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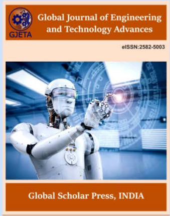

(RESEARCH ARTICLE)

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Research on a hybrid optical storage control strategy based on a DC virtual synchronous generator and MPC

Xiaoge Chen *

School of Electric Power Engineering, Nanjing Institute of Technology, Nanjing, Jiangsu, China.

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Abstract

There are many problems in optical storage systems, including fault ride-through and disturbance, inadequate DC bus voltage support, and high state variable overshoot. The main problem is caused by the slow dynamic reaction speed of the energy storage system based on traditional PI control to the DC voltage of the optical storage system. A hybrid optical storage system control optimization strategy based on a DC virtual synchronous machines and improved model predictive control (MPC) was proposed in the paper as a solution to the aforementioned issues. A strategy based on DC virtual synchronous generator can improve the damping braces and overshoot suppression of DC voltage fluctuation during the disruption process of the energy storage system in the optical storage system. The dynamic response speed of energy storage in optical storage systems may be further increased based on the improved MPC. The effectiveness and validity of the control strategy proposed in the paper were verified by the simulation examples.

Keywords: Optical storage system; DC virtual synchronous machine; Improved model predictive control; Hybrid energy storage; Fault ride-through

1. Introduction

The vigorous development of wind power, PV, and other new energy sources is an important way to establish a new power system and promote the realization of the "carbon peak and carbon neutralization" development goal[1], However, the large-scale access of wind power and PV to the inverter interface emphasizes the power electronic characteristics of the power system, lowers the equivalent inertia of the system, and deteriorates the dynamic response to frequency [2-4], Therefore, the successful realization of low voltage ride-through in a short period of time has become an essential criterion to measure grid connection [5], In recent years, grid-connected inverters represented by virtual synchronous generators (VSG) have garnered more attention [6-8], Grid-connected inverters can offer the necessary inertia and damping bracing for the system to alleviate the stability concerns caused by traditional grid-connected inverters by configuring energy storage or power standby.

There are several studies on PV grid-connected inverters. According to the literature [9], the inverter takes current instructions and adjusts them via the PR controller, and then uses the PI controller to adjust the phase between the grid-side voltage and the inverter voltage during the voltage sag. It is difficult to achieve, and the recovery process is slow. According to reference [10], VSG's transient power angle stability during the fault period was improved by adjusting the phase deviation between the VSG output voltage and the grid voltage during active command suppression faults. According to reference[11], grid voltage feedforward and active command regulation mode were adopted to prevent the VSG overcurrent phenomenon in the event of grid failure. According to Reference[12], proposes two current-limiting methods, fast current-limiting control and virtual impedance current-limiting control, which are used for near-end faults with severe fault degrees and far-end faults with mild fault degrees, respectively. According to reference [13], in

* Corresponding author: Xiaoge Chen

the VSG active control loop, dynamic power angle adjustment is introduced to balance the imbalanced torque in case of grid failure, and virtual impedance is introduced to suppress transient impulse current. The above research results provide a suitable solution for VSG low voltage ride-through; however, the output characteristics and reactive power support capabilities of VSG during grid voltage faults are rarely discussed.

In the study, a control optimization method for a hybrid optical storage control system based on DC virtual synchronous generator and enhanced MPC was developed to address the problems of the insufficient dynamic response of energy storage systems to DC voltage braces in optical storage systems. A strategy based on a DC virtual synchronous generator can improve the damping braces and overshoot suppression of DC voltage fluctuation during the disturbance process of the energy storage system in the optical storage system. The dynamic response speed of energy storage in optical storage systems may be further enhanced based on the improved MPC.

The following content is a general summary: The study's first part introduces the frequency modulation control strategy of hybrid energy storage based on the virtual DC motor. The second part provides a detailed introduction to the bidirectional DC-DC hybrid energy storage control based on improved MPC. The study's third part introduces the simulation example, which verifies the effectiveness and correctness of the control strategy.

