering there are three switching function values \( S_a, S_b, \) and \( S_c \), there are eight possible switching states and eight corresponding voltage vectors. Moreover, since \( U_0 = U_f \), seven possible voltage output vectors are shown in Table 1.

| Value function | Switching combinations \((S_a, S_b, S_c)\) | Voltage vectors |
|-----------------|----------------------------------------|-----------------|
| \( g_0 \)       | 000                                    | \( U_0 = 0 \)   |
| \( g_1 \)       | 100                                    | \( U_1 = 2/3u_{dc} \) |
| \( g_2 \)       | 110                                    | \( U_2 = 1/3u_{dc} + j\sqrt{3}/3u_{dc} \) |
| \( g_3 \)       | 010                                    | \( U_3 = -1/3u_{dc} + j\sqrt{3}/3u_{dc} \) |
| \( g_4 \)       | 011                                    | \( U_4 = -2/3u_{dc} \) |
| \( g_5 \)       | 001                                    | \( U_5 = -1/3u_{dc} - j\sqrt{3}/3u_{dc} \) |
| \( g_6 \)       | 101                                    | \( U_6 = 1/3u_{dc} - j\sqrt{3}/3u_{dc} \) |
| \( g_7 \)       | 111                                    | \( U_7 = 0 \)   |

The traditional GS-VSC uses the double closed loop structure (outer loop of power and inner loop of current) to determine the switching functions \( (S_a, S_b, S_c) \) to control the AC voltage output and current (power output) of the GS-VSC. However, parameters of the PI controller are sensitive to the system parameters and it is difficult to tune PI parameters. In addition, the feedforward compensator term affected by the circuit parameters is required to be decoupled in the traditional control strategy. To overcome these issues, a FCS-MPC based control strategy is proposed.

FCS-MPC is a model-based closed loop control method. Based on the eight possible switching combinations and eight corresponding voltage vectors (U), the predicted GS-VSC current value of the next period can be obtained using the discrete predicted model of the GS-VSC given by (8). Then, comparing the predicted value with the reference value using the value function defined in (9), the optimal switching combination corresponding to the smallest value of value function is obtained and used to generate trigger pulse, which can achieve the optimal control of the GS-VSC.

\[
g = \left| i_{gs} (k+1) - i_{gs} (k) \right| + \left| i_{gb} (k+1) - i_{gb} (k) \right|
\]

(9)

where \( i_{gs} (k+1) \) and \( i_{gb} (k+1) \) are the real and imaginary parts of the predicted current vector in the \( k+1 \) period under a given voltage vector, respectively; \( i_{gs}^* (k+1) \) and \( i_{gb}^* (k+1) \) are the real and imaginary parts of the predicted current vector in the \( k+1 \) period under a given voltage vector, respectively.

Repeat the above procedures in the following sampling periods and thus the output current of the GS-VSC is optimized and controlled over the rolling horizon. Based on the above analyses, compared with the traditional PI control-based double closed loop control strategy, the FCS-MPC strategy controls converters directly according to the limited switching combinations. As such, there is no need to implement the decoupling process and the complex PI tuning process. Moreover, no modulators are required and
multilevel constraints can be considered. In particular, there is the lowest calculation complexity when two-level converter is used.

3.3. Consideration of Delay Compensation in the Proposed Strategy. The difference between the current reference and current measurement is used to construct the objective function, namely, the value function in (9), which transforms the problem of finding the optimal modulation satisfying control targets into a problem of finding the optimal switching combination corresponding to the value function with the smallest value. However, the current reference in (9) is the value in the future period, which causes delay in the control of the GS-VSC and affects the control accuracy and response speed of the GS-VSC with the FCS-MPC strategy. To deal with this problem, this study proposes to modify the value function using the predicted current value in the\((k+2)\)th period.

The predicted function of current in the\((k+2)\)th period is

\[
i(k+2 | k) = \frac{T_s}{L} (u(k+1) - e(k+1)) + \left(1 - \frac{RT_s}{L}\right) i(k+1)
\]

where \(i(k+1)\) and \(i(k+2 | k)\) are the predicted currents in the \((k+1)\)-th and \((k+2)\)-th periods using information collected in the \(k\)-th period, respectively; \(u(k+1)\) is the output voltage in the \((k+1)\)-th period; \(e(k+1)\) is the grid voltage in the \((k+1)\)-th period.

