

Article

Adaptive Hybrid Control Strategy for Grid-Connected VSCs Based on Model Predictive Control

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Abstract

With the widespread adoption of voltage-source converters for grid-connected new energy power generation, the transient stability of VSCs under high penetration of new energy has become a key issue in the construction of modern power systems. Grid-following (GFL) and grid-forming (GFM) controls each have their applicable scenarios and inherent limitations. Traditional hybrid synchronous control uses fixed parameters, making it difficult to adapt to complex and variable grid conditions. Therefore, this paper proposes a control method suitable for an adaptive hybrid synchronous architecture with grid-following and grid-forming dual characteristics, employing a model predictive control strategy to achieve dynamic adjustment of GFL and GFM control ratios in both the synchronization loop and the voltage loop. A simulation model was built in PSCAD/EMTDC to verify the effectiveness and adaptability of the proposed control method under various transient conditions, such as load changes and voltage sags. The simulation results indicate that the method can effectively suppress system frequency and voltage fluctuations, enhance the transient stability of VSCs, and provide a feasible control reference for practical engineering applications.

Keywords: voltage-source converter; grid-following and grid-forming control; adaptive hybrid control; model predictive control

1. Introduction

With the widespread application of new energy power generation, the question of how to integrate new energy generation into the grid has become an urgent problem to be solved. Currently, most new energy generation uses voltage source converters (VSCs) for grid connection. The transient stability issue of VSCs connected to the grid under a high proportion of new energy has become a major challenge in the construction of modern power systems.

VSCs currently have two architectures: grid-following and grid-forming [1–4]. Currently, most VSCs adopt the grid-following (GFL) control architecture, which measures the voltage and phase angle at the point of common coupling (PCC) of the VSC through a phase-locked loop (PLL) to track the grid and maintain synchronization with the connected AC grid, exhibiting characteristics of a current source [5]. Under weak grid conditions, since the system as a whole behaves as a current source in series with a large impedance, when the grid is subjected to large disturbances, the grid voltage amplitude drops, and the PLL will fail to track the grid voltage with an excessively small amplitude, causing instability



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and resulting in poor transient stability [6–8]. Another control architecture for VSCs is grid-forming (GFM) control, which actively controls its own output power to synchronize with the grid through a power synchronization loop (PSL), exhibiting characteristics of a voltage source [9]. Under weak grid conditions, the transient stability of GFM-VSC is higher than that of GFL-VSC. However, under strong grid conditions, the system with GFM-VSC integrating into the grid as a whole behaves as two voltage sources in parallel, resulting in poor transient stability [10–12]. Therefore, using GFL-VSC or GFM-VSC alone has its own inherent transient stability problems that are difficult to resolve.

In order to address the inherent limitations of GFL control and GFM control, some papers have proposed a method for switching between GFL control and GFM control. This method automatically switches the control method by identifying the state of the power system [13–16]. However, since the voltage and amplitude controlled by GFL control and GFM control are not equal, there will be a large overcurrent during the control switchover, affecting system stability [17]. To solve this problem, some papers have proposed a hybrid synchronous control method that combines GFL control and GFM control [18–22]. This hybrid synchronous control method integrates the PLL and PSL in the synchronization link through a fixed hybrid synchronization coefficient, blending the respective advantages of GFL control and GFM control. However, since the operating conditions of the power system vary continuously, a fixed hybrid synchronization coefficient cannot adequately accommodate diverse system conditions. For this reason, further research has combined GFL and GFM controls using variable adaptive coefficients, proposing an adaptive control system with grid-following and grid-forming dual characteristics [23–27]. This method integrates GFL and GFM controls using adaptive coefficients in both the synchronization loop and the voltage loop, flexibly changing the characteristics of the control system by adjusting the adaptive coefficients in the synchronization and voltage loops to adapt to complex and diverse power system operating conditions. However, the current adaptive control system with grid-following and grid-forming dual characteristics only proposes qualitative methods for determining the adaptive coefficients and further research has not been conducted on the methods for determining the values of the adaptive coefficients.

To this end, this paper optimizes the values of the adaptive coefficients for the hybrid synchronization loop and the hybrid voltage loop based on Model Predictive Control (MPC). First, a discrete model of the adaptive hybrid control is established to predict the future trend of the phase angle of the voltage at the converter's point of common coupling. Then, with the minimization of the system frequency variation and the voltage tracking error at the converter's PCC as the optimization objectives—and under the constraints of the system frequency and PCC voltage—the optimal values of the adaptive coefficients for the hybrid synchronization loop and the hybrid voltage outer loop are solved to reduce the deviation of the system frequency and PCC voltage. Furthermore, a strategy for system stability enhancement was proposed. Finally, the correctness of the adaptive coefficient optimization method is verified through PSCAD/EMTDC simulations.

2. Materials and Methods

2.1. Control Structure of Adaptive Hybrid Control

In Figure 1, U_g is the infinite bus voltage; ω_0 is the reference value of the grid angular frequency; U_{PCC} is the VSC point of common coupling (PCC) voltage; $U_{PCC,d}$ and $U_{PCC,q}$ are the d- and q-axis components of the PCC voltage; $U_{PCC,d}^*$ and $U_{PCC,q}^*$ are the reference values of the d-axis and q-axis components of the PCC voltage; V_{PCC}^* is the three-phase modulation voltage of the VSC at the PCC; V_d^* and V_q^* are the d- and q-axis components of the voltage modulation wave, respectively; U_{dc} is the DC-side voltage; I_{abc} is the VSC output current; I_d and I_q are the d-axis and q-axis components of the VSC output current,

respectively; I_d^* and I_q^* are the d-axis and q-axis components of the reference value of the VSC output current; L_{line} is the line inductance; L_f and C_f are the filter inductance and filter capacitance of the VSC, respectively; K_{a1} is the adaptive coefficient of the synchronous control loop; K_{a2} is the adaptive coefficient of the voltage outer loop; $G_{PSL}(s)$ and $G_{PLL}(s)$ are the controllers of PSL and PLL; $G_{VFM}(s)$ is the controller for GFM control; $G_{PFL}(s)$ is the active power controller for GFL control; $G_{VFL}(s)$ is the voltage controller for GFL control; P^* and P are the reference and actual values of active power, respectively; U_0 is the reference value of voltage amplitude; and K_{amp} is the amplification coefficient of the active power feedforward link in the GFL control section. Among them, the synchronous control loop is composed of the PSL and PLL; the voltage outer loop is composed of GFM control and GFL control. Furthermore, the proportion of these two control parts within the control loops is adjusted through the adaptive coefficients.