2. Frequency Modulation Control Strategy of a Hybrid Energy Storage Based on Virtual DC Motor

The buck-boost circuit is often used in the DC-DC energy storage converter to achieve bidirectional power flow. Figure 1 shows the control block diagram of a DC-DC converter based on DC virtual synchronous motor. The outer loop adopts constant DC voltage control. The inner loop adopts virtual DC motor control. The armature circuit equation of the DC motor is as follows:

$$U = E_a - i_a R_a - L_a \frac{di_a}{dt} \quad (1)$$

Where, $E_a=C_T\varphi\omega$, C_T is the torque coefficient, φ is the magnetic flux, and ω is the actual mechanical angular velocity of the DC motor. The physical meaning of the equation is to use the electromagnetic relationship of the DC motor to simulate the voltage and current relationship of the DC-DC converter. The mechanical equation of a DC motor corresponds to the following:

$$T_m - T_e = J\frac{d\omega}{dt} + D\left(\omega - \omega_0\right) \quad (2)$$

T_m and T_e correspond to the mechanical torque and electromagnetic torque of the DC motor, respectively; J is the rotational inertia; D is the damping coefficient; ω_0 corresponds to the rated mechanical angular velocity of the DC motor. The equation is analogous to the virtual synchronous machine control on the DC side, which can provide precise control of damping and inertia of DC voltage in the coordinated control of energy storage and PV.

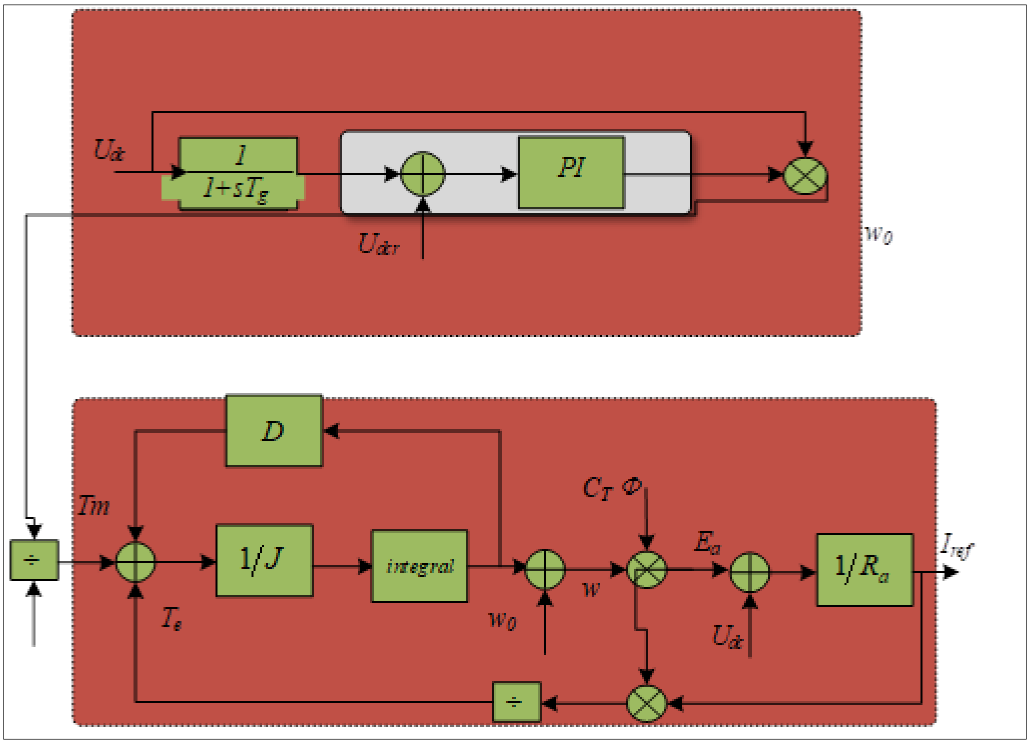

Figure 1 DC-DC inverter control based on virtual DC motor

3. Bidirectional DC-DC Hybrid Energy Storage Control Based on Improved MPC

Taking a typical bidirectional DC-DC converter as an example, the bidirectional DC-DC hybrid energy storage control based on MPC is derived as follows: When T_1 is on, the system charges the energy storage through the freewheeling diode D_1. When T_1 and T_2 are off, the system discharges through the freewheeling diode D_1. When T_2 is on, the energy storage system is disconnected from the external system.