The value function considering the delay compensation is as follows:

\[
\tilde{g} = \left|i_{gs}^* \big(k + 2 | k\big) - i_{gs} \big(k + 2 | k\big)\right| + \left|\mu_{gs}^* \big(k + 2 | k\big) - \mu_{gs} \big(k + 2 | k\big)\right| + \lambda |u_{dc}^* - u_{dc}|
\]

To ensure the stability of the DC voltage under the fault occurrence and wind power fluctuation, the DC current error is introduced into the value function as below:

\[
\tilde{g} = \left|i_{gs}^* \big(k + 2 | k\big) - i_{gs} \big(k + 2 | k\big)\right| + \lambda \left|u_{dc}^* - u_{dc}\right|
\]

where \(\lambda\) is the weight coefficient. The predicted value of the DC voltage is introduced to the value function to improve the stability of the DC voltage under steady state and fault occurrences.

3.4. The Algorithm of the FCS-MPC Based Control Strategy. The algorithm of the FCS-MPC based control strategy is illustrated in Figure 7 and has the following steps.

Step 1. Formulate the mathematical model of the GS-VSC based on the eight switching combinations and the relation between the switching combination and corresponding input/output voltage and current.

Step 2. Construct the discrete-time model in order to predict the values of control variables in future periods.

Step 3. Based on the switching states currently applied, construct the discrete current model (8) in order to predict the current in \(k+1\)th period.

Step 4. Predict the current in \(k+2\)th period for each possible switching combination.

Step 5. Use the value function representing the expected performance of the system to evaluate all possible switching combinations.

Step 6. Choose the voltage vector corresponding to the value function with the smallest value and obtain the corresponding optimal switching combination.

Step 7. Update the status of switches based on the optimal switching combination and go back to step 2 for the next sampling period.

4. Case Studies

The VSC-HVDC connected offshore WF, as shown in Figure 1, is modeled in the MATLAB/Simulink to validate the efficiency of proposed FCS-MPC strategy. The simulation parameters are listed in Table 2.

4.1. Case 1: Wind Power Fluctuation. The comparisons between the proposed FCS-MPC strategy and traditional PI double closed loop control strategy under the wind power
Table 2: Simulation parameters.

| Parameters                               | Values       |
|------------------------------------------|--------------|
| Rated capacity of wind farms P/MW        | $4 \times 300$ |
| DC voltage $u_{dc}$/kV                   | $\pm 320$   |
| Length of DC transmission line /km       | 300          |
| DC capacitor $C/\mu F$                   | 75           |
| Reactance of line $L/mH$                 | 200          |
| Sampling period $T/\mu s$                | 50           |
| Number of time steps                     | 60000        |

Fluctuation are carried out in this case. The wind power output is 600MW between 0s to 1s and increases to 1100MW at 1.1s and then remains unchanged. It is assumed that the wind farm operates with the unity power factor. The simulation results of the GS-VSC with two strategies are shown in Figures 8(a)–8(c).

As shown in Figures 8(a)–8(c), the GS-VSC with two strategies can quickly respond to the WF power output variation and achieve steady wind power integration. Compared with the traditional double closed PI control strategy, the FCS-MPC adopts the single loop (outer loop of voltage) control strategy, which enables the GS-VSC to have a faster response speed and higher response accuracy, as shown in Figures 9(a)–9(b). Moreover, as shown in Figure 9(c), the DC voltage of the VSC-HVDC system is restored to the reference value more rapidly when the FCS-MPC control strategy is used because the term involved in the DC predicted voltage is considered in the value function. Therefore, the GS-VSC with the proposed FCS-MPC strategy can ensure the steady operation of the VSC-HVDC system and has better performance under the steady state operation.

4.2. Case 2: AC Fault Occurrence at Grid Side. It is assumed that a three-phase short-circuit fault occurs at grid side at 2s and lasts for 10 ms. The response characteristic of the GS-VSC system is shown in Figures 9(a)–9(c).