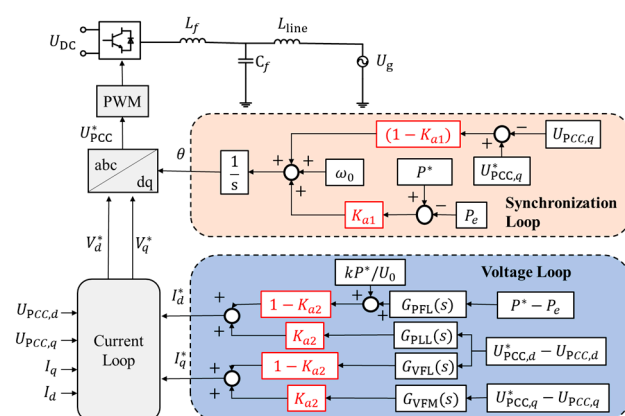


Figure 1. Control Structure of adaptive hybrid control. K_{a1} is the adaptive coefficient of the synchronous control loop; K_{a2} is the adaptive coefficient of the voltage outer loop.

The control equations for the synchronous control loop and the voltage outer loop are represented by Equations (1) and (2).

$$\begin{cases} \theta = \frac{1}{s} [K_{a1} G_{PSL}(s)(P^* - P) - (1 - K_{a1}) G_{PLL}(s) U_{PCC,q} + \omega_0] \\ G_{PSL}(s) = \frac{1}{Js + D} \\ G_{PLL}(s) = K_{PLL} \end{cases} \quad (1)$$

In (1), $G_{PSL}(s)$ employs a virtual synchronous machine control, enabling the VSC to possess inertia and damping characteristics similar to those of a synchronous generator. $G_{PLL}(s)$ opts to use proportional control, where J and D represent the virtual inertia and damping coefficients, respectively; and K_{PLL} is the proportional coefficient of the PLL.

$$\begin{cases} I_d^* = K_{a2} G_{VFM}(s)(U_0 - U_{PCC,d}) + (1 - K_{a2}) [G_{PFL}(s)(P^* - P) + K_{amp} \frac{P^*}{U_0}] \\ I_q^* = -K_{a2} G_{VFM}(s) U_{PCC,q} - (1 - K_{a2}) G_{VFL}(s)(U_0 - U_{PCC,d}) \\ G_{VFM}(s) = \frac{1}{sL_v + R_v} \\ G_{VFL}(s) = K_v \\ G_{PFL}(s) = \frac{1}{sL_p + R_p} \end{cases} \quad (2)$$

In (2), $G_{VFM}(s)$ and $G_{PFL}(s)$ use virtual impedance control, while $G_{VFL}(s)$ uses proportional control. L_v and R_v are the virtual inductance and resistance of the controller in GFM control, respectively; L_p and R_p are the virtual inductance and resistance of the controller in GFL control, respectively; and K_v is the proportional coefficient of the controller in GFL control.

The hybrid synchronous control equation can be rewritten in the form of a rotor motion equation, as shown in:

$$\dot{\omega}' = -\frac{D}{J}\omega' + \frac{1}{J}K_{a1}(P^* - P_e) - \frac{(Js + D)}{J}(1 - K_{a1})K_{PLL}U_{PCC,q} \quad (3)$$

where $\omega' = \omega - \omega_0$, which is the system angular frequency deviation (the actual value of the system angular frequency minus the reference value of the system angular frequency), represents the derivative of the system angular frequency deviation.

2.2. Predictive Model of Adaptive Hybrid Control

Model Predictive Control (MPC) is an advanced control strategy widely used in industrial control. Its basic idea is to utilize the current system state and constraints to predict the future states and input variables over a period of time through the MPC optimization method, solve for a series of optimal control inputs, and apply the first element of the sequence to the system. Figure 2. shows a schematic diagram of the MPC optimization method. In Figure 2, x represents the system state variable and y represents the controller output.

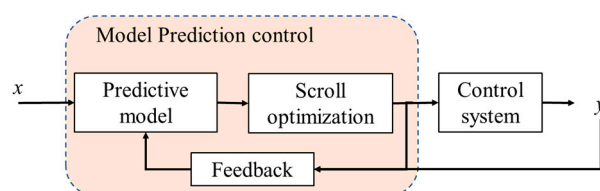


Figure 2. Schematic diagram of MPC optimization method.

When load switching occurs in the power grid, the system frequency will fluctuate. From the analysis in the literature [23], it is known that when the hybrid synchronization loop adaptive coefficient changes, the VSC active power reference value will change, and the system frequency will also fluctuate. Therefore, x is set as the disturbance input, and y is set as the control input. Consequently, the rotor motion equation in (3) can be required to be transformed into a discrete model.