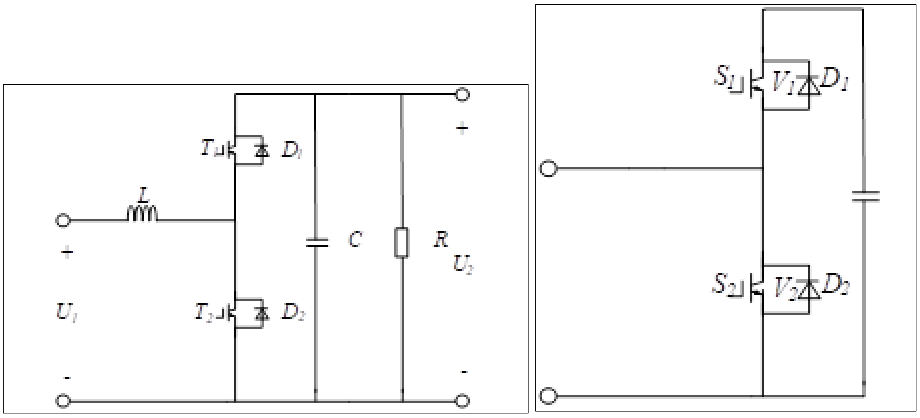

Figure 2 Bidirectional DC-DC hybrid energy storage control converter

When T_1 is on, the state equation of the system is as follows:

$$\begin{cases} \dfrac{di_b}{dt} = -\dfrac{R_b}{L_b} i_b + \dfrac{U_1 - U_2}{L_b} \\ \dfrac{dU_2}{dt} = \dfrac{i_b}{C_b} - \dfrac{U_2}{R_b C_b} \end{cases} \qquad (3)$$

i_b corresponds to the inductor current; L_b and R_b correspond to circuit resistance and inductor parameters, respectively; and C_b corresponds to the energy storage capacitor parameters. When T_2 is on, the state equation of the system is as follows:

$$\begin{cases} \frac{di_b}{dt} = -\frac{R_b}{L_b} i_b + \frac{U_1}{L_b} \\ \frac{dU_2}{dt} = -\frac{U_2}{R_b C_b} \end{cases} \quad (4)$$

The improved MPC algorithm was proposed in the paper as follows: It is important to understand that when using traditional PI control strategies, the function of the current inner loop is to adjust the bias between the input inductance current of the bidirectional DC-DC and the reference value provided by the outer loop for the current loop PI. However, during the PV low-voltage ride-through process, if the energy storage is directly connected in parallel through the DC bus and only PI controllers are used, the voltage stabilization effect of the energy storage on the DC bus is not good, and there are many problems such as slow dynamic response. Therefore, the paper introduces MPC, which, in contrast to traditional PI controllers, can optimize the dynamic response speed by optimizing the predicted value of the inductance current and the objective function to obtain the optimal switch control quantity.

$$i_b(k+1) = \left(1 - \frac{T_s R_b}{L_b}\right) i_b(k) + \frac{T_s\left[U_1(k) - U_2(k) - U_d\right]}{L_b} \quad (5)$$

The prediction model of the current inner loop is obtained through the differentiation of the system state equation. Specifically, when T_1 is off, the difference equation of the system is as follows:

The algorithm adopts the backward Euler algorithm. Similarly, when T_2 is on, the difference equation of the system can be derived as follows, where $d(k)=\{0,1\}$, where 1 represents on and 0 represents off.

$$i_b(k+1) = \left(1 - \frac{T_s R_b}{L_b}\right) i_b(k) + \frac{T_s\left[U_1(k) - U_2(k) - U_d\right]\left(1 - d(k)\right)}{L_b} \quad (6)$$

The control objective function of the MPC current loop in the paper considers both the current deviation and the DC voltage deviation of the outer loop, which can better accelerate the voltage stabilization effect of the outer loop. The corresponding control objective function is as follows:

$$J[k] = \alpha\left[i_b^*(k+1) - i_b(k+1)\right]^2 + \beta\left[\Delta U_{dc}(k)\right]^2 \quad (7)$$

$i^*_b(k+1)$ is the reference value of the current inner loop, α and β are the weight coefficients.

A control diagram of a bidirectional DC-DC hybrid energy storage control strategy based on improved MPC is shown as follows:

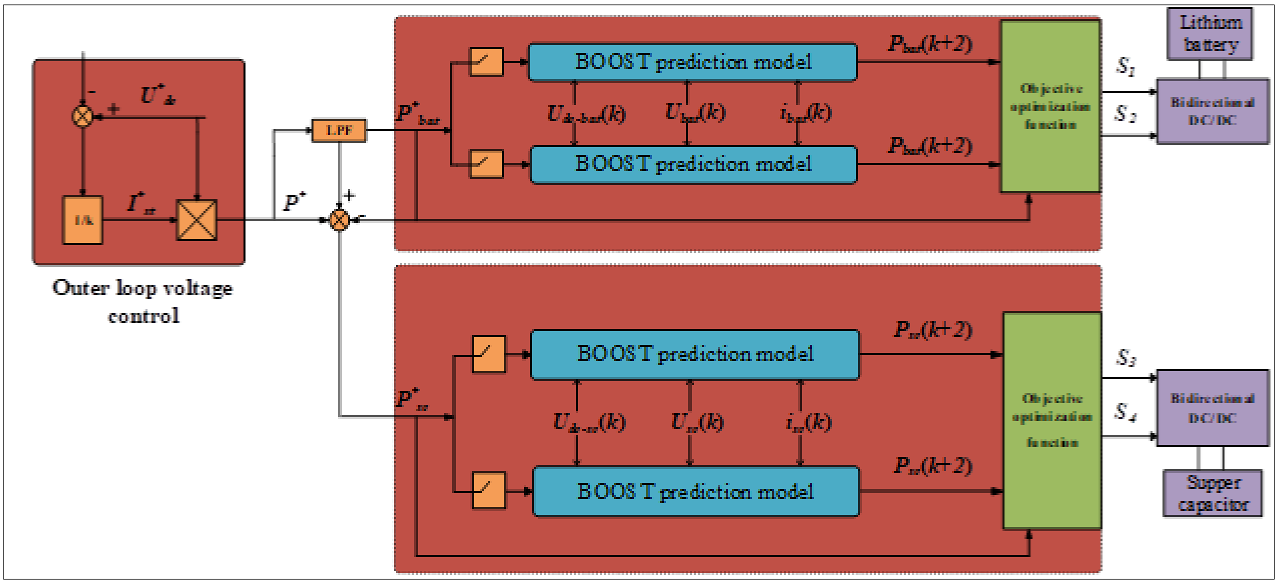

Figure 2 Control block diagram of bidirectional DC-DC hybrid energy storage control strategy based on improved MPC

4. Verification of Simulation Results

A model was developed based on Matlab/Simulink to test the feasibility of the aforementioned control strategy, as shown in Figure 4. The voltage of the PV inverter was increased to 35KV before the grid connection. The voltage dropped at 0.5s and then resumed after 100ms. The inverter does not generate reactive power when the control strategy is not attached. Moreover, during the voltage drop period, the current at the grid-connected point increases sharply, causing the PV system to operate offline. The analysis of the low voltage ride-through characteristics of PV power plants in the event of asymmetric faults in the power grid and a comparison of the system power recovery characteristics after adding energy storage control are shown as follows:

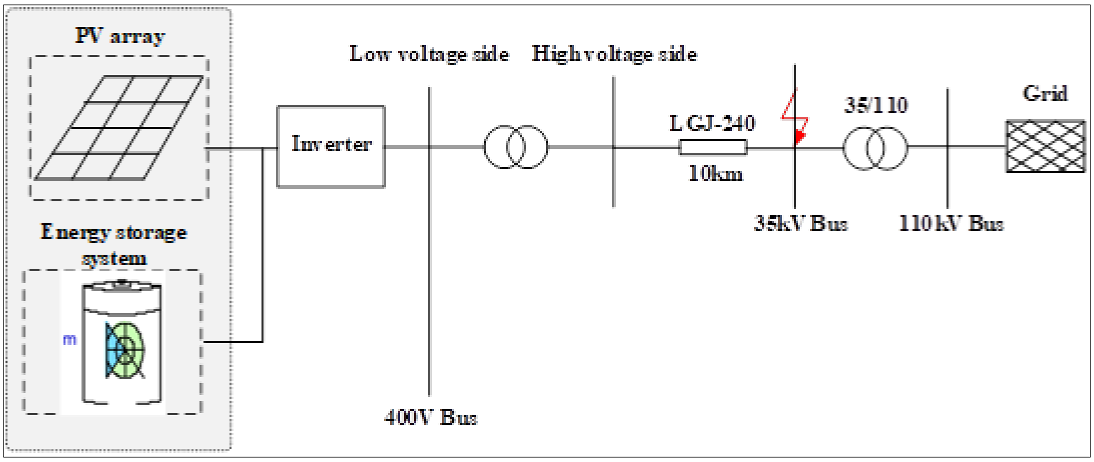

Figure 3 Control block diagram of bidirectional DC-DC hybrid energy storage control strategy based on improved MPC

4.1. Test Verification of Hybrid Energy Storage Virtual DC Motor

The test verification of hybrid energy storage based on a virtual DC motor is shown as follows: Figure 5 depicts the voltage of hybrid energy storage at stable DC under different *J* parameters. The figure shows that the *J* parameter is critical to the rate of change in DC voltage, particularly during the hybrid energy storage start-up process. The following conclusion can be drawn: the smaller the *J* parameter, that is to say, the smaller the inertia, the shorter the time required for the system to initiate and attain steady-state.