As shown in Figure 9, when the traditional PI control strategy is applied to the GS-VSC, the fault occurrence has big impacts on the active/reactive power outputs, voltage, and current outputs of GS-VSC and they are restored to the reference values slowly. In addition, due to the limited ability of the traditional PI control strategy in controlling the DC voltage, the DC voltage cannot be restored to reference value within 3s, as shown in Figure 9(c). However, when applying the proposed FCS-MPC strategy, the impacts of the fault occurrence on the outputs of GS-VSC are limited, and the active/reactive power outputs and voltage and current outputs of GS-VSC are restored to the reference values rapidly. Moreover, the DC voltage is restored to the reference value...
within 2.5s because the predictive control for the DC voltage is considered in the proposed strategy, thus improving the ability of the GS-VSC in controlling the DC voltage under fault occurrences.

4.3. Case 3: DC Fault Occurrence. It is assumed that a DC line fault occurs at the left side of the DC transmission line at 2.0s and lasts for 100 ms. The response characteristics of the VSC-HVDC system with two control strategies are shown in Figures 10(a)–10(e).

As shown in Figure 10(a), the active and reactive power decrease to -2200 MW and -2000 MW, respectively, in the PI control strategy while both the active and reactive power decrease to -1000 MW in the proposed FCS-MPC strategy. As shown in Figures 10(b) and 10(c), the AC voltage decreases to 0.75 p.u. and the maximum transient current reaches 5 p.u. that far exceeds the maximum tolerant level of the GS-VSC. When the FCS-MPC strategy is applied to the GS-VSC, as shown in Figures 10(d) and 10(e), the AC voltage decreases to 0.9 p.u and the maximum transient current is 2.4 p.u. It can been seen that the fluctuations of AC voltage, AC current, and active/reactive power are smaller in the proposed FCS-MPC strategy, which demonstrates the better performance of the FCS-MPC strategy.

4.4. Case 4: Grid Voltage Drops. To further validate the effectiveness of the proposed FCS-MPC strategy, the simulations are conducted when grid voltage drops. It is assumed that the grid voltage decreases from 1 p.u. to 0.5 p.u. at 2.0s and the voltage remains 0.5 p.u. for 100 ms. The simulation results are shown in Figures 11(a)–11(e).

As shown in Figures 11(a)–11(e), when the proposed FCS-MPC strategy is applied, the active power decreases to 540 MW and is restored to the normal level at 2.14s. The reactive power has a very small fluctuation. The AC voltage can be restored to 1.0 p.u. rapidly after the fault is cleared and there is a very small fluctuation in AC current. However, when the PI control strategy is used, the active power decreases to 550 MW and is restored to the normal level at 2.25s. The reactive power increases to 500 MVar and is restored to the normal level slowly. Likewise, the AC voltage and AC current are restored to the normal level slowly. Therefore, the FCS-MPC strategy makes the system more resistant to system disturbances.

4.5. Case 5: Comparative Analysis of Harmonic Distortion Rates of Cases 1-4. Perform the Fourier analyses under selected conditions, namely, the period (1.2s-1.4s) in Case 1 with the maximum wind power output and periods (2.3s-2.5s) in Case 2–Case 4. The distortion rates of the AC voltage and AC current under different operation conditions are shown in Table 1.

As shown in Table 3, Cases 1-4 represent the Fourier analysis results under the steady state conditions under the wind power fluctuation, under AC fault occurrence at the grid side, under DC fault occurrence, and under grid voltage drop, respectively. It can be seen from Table 1 that, in the proposed FCS-MPC strategy, the distortion rates of grid-connected voltage and current of GS-VSC are lower than 1%, which is far lower than the one in the traditional PI control strategy.