First, regard $K_{a1}(P^* - P_e)$ and $K_{PLL}(1 - K_{a1})U_{PCC,q}$ as control variables and solve the rotor motion equation:

$$e^{-\frac{D}{J}t} \frac{d\omega'}{dt} + e^{-\frac{D}{J}t} \frac{D}{J} \omega' = \frac{e^{-\frac{D}{J}t}}{J} K_{a1}(P^* - P_e) - e^{-\frac{D}{J}t} \frac{(Js + D)}{J} (1 - K_{a1}) K_{PLL} U_{PCC,q} \quad (4)$$

Integrate both sides with respect to (4):

$$\int_{t_0}^t \frac{de^{-\frac{D}{J}t}}{dt} \omega' dt = \int_{t_0}^t \left(\frac{e^{-\frac{D}{J}t}}{J} K_{a1}(P^* - P_e) - e^{-\frac{D}{J}t} \frac{(Js + D)}{J} (1 - K_{a1}) K_{PLL} U_{PCC,q} \right) dt \quad (5)$$

$$\omega'(t) = e^{-\frac{D}{J}(t-t_0)} \omega'(t_0) + e^{-\frac{D}{J}t} \int_{t_0}^t \left(\frac{e^{-\frac{D}{J}\tau}}{J} K_{a1}(P^* - P_e) - e^{-\frac{D}{J}\tau} \frac{(Js + D)}{J} (1 - K_{a1}) K_{PLL} U_{PCC,q} \right) d\tau \quad (6)$$

T_s is defined as the sampling time of the simulation system, $T_s = (t - t_0)$. This paper chooses $T_s = 0.001$ s. Use a zero-order holder for the control variables. Therefore, the control variables are constant in a period of sampling time.

The discrete model is shown below:

$$\omega'(k+1) = A\omega'(k) + B_V K_{a1}(k)(P^* - P_e(k)) + B_d K_{PLL}(1 - K_{a1}(k))U_{PCC,q}(k) \quad (7)$$

$$\left\{ \begin{array}{l} A = e^{-\frac{D}{J}T_s} \\ B_V = \int_{t_0}^t e^{-\frac{D}{J}(t-\tau)} d\tau = \frac{1}{D}(1 - e^{-\frac{D}{J}T_s}) \\ B_d = \int_{t_0}^t e^{-\frac{D}{J}(t-\tau)} \frac{(Js + D)}{J} d\tau = -\frac{1}{D}(1 - e^{-\frac{D}{J}T_s}) \end{array} \right. \quad (8)$$

The discrete model of the motion equation is further transformed into an incremental model, as shown below:

$$\Delta\omega'(k+1) = A\Delta\omega'(k) + B_V(P^* - P_e(k))\Delta K_{a1}(k) - B_V K_{a1}(k-1)\Delta P_e(k) + B_d K_{PLL}[\Delta K_{a1}(k)U_{PCC,q}(k) + (1 - K_{a1}(k-1))\Delta U_{PCC,q}(k)] \quad (9)$$

where $\Delta\omega'$ is the system angular frequency increment. The first term $A\Delta\omega'(k)$ in the incremental model represents the change in the system angular frequency increment from the previous moment. The second term $B_V(P^* - P_e(k))\Delta K_{a1}(k)$ represents the direct influence of the incremental change $\Delta K_{a1}(k)$ of the hybrid synchronization loop adaptive coefficient on the system angular frequency. The third term— $B_V K_{a1}(k-1)\Delta P_e(k)$ represents the indirect influence of the load power change $\Delta P_e(k)$ on the system angular frequency through the current adaptive coefficient $K_{a1}(k-1)$. The term— $B_d K_{PLL}\Delta K_{a1}(k)U_{PCC,q}$ represents the influence of the incremental change in the hybrid synchronization loop adaptive coefficient on the disturbance of the VSC PCC q-axis voltage, and $B_d K_{PLL}(1 - K_{a1}(k-1))\Delta U_{PCC,q}(k)$ represents the direct influence of the VSC PCC q-axis voltage increment $\Delta U_{PCC,q}(k)$ on the system angular frequency.

With the incremental model in (6), the prediction equation $Y_p = [y(k+1) \ y(k+2) \ \dots \ y(k+p)]^T$ for the system angular frequency can be obtained, as follows:

$$\begin{aligned} Y_p(k+1|k) &= [\Delta\omega'(k+1|k) \ \Delta\omega'(k+2|k) \ \dots \ \Delta\omega'(k+p|k)] \\ &= S_\omega \Delta\omega'(k) + S_V \Delta K_{a1}(k) + S_d \Delta P_e(k) + S_q \Delta U_{PCC,q}(k) \end{aligned} \quad (10)$$

To reduce the computational scale of the MPC optimization method while maintaining the optimization effectiveness, the prediction horizon p in this section is chosen to be 3. For $p = 3$, the expressions for the coefficient matrices of the prediction equation are represented by (11):

$$\left\{ \begin{array}{l} S_\omega = \begin{bmatrix} A & \sum_{i=1}^2 A^i & \sum_{i=1}^3 A^i \end{bmatrix}^T \\ S_V = \begin{bmatrix} B_V & 0 & 0 \\ AB_V & B_V & 0 \\ \sum_{i=1}^2 A^i B_V & AB_V & B_V \end{bmatrix} \\ S_d = \begin{bmatrix} B_d & 0 & 0 \\ AB_d & B_d & 0 \\ \sum_{i=1}^2 A^i B_d & AB_d & B_d \end{bmatrix} \\ S_q = \begin{bmatrix} B_d K_{PLL} & 0 & 0 \\ AB_d K_{PLL} & B_d K_{PLL} & 0 \\ \sum_{i=1}^2 A^i B_d K_{PLL} & AB_d K_{PLL} & B_d K_{PLL} \end{bmatrix} \end{array} \right. \quad (11)$$

For the convenience of subsequent analysis, the angular frequency prediction error E_p is defined as follows:

$$E_p(k+1|k) \triangleq -(S_\omega \Delta \omega'(k) - S_d \Delta P_e(k) - S_q \Delta U_{PCC,q}(k)) \quad (12)$$