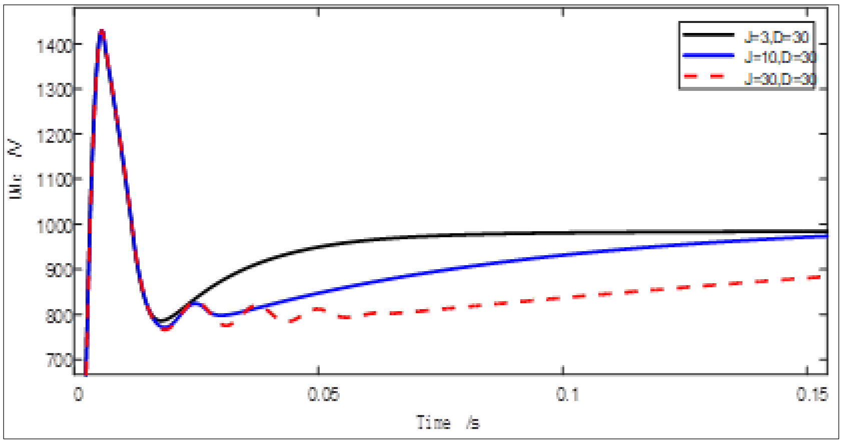

Figure 4 Comparison 1 of the effects of bidirectional DC-DC hybrid energy storage motors

Figure 6 shows the comparative effect of the hybrid energy storage under virtual DC motor control with varied *D* parameters. It can be seen from the figure that the *D* parameter plays a very important role in the voltage stabilization of the system during small disturbances. The larger the *D* parameter, the better the damping effect of the system. However, this will have the drawback of causing excessive overshoot.

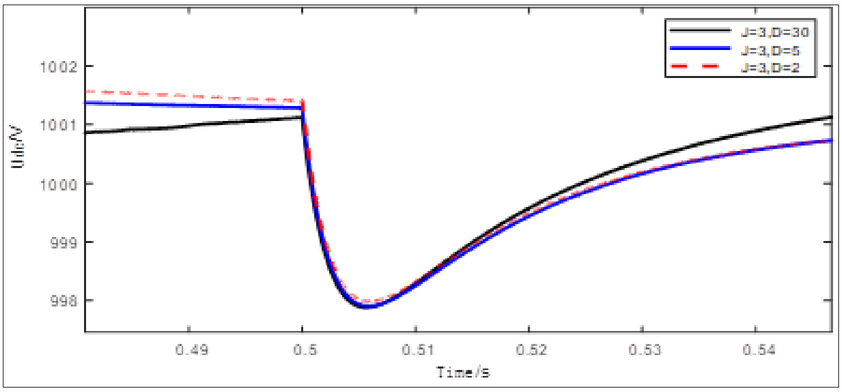

Figure 5 Comparison 2 of the effects of bidirectional DC-DC hybrid energy storage motors

5. Verification of the Effect of Hybrid Energy Storage under PV Low-voltage Ride-through Control

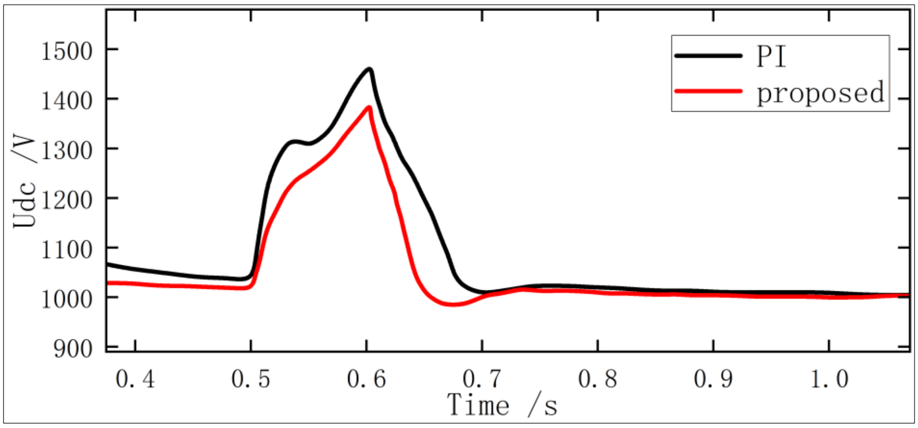

Figure 6 DC voltage comparison results of hybrid energy storage under PV low-voltage ride-through control

