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Improved Model Predictive Current Control for Three-Level NPC Inverter-Fed Long-Stator LSM Drives

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Abstract

Due to the inability of traditional finite set model predictive control to achieve precise and continuous control, the steady-state current ripple is relatively large, and the control performance is easily affected by operating conditions such as bus voltage utilization.Additionally, for the three-level inverter, there exists a coupling problem between neutral point voltage balancing control and current control within the cost function. To address these challenges, an improved model predictive current control method is proposed. The method is based on the principle of deadbeat control and employs a Bang-Bang Neutral Point Balancing strategy, enabling more precise voltage vector output and eliminating weighting factors. Under the same control frequency, it achieves better current control performance and decoupled control for neutral point potential balance. Simulink simulation results verify the effectiveness of the proposed method.

1 Introduction

The high-speed maglev train, known as the fastest land vehicle, utilizes a long-stator linear synchronous motor for both traction and levitation [1]. Control of the current loop is a critical technology in this system. However, traditional two-level inverter-fed motor drive systems suffer from torque and speed fluctuations due to the significant current harmonics at low speeds, leading to high losses and low efficiency.

To address this issue, multilevel inverters are considered a viable solution. Increasing the inverter's levels improves waveform quality. Therefore, in high-voltage and high-current systems like maglev trains, a three-level inverter is used to improve waveform quality and enhance system safety.

High-speed maglev is a large inertia system.The innermost current loop is a critical technology in this system. Traditional proportional-integral (PI) control based on voltage feed-forward decoupling (VFD) has the advantages of a simple algorithm and easy parameter adjustment. However, its dynamic performance is constrained by the system bandwidth and cannot meet the requirements of high-performance control. Additionally, the use of a three-level inverter introduces an additional control objective of balancing the neutral potential(NPP). For multi-objective control, PI control may be somewhat inadequate.

Model predictive control (MPC) has been successfully applied in industrial applications, due to its high dynamic performance and advantages in multi-objective control[2].In [3],It proposes a cascaded structure finite set predictive control(FSPC), utilizing an optimized voltage vector selection method, reducing computational time, and improving steady-state performance.In [4],An improved cost function is proposed for the three-level inverter-fed permanent magnet synchronous motor, aiming to better balance the current tracking performance and neutral point potential (NPP) control.This method does not require bus capacitor information and exhibits excellent control performance. However, it still requires tuning of weighting factors and cannot achieve fundamental decoupling.

Overall, traditional FSPC cannot output the optimal voltage vector, limiting its control performance [5], [6]. This paper, based on the principle of deadbeat control, enhances the steady-state performance of predictive control. Moreover, this method eliminates the weighting factors in the cost function, achieving decoupling of neutral point potential and current control, resulting in excellent results.

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The organization of this paper is as follows: Section II introduces the mathematical model of the motor and traditional finite set model predictive control. The proposed method is detailed in Section III, and simulations and results are illustrated and discussed in Section IV.

2 Mathematical Model and Principle of MPC Method

2.1 Mathematical Model of LSM

The machine discussed in this article is the Long Stator Linear Synchronous Machine. For analytical purposes, the mathematical model of this motor on the dq-axis is utilized, which can be expressed as follow.

$$\begin{cases} u_d = Ri_d + L_d\dot{i}d - \omega_c L_q i_q \\ u_q = Ri_q + L_q\dot{i}q + \omega_c\left(L_d i_d + \Psi_f\right) \\ \omega_c = \frac{\pi v}{\tau} \\ \Psi_f = Mi_f \end{cases} \tag{1}$$

In the formula 1,L_d, L_q represent The inductance of the stator winding in the dq coordinate system.τ is the pole pitch. M is the excitation inductance, i_f is the excitation current.

u_d and u_q are the control variables, and i_d and i_q are the controlled variables. Using the forward Euler discretization method, Equ.1 is discretized into Equ.2.

$$\begin{cases} i_{d(k+1)} = & i_{d(k)} + \frac{T}{L_d}(u_{d(k)} - Ri_{d(k)} \\ & +\omega_c L_q i_{q(k)}) \\ i_{q(k+1)} = & i_q(k) + \frac{T}{L_q}(u_{q(k)} - Ri_{q(k)} \\ & -\omega_c(L_d i_{d(k)} + \Psi_f)) \end{cases} \tag{2}$$

2.2 Conventional MPCC Method

The basic principle of the conventional FCS-MPC method is shown in Fig.1, which mainly includes three parts: (1)predictive model,(2)delay compensation and (3)cost function minimizing [4]. Referring to 2, the model predictive control method predicts the current change at the next moment through the input voltage.The voltage output of the three-level inverter has 27 basic vectors to choose as shown in Fig.3.

For the part 1, predictive model.The Finite set predictive control algorithm sequentially incorporates

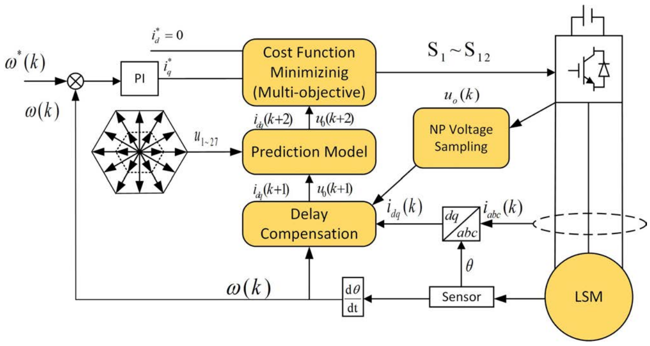

Fig. 1: Control structure diagram of conventional MPC.