By substituting the angular frequency prediction error E_p from (12) into (10), the prediction equation for the system angular frequency can be written as follows:

$$Y_p(k+1|k) = -E_p(k+1|k) + S_v \Delta K_{a1}(k) \quad (13)$$

The objective function represents the desired system performance index and can judge the performance quality of the system. A smaller objective function value indicates better performance and a better optimization result. In this paper, the goal is to keep the system frequency stable, so the objective function is designed as:

$$\begin{aligned} J_{obj} &= \|Y_p(k+1|k)\|^2 = \|-E_p(k+1|k) + S_v \Delta K_{a1}(k)\|^2 \\ &= \Delta K_{a1}(k)^T S_v^T S_v \Delta K_{a1}(k) - 2 \Delta K_{a1}(k)^T S_v^T E_p(k+1|k) + E_p(k+1|k)^T E_p(k+1|k) \quad (14) \\ &= \Delta K_{a1}(k)^T H \Delta K_{a1}(k) + G(k+1|k)^T \Delta K_{a1}(k) + E_p(k+1|k)^T E_p(k+1|k) \end{aligned}$$

$$\begin{cases} H = S_v^T S_v \\ G(k+1|k) = -2 S_v^T E_p(k+1|k) \end{cases} \quad (15)$$

When the system performance criteria require not only frequency stability but also minimal fluctuation in the hybrid synchronization loop adaptive coefficient, the objective function can further be set as:

$$\begin{aligned} J_{obj} &= \|Y_p(k+1|k) + \Gamma_v \Delta K_{a1}(k)\|^2 \\ &= \Delta K_{a1}(k)^T (S_v + \Gamma_v)^T (S_v + \Gamma_v) \Delta K_{a1}(k) - 2 \Delta K_{a1}(k)^T (S_v + \Gamma_v)^T E_p(k+1|k) + \\ &\quad E_p(k+1|k)^T E_p(k+1|k) \quad (16) \\ &= \Delta K_{a1}(k)^T H_1 \Delta K_{a1}(k) + G_1(k+1|k)^T \Delta K_{a1}(k) + E_p(k+1|k)^T E_p(k+1|k) \end{aligned}$$

where Γ_v is the weighting coefficient matrix for the hybrid synchronization loop adaptive coefficient, $\Gamma_v = \text{diag}(\beta, \beta, \beta)$, and β is the weighting coefficient for the hybrid synchronization loop adaptive coefficient. This paper chooses $\beta = 0.01$. The weighting coefficient is introduced to adjust the proportion of the sub-objective of the hybrid synchronization loop adaptive coefficient in the overall objective function. When the requirement for small adaptive coefficient fluctuation is higher, a larger weighting coefficient value is chosen. The expressions for H_1 and G_1 in are:

$$\begin{cases} H_1 = (S_v + \Gamma_v)^T (S_v + \Gamma_v) \\ G_1(k+1|k) = -2(S_v + \Gamma_v)^T E_p(k+1|k) \end{cases} \quad (17)$$

When the system performance criteria require that the fluctuations of frequency and VSC PCC voltage not be too large, the objective function can be set as follows:

$$J_{obj} = \|Y_p(k+1|k)\|^2 + \lambda \|Y_u(k+1|k)\|^2 \quad (18)$$

where λ is the weighting coefficient for the VSC PCC voltage, and its value depends on the system's performance requirements for both frequency and PCC voltage; and Y_u is the prediction equation for the system PCC voltage. Since a stable system frequency is beneficial for the stability of the PCC voltage, ensuring system frequency stability is usually

prioritized, followed by voltage stability. Therefore, the weighting coefficient λ for the VSC PCC voltage is chosen as 0.3 in this paper.

The first term of (18) is the frequency sub-objective term, which has been described in (13); the second term is the voltage sub-objective term, whose expression can be expanded in the form of the PCC voltage prediction error and the incremental change in the hybrid voltage loop adaptive coefficient, as follows:

$$Y_u(k+1|k) = -E_u(k+1|k) + S_{v2}\Delta K_{a2}(k+1|k) \quad (19)$$

where S_{v2} is the sensitivity of the hybrid voltage loop K_{a2} to the VSC PCC voltage. Define the VSC PCC voltage prediction error $E_U = -\Delta U_{PCC}$.

In the hybrid voltage loop, the VSC PCC voltage control is divided into d-axis component control and q-axis component control. Therefore, S_{v2} will consist of two components: the d-axis sensitivity and the q-axis sensitivity, i.e., $S_{v2} = [S_{v2,d} \ S_{v2,q}]$. According to [23], the relational expression linking the PCC voltage U_{PCC}^{eq} to K_{a2} under steady-state conditions is listed:

$$\begin{cases} U_{PCC,d}^{eq} = U_0 + \frac{(1-K_{a2})K_{amp}R_v P^*}{K_{a2}U_0} \\ U_{PCC,q}^{eq} = -\frac{(1-K_{a2})K_v R_v (U_0 - U_{PCC,d}^{eq})}{K_{a2}} \end{cases} \quad (20)$$

The d-axis sensitivity is obtained by taking the partial derivative of the d-axis voltage with respect to K_{a2} , and the q-axis sensitivity is obtained by taking the partial derivative of the q-axis voltage with respect to K_{a2} , as shown in (18):

$$\begin{cases} S_{v2,d} = \frac{\partial U_{PCC,d}^{eq}}{\partial K_{a2}} = -\frac{kR_v P^*}{K_{a2}^2 U_0} \\ S_{v2,q} = \frac{\partial U_{PCC,q}^{eq}}{\partial K_{a2}} = \frac{K_v R_v^2 k P^*}{U_0} \left(\frac{2}{K_{a2}^2} - \frac{2}{K_{a2}^3} \right) \end{cases} \quad (21)$$