5. Conclusions

To overcome the issues in the operation of the complex energy system, this study proposes a FCS-MPC based novel
The proposed control strategy has a simple control structure, removes the inner loop of current and complex PI parameter tuning process, and achieves multi-objective optimization of the complex energy system. Moreover, the proposed control strategy considers the impact of delay and introduces the term of the DC voltage prediction in the value function to improve the stability of DC voltage control and enhances the abilities of the complex energy system in resisting disturbances and recovering after faults. The simulation results under the wind power fluctuation, three-phase short circuit fault, and grid voltage drop validate that the system with the FCS-MPC strategy has better dynamic characteristics and parameter robustness. Moreover, the proposed strategy improves the abilities of the VSC-HVDC in resisting disturbances and fault recovery and reduces distortion rates of the grid-connected voltage and current of the GS-VSC.

**Figure 10:** Response characteristic with two control strategies under DC fault.

**Table 3: Harmonic distortion rates of Cases 1-4 with the FCS-MPC and PI strategy.**

| Case | Current FCS-MPC | Current PI | Voltage FCS-MPC | Voltage PI |
|------|-----------------|------------|-----------------|------------|
| 1    | 0.98            | 1.55       | 0.53            | 2.25       |
| 2    | 0.62            | 2.05       | 0.48            | 2.94       |
| 3    | 0.37            | 4.22       | 0.42            | 5.20       |
| 4    | 0.48            | 3.59       | 0.75            | 6.94       |
**Nomenclature**

- \( u_{sd}, u_{sq} \): d-axis and q-axis components of the three-phase voltage
- \( i_{sd}, i_{sq} \): d-axis and q-axis components of the three-phase current
- \( v_{sd}, v_{sq} \): d-axis and q-axis components of the voltage at the converter side
- \( S_{sd}, S_{sq} \): d-axis and q-axis components of the switching function
- \( \omega_s \): Synchronized angular velocity
- \( u_{xa}, u_{xb}, u_{xc} \): Three-phase output voltage of the converter
- \( i_{xa}, i_{xb}, i_{xc} \): The three-phase grid current
- \( e_{xa}, e_{xb}, e_{xc} \): The three-phase grid voltage
- \( u_{xa}, u_{xb}, u_{xc} \): The three-phase output voltage of the converter
- \( L \): Reactance
- \( R \): Resistance

- \( C \): Capacitance
- \( u_{dc}, i_{dc}, i_L \): The DC voltage, DC input current, and DC output current
- \( i, u, e \): The vector of current, the vector of output voltage of converter, and the vector of the grid voltage
- \( u_{xN} \): x=a, b, c, the three-phase output voltage of the converter to the neutral point
- \( S_x \): x=a, b, c, the switching function representing the switching status of each bridge arm of the converter
- \( u_{dc} \): The DC voltage of the VSC-HVDC system
- \( i(k) \): The sampling current value in \( k \)-th sampling period
- \( i_{a}(k+1) \): \( \alpha \)-axis component of the current in \( (k+1) \)-th period
- \( i_{b}(k+1) \): \( \beta \)-axis component of the current in \( (k+1) \)-th period

**Figure 11:** Response characteristic with two control strategies when grid voltage drops.
\( u_a(k + 1): \) \( \alpha \)-axis component of the output voltage of the converter in \((k+1)\)-th period

\( u_b(k + 1): \) \( \beta \)-axis component of the output voltage of the converter in \((k+1)\)-th period

\( e_a(k + 1): \) \( \alpha \)-axis component of the grid voltage in \((k+1)\)-th period

\( e_b(k + 1): \) \( \beta \)-axis component of the grid voltage in \((k+1)\)-th period

\( i_{bs}(k + 1): \) The real part of the predicted current in the \((k+1)\)-th period under a given voltage vector

\( i_{bg}(k + 1): \) The imaginary part of the predicted current in the \((k+1)\)-th period under a given voltage vector

\( i^*_a(k + 1): \) The real part of the reference current in the \((k+1)\)-th period under a given voltage vector

\( i^*_b(k + 1): \) The imaginary part of the reference current in the \((k+1)\)-th period under a given voltage vector

\( \lambda: \) The weight coefficient

\( i(k + 2 | k): \) The predicted current value in the \((k+2)\)-th period using information collected from \(k\)-th period

\( g_{op}: \) The initial value of the value function.

Data Availability

The no secret-involvement data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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