Figure 7 shows the comparative effect diagram of hybrid energy storage under the control of the MPC. The figure shows that the control strategy proposed in the paper can stabilize the DC voltage more quickly and achieve the optimization effect of DC-DC for low-voltage ride-through of PV power stations. Figures 8 and 9, respectively, show the comparison results of active power and reactive power during low-voltage ride through. The figure shows that the hybrid energy storage has little impact on the PV itself; hence, faster optimal control is required for a stable DC voltage.

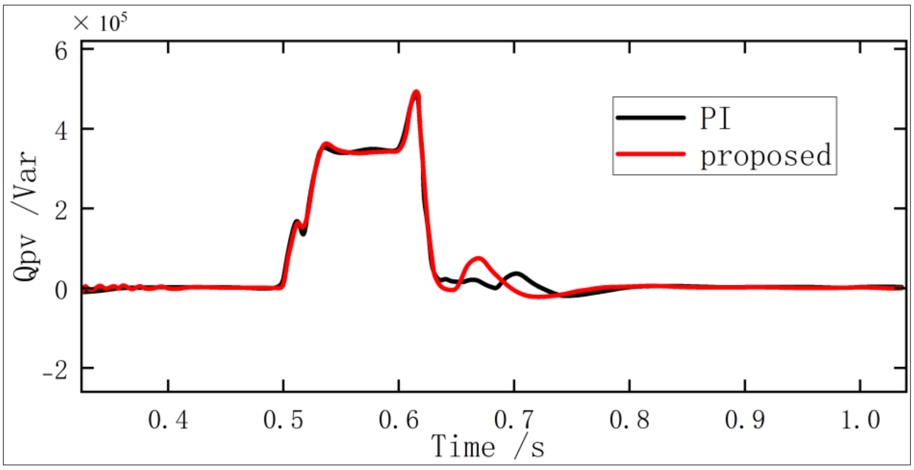

Figure 7 Comparison results of reactive power of hybrid energy storage under PV low-voltage ride-through control

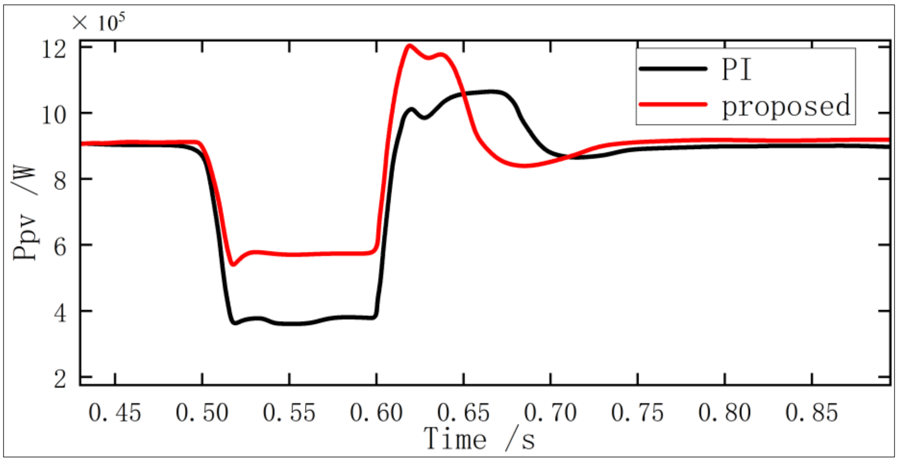

Figure 8 Comparison results of the active power of hybrid energy storage under PV low-voltage ride-through control

6. Conclusion

An optimization strategy for the control of the hybrid optical storage system based on the DC virtual synchronous generator and improved MPC was proposed in the paper to address many issues with the insufficient dynamic response of the energy storage system to the DC voltage support in the optical storage system. A strategy based on a DC virtual synchronous generator can improve the damping braces and overshoot suppression of DC voltage fluctuation during the disturbance process of the energy storage system in the optical storage system. The dynamic response speed of energy storage in optical storage systems may be further enhanced based on the improved MPC. According to the simulation results:

- The optical storage system based on DC virtual synchronous generator control can provide inertia and damping braces for DC voltage.
- The dynamic response speed of energy storage in the optical storage system can be further improved based on the improved MPC.

Compliance with ethical standards

Acknowledgments

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