The objective function can ultimately be expressed as follows:

$$\begin{aligned} J_{obj} &= \|Y_p(k+1|k)\|^2 + \lambda \|Y_u(k+1|k)\|^2 \\ &= \Delta K_{a1}(k)^T S_v^T S_v \Delta K_{a1}(k) - 2\Delta K_{a1}(k)^T S_v^T E_p(k+1|k) + E_p(k+1|k)^T E_p(k+1|k) + \\ &\quad \lambda \Delta K_{a2}(k)^T S_{v2}^T S_{v2} \Delta K_{a2}(k) - 2\lambda \Delta K_{a2}(k)^T S_{v2}^T E_u(k+1|k) + E_u(k+1|k)^T E_u(k+1|k) \\ &= \Delta K_{a1}(k)^T H \Delta K_{a1}(k) + G(k+1|k)^T \Delta K_{a1}(k) + E_p(k+1|k)^T E_p(k+1|k) + \\ &\quad \lambda \Delta K_{a2}(k)^T H_3 \Delta K_{a2}(k) + \lambda G_3(k+1|k)^T \Delta K_{a2}(k) + \lambda E_u(k+1|k)^T E_u(k+1|k) \end{aligned} \quad (22)$$

where the expressions for H_3 and G_3 are:

$$\begin{cases} H_3 = S_{v2} S_{v2}^T \\ G_3(k+1|k) = -2S_{v2}^T E_u(k+1|k) \end{cases} \quad (23)$$

The final objective function reflects the performance requirements for system frequency and PCC voltage (requiring small fluctuations in frequency and PCC voltage). The expression contains two control variables to be optimized: the hybrid synchronization loop adaptive coefficient K_{a1} and the hybrid voltage loop adaptive coefficient K_{a2} . The MPC optimization algorithm predicts the sequence of adaptive coefficient values that minimizes frequency and PCC voltage fluctuations, and the first set of control variables from the sequence is input to the controller, enabling the system to achieve optimal performance indicators at the next time step.

2.3. Constraints of Adaptive Hybrid Control

During actual system operation, the system frequency and system voltage risk exceeding their limits, and VSC controller parameters exceeding a reasonable range can also cause system instability. Therefore, it is necessary to constrain the system frequency, system voltage, and the controller parameters output by the MPC optimization to avoid system instability caused by these electrical quantities or control parameters exceeding limits. The system frequency is constrained by its fluctuation range and rate of change: $\omega_{\min} \leq \omega \leq \omega_{\max}$, $\Delta\omega_{\min} \leq \Delta\omega \leq \Delta\omega_{\max}$. The allowable range for the VSC PCC voltage is restricted to a reasonable operating range: $U_{PCC,\min} \leq U_{PCC} \leq U_{PCC,\max}$. The value range of the adaptive coefficients is derived from the small-signal stability analysis and transient stability analysis of the adaptive hybrid control: $0.1 \leq K_{a1} \leq 1.0$, $K_{a2,\min} \leq K_{a2} \leq 1.0$. The resulting MPC optimization problem for the adaptive hybrid control is:

$$\begin{cases} \min_{\Delta K_a} J_{\text{obj}} = \|Y_p(k+1|k)\|^2 + \lambda \|Y_u(k+1|k)\|^2 \\ \Delta\omega'(k+1) = A\Delta\omega'(k) + B_v(P^* - P_e(k))\Delta K_{a1}(k) - B_v K_{a1}(k-1)\Delta P_e(k) - \\ B_d K_{\text{PLL}} \Delta K_{a1}(k) U_{PCC,q}(k) + (1 - K_{a1}(k-1)) B_d K_{\text{PLL}} \Delta U_{PCC,q}(k) \\ \text{s.t.} \begin{cases} \omega'_{\min}(k+i) \leq \omega'(k+i) \leq \omega'_{\max}(k+i) \\ \Delta\omega'_{\min}(k+i) \leq \Delta\omega'(k+i) \leq \Delta\omega'_{\max}(k+i) \\ 0.1 \leq K_{a1} \leq 1.0 \\ K_{a2,\min} \leq K_{a2} \leq 1.0 \end{cases} \end{cases} \quad (24)$$

where $\Delta K_a = [\Delta K_{a1} \ \Delta K_{a2}]^T$. By solving the optimization problem in (24), the values of the hybrid synchronization loop adaptive coefficient K_{a1} and the hybrid voltage loop adaptive coefficient K_{a2} after MPC optimization can be obtained.

With (17), (23) and (24), the value of ΔK_{a1} and ΔK_{a2} satisfied:

$$\begin{cases} \Delta K_{a1}(k) = -H_1^{-1} G_1 \\ \Delta K_{a2}(k) = -H_3^{-1} G_3 \end{cases} \quad (25)$$

The specific process of MPC optimizing the adaptive coefficients is shown in Figure 3.

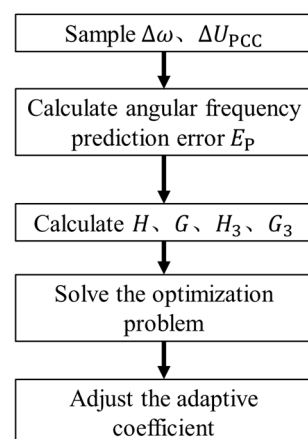


Figure 3. Specific process of MPC optimizing adaptive coefficients.

3. Simulation Verification

To verify the effectiveness of MPC in optimizing the adaptive coefficients in adaptive hybrid control, we built the circuit shown in Figure 1 in the PSCAD/EMTDC simulation software (version 4.6.2). The system main circuit parameters are shown in Table 1.

Table 1. System main circuit parameters.

Symbol	Parameter	Value
f_N	Frequency Reference Value	50 Hz
U_N	Line Voltage reference Value	35 kV
S_N	Power Reference Value	5 MVA
L_f	Filter Inductor Value	77.986 mH
C_f	Filter Capacitor	0.467 μ F
T_s	Sampling Time	1 ms
J	Virtual Inertia	0.00333
D	Damping Coefficient	0.333
K_{PLL}	Proportional Coefficient of the PLL	2
K_{amd}	Magnification factor	20
L_v	Virtual inductance of GFM	0.0015
R_v	Virtual resistance of GFM	0.002
L_p	Virtual inductance of PFL	2.5
R_p	Virtual resistance of PFL	1
K_v	The coefficient of GFL controller	0.5

The VSC adopts adaptive hybrid control, and the adaptive coefficients in the adaptive hybrid control are optimally determined using MPC. Scenarios of system load mutation and grid voltage sag are set up to observe system frequency, VSC PCC voltage, and other electrical quantities, as well as the fluctuation of the adaptive coefficients, comparing the performance of the adaptive hybrid control system without MPC optimization [23] (method (a)), adaptive LVRT control [24] (method (b)), and adaptive hybrid control system with MPC optimization (method (c)).

3.1. Comparison of System Response Under Load Change Conditions

First, it is verified that the adaptive hybrid control, after MPC optimization, can respond to load changes and system frequency variations. The VSC with MPC-optimized adaptive hybrid control is connected to a 5 MW (VSC rated power) passive load. At $t = 6$ s, a 2 MW active power load is shed, and restored at $t = 8$ s. Figure 4 shows a comparison of the system response with and without MPC optimization. From Figure 4a, the adaptive coefficients of the non-optimized adaptive hybrid control do not change when the load active power changes (both remain at the initial value of 0.9), indicating that it does not respond to changes in system load and frequency. During the load reduction period, the system frequency increases to 50.17 Hz. From Figure 4b,c, when the load active power changes, the hybrid synchronization loop adaptive coefficient K_{a1} changes from the original 0.92 to 0.3. However, the proposed method responds faster compared to method (b) and can regulate frequency more effectively. From the analysis in Section 2.3, it is known that a decrease in K_{a1} can reduce the VSC active power reference value, causing the VSC to reduce its own active power output. Accordingly, the system frequency increases to 50.06 Hz during the load change period, a smaller increase than that observed in the non-optimized adaptive hybrid control. Moreover, the MPC-optimized hybrid voltage loop adaptive coefficient K_{a2} does not change during the load change and system frequency fluctuation period (maintained at the initial value of 0.9), indicating that under active power variation conditions, MPC only optimizes the hybrid synchronization loop adaptive coefficient K_{a1} and does not affect the value of the hybrid voltage loop adaptive coefficient K_{a2} .

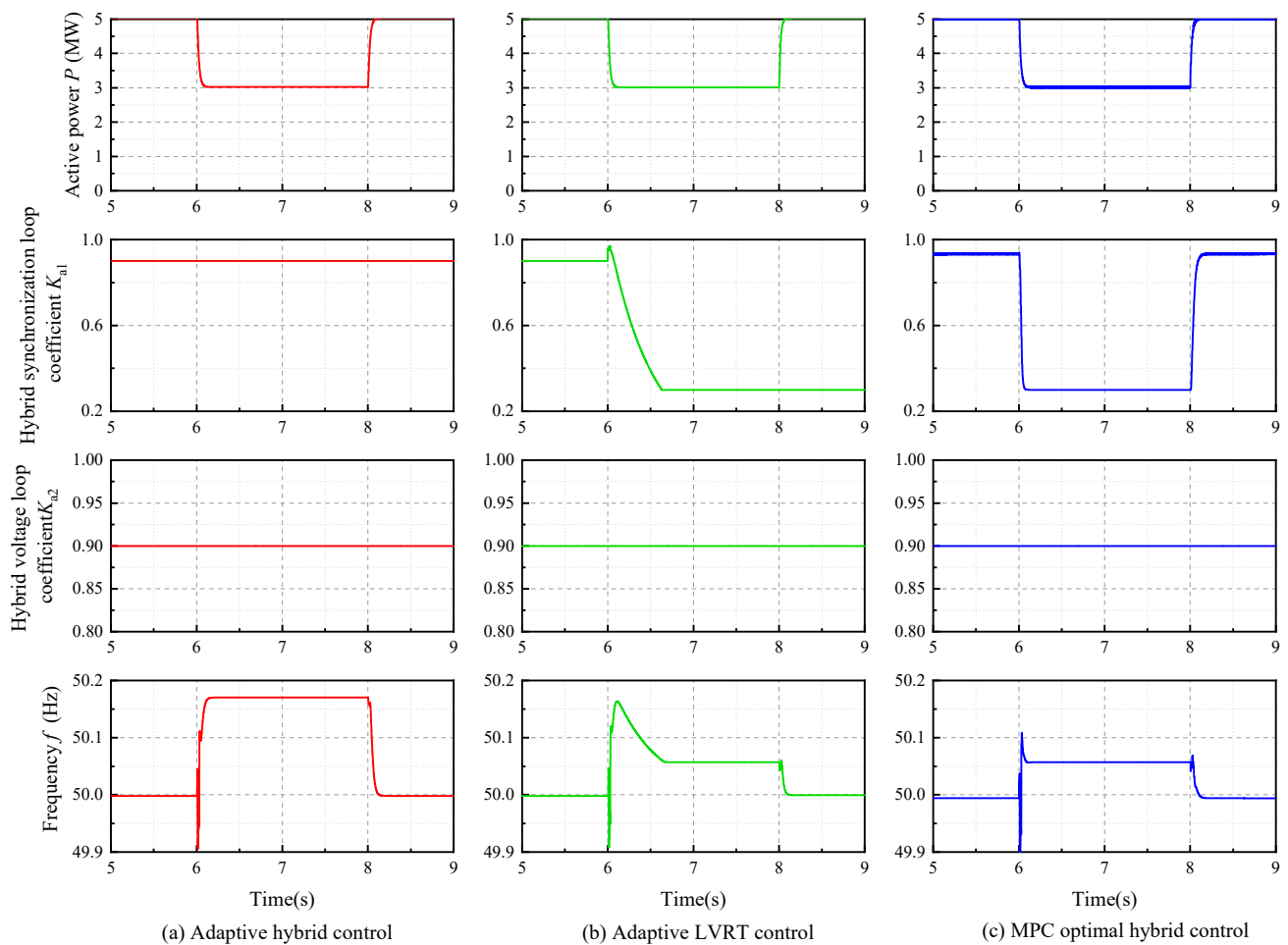


Figure 4. System response under load change conditions. (a) Adaptive hybrid control [23]. (b) Adaptive LVRT control [24]. (c) MPC optimal hybrid control.

3.2. Comparison of System Response Under Voltage Sag Conditions

Next, it is verified that the adaptive hybrid control, after MPC optimization, possesses the capability to stabilize the VSC PCC voltage and reduce voltage fluctuations. The VSC adopting MPC-optimized adaptive hybrid control is connected to an infinite bus. A symmetrical fault is set where the grid voltage sags from 1 p.u. to 0.6 p.u. at $t = 6$ s and recovers to 1 p.u. at $t = 8$ s. Figure 5 shows a comparison of the system response of the adaptive hybrid control with and without MPC optimization under this condition. From Figure 5a, it can be observed that for the non-MPC-optimized adaptive hybrid control, the hybrid synchronization loop adaptive coefficient K_{a1} and the hybrid voltage loop adaptive coefficient K_{a2} do not change during the grid voltage sag condition. This means the adaptive coefficients do not respond to the fluctuation of the VSC PCC voltage. Under this condition, the maximum fluctuation of the VSC PCC voltage reaches 1.057 p.u., and in steady-state, $U_{PCC} = 1.003$ p.u., exhibiting a certain deviation from the set reference value ($U_0 = 1$ p.u.). From Figure 5b, the adaptive LVRT control, by regulating K_{a2} , suppresses voltage oscillations to a certain extent and stabilizes the voltage difference within 0.022 p.u. From Figure 5c, for the MPC-optimized control, the hybrid voltage loop adaptive coefficient K_{a2} responds during the VSC PCC voltage fluctuation period, controlling the VSC PCC voltage near U_0 and reducing the voltage fluctuation amplitude. Under this condition, the maximum fluctuation of the VSC PCC voltage for the MPC-optimized adaptive hybrid control is 1.022 p.u., and the steady-state value is $U_{PCC} = U_0 = 1$ p.u.

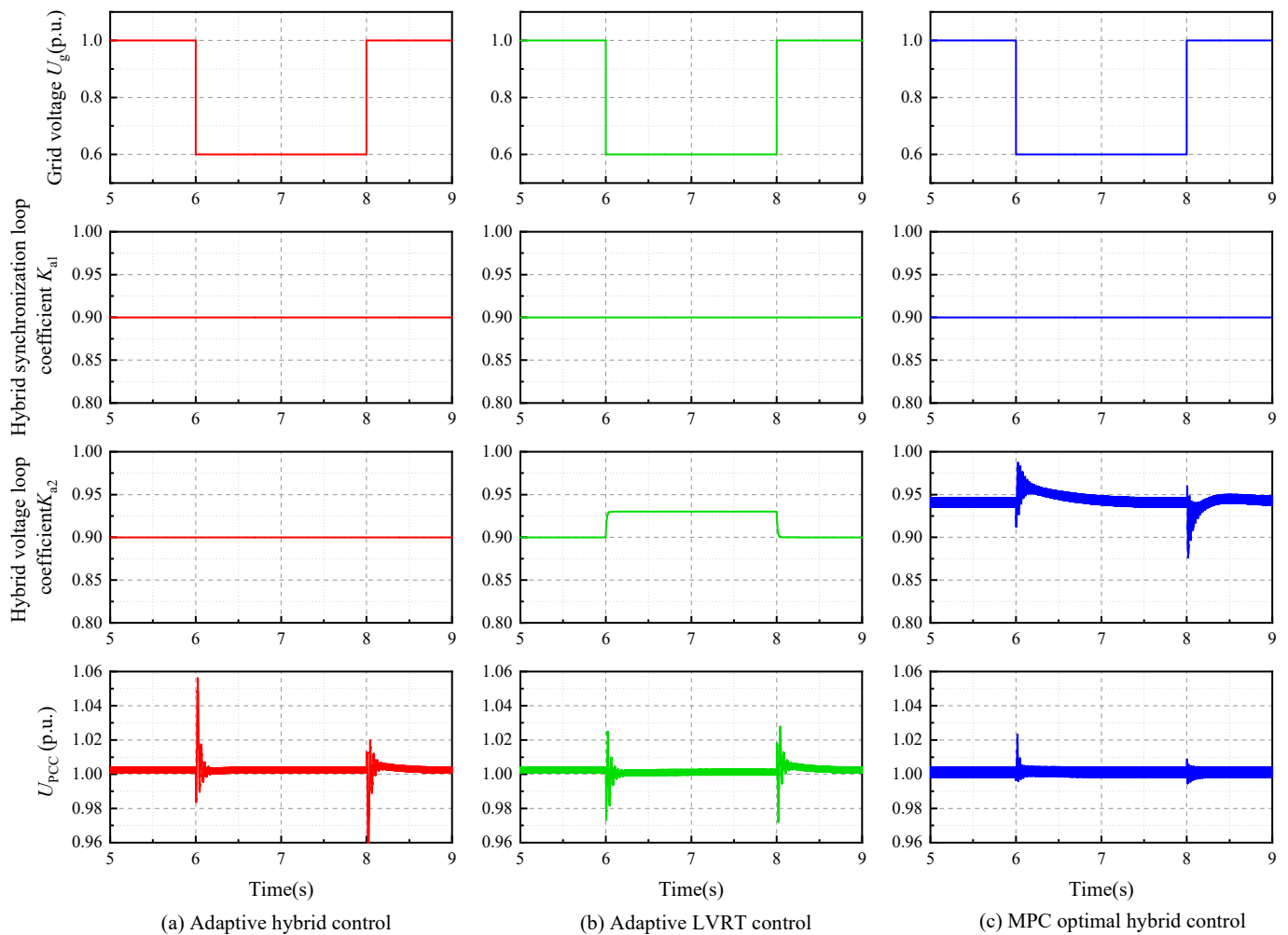


Figure 5. System response under voltage sag conditions. (a) Adaptive hybrid control [23]. (b) Adaptive LVRT control [24]. (c) MPC optimal hybrid control.

3.3. Comparison of System Response Under SCR Change

Then, it is verified that the adaptive hybrid control, after MPC optimization, possesses the capability to adapt grid SCR change. The VSC adopting MPC-optimized adaptive hybrid control is connected to an infinite bus. Set the grid SCR changes from 2 to 10 at $t = 6$ s. Figure 6 shows a comparison of the system response of the adaptive hybrid control with and without MPC optimization under this condition. From Figure 6a, it can be observed that for the non-MPC-optimized adaptive hybrid control, K_{a1} and K_{a2} do not change during the SCR change condition. Under this condition, the system under adaptive hybrid control is unstable. From Figure 6b, although the control of Figure 6b can stabilize the system, its regulation method still results in significant power angle and voltage oscillations. From Figure 6c, for the MPC-optimized control, K_{a1} and K_{a2} respond during the SCR change period, keeping the stability of system.

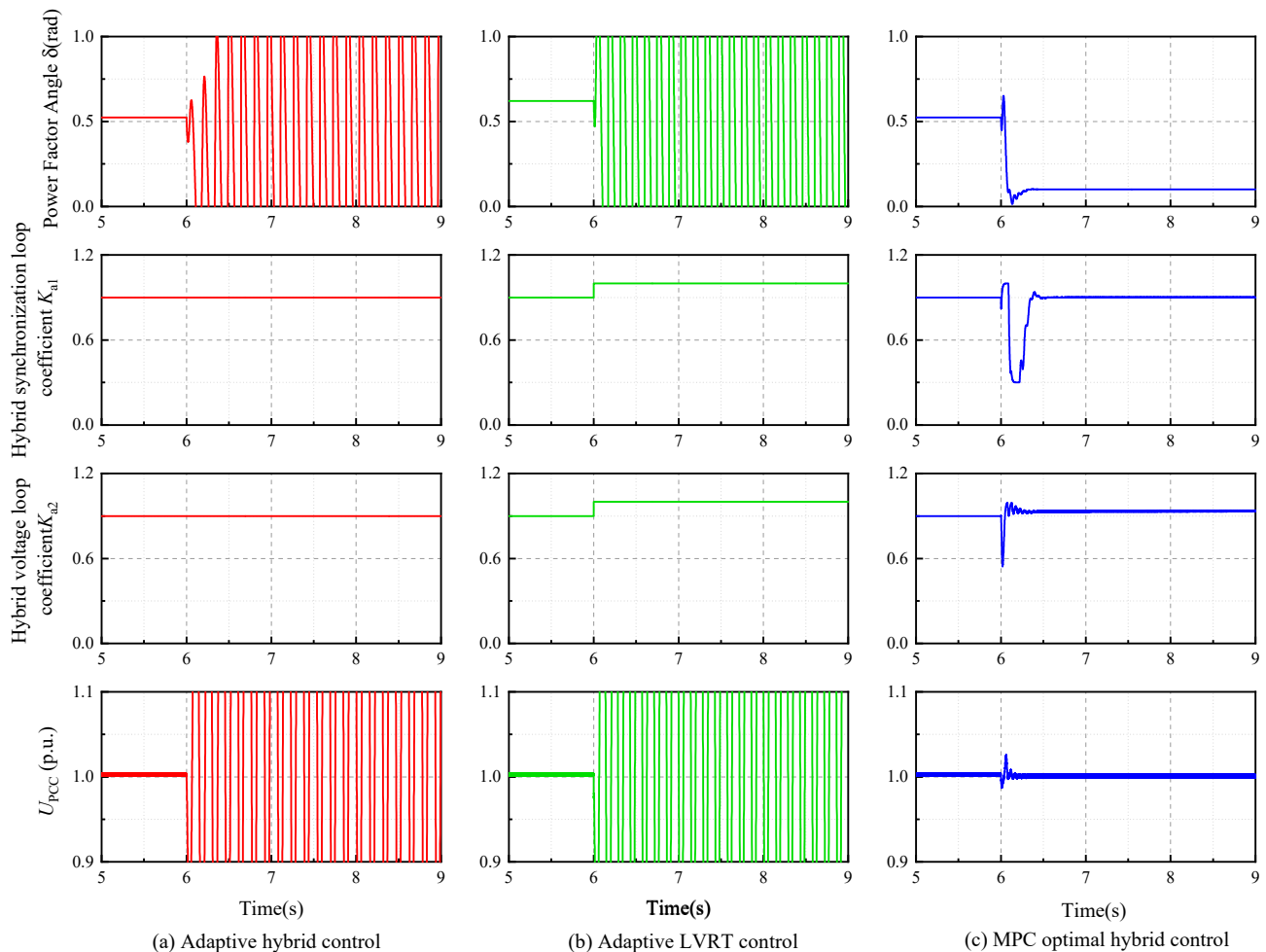


Figure 6. System response under SCR changing from 2 to 10. (a) Adaptive hybrid control [23]. (b) Adaptive LVRT control [24]. (c) MPC optimal hybrid control.

4. Conclusions

To address the issue that the adaptive coefficient determination rule derived in [23] is only applicable to grid voltage sag conditions, this chapter optimizes the adaptive coefficients in the adaptive hybrid control proposed in the literature using MPC. A predictive model for the adaptive hybrid control is established, objective functions are formulated based on the desired system performance indicators, constraints are set considering operational limitations, and the optimization problem is finally obtained. By solving the optimization problem, the optimal values of the adaptive coefficients for the next control step are determined, enabling the adaptive coefficients to respond to changes in system frequency and VSC PCC voltage. Simulation results verify that the adaptive coefficients can be adjusted at each control horizon, reducing system frequency fluctuations and making the PCC voltage track its reference value more accurately, thereby effectively enhancing system performance. Under the operating conditions of large disturbances in the grid impedance, MPC better maintains the stability of the system.

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