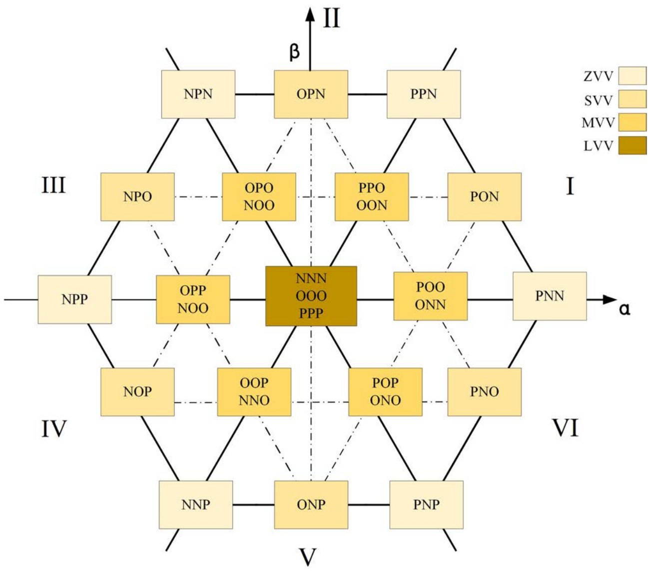

Fig. 2: 27 alternative voltage control vectors for three-level inverter.

27 voltage vectors from the three-level inverter into a well-designed cost function. It selects a voltage vector that minimizes the cost function as the control vector. By outputting this voltage vector, the optimal control effect can be achieved. The prediction of the current is realized through Formula (2).The variation in bus capacitor voltage is related to the neutral point current and can be predicted using the following mathematical model.

$$i_{np} = -i_2 - i_1 = 2C\frac{dV_0}{dt} \tag{3}$$

For the part 2,one step delay between selected voltage vectors and applied voltage vectors exists, because the selected voltage vector at current control period would be applied until next control period, as the Fig.4. Therefore, in order to reduce the negative impact of one step delay on the control performance, delay compensation is very necessary. In the conventional MPC, one-step current prediction is adopted to achieve delay compensa-

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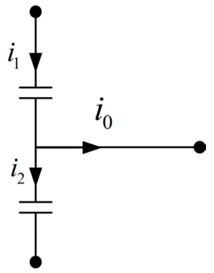

Fig. 3: Equivalent Neutral Point Potential Model.

tion, and the current delay compensation equation is expressed as follows:

$$\begin{cases} i_{d.comp} = & (1-\frac{TR}{L_d})i_{d(k)} + \frac{T}{L_d}(u_{d(k)} \\ & +\omega_c L_q i_{q(k)}) \\ i_{q.comp} = & (1-\frac{TR}{L_q})i_{q(k)} + \frac{T}{L_q}(u_{q(k)} \\ & -\omega_c\left(L_d i_{d(k)} + \Psi_f\right)) \end{cases} \tag{4}$$

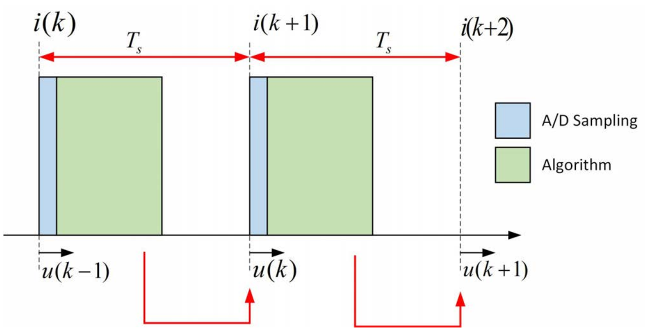

Fig. 4: One step delay of digital controller.

For the part 3,Cost Function. It is crucial to emphasize that, due to the utilization of a three-level three-phase inverter, in the cost function, there exists not only the error in current but also the deviation in the neutral point voltage. With multiple control objectives, coupling issues are introduced, making parameter tuning a challenging task. Overly aggressive parameter settings, while enhancing the balancing capability of the neutral potential balancing, may also adversely affect the control effectiveness of the current

$$g = |i_d^* - i_d(k+2)| + |i_q^* - i_q(k+2)| + k * |u_0(k+2)| \tag{5}$$

In (5), i_d^* and i_q^* is the reference current, u_0 is the deviation in neutral voltage, and k the weight coefficient.

In traditional Model Predictive Control (MPC), a voltage vector is selected from a discrete control set at each control cycle, which minimizes a cost function. However, due to the imprecise and discontinuous features of the output voltages, this can lead to relatively high steady-state fluctuations and significant computational overhead [4]. Additionally, the problem of balancing neutral point potentials also has a bad effect on the performance of traditional predictive current control. This paper proposes a improved predictive control method based on the deadbeat control. The algorithm consists of two main parts: 1) Optimal voltage vector selection. 2) An active balancing strategy using SVPWM modulation.

3 Improved MPC Method

Fig.5 illustrates the overall control diagram of the Proposed MPC. Through this method, decoupling of current control and neutral point potential control can be achieved. By utilizing the self-balancing ability of SVPWM and combining it with external Bang-Bang control to actively control the active time of redundant small vectors, we can achieve balance in the neutral point potential while satisfying current control requirements. This method achieves multi-objective optimization control with reduced computational complexity, enhancing the robustness of bus voltage and control frequency. The cost function can be expressed as follows, without weighting factors.

$$g = |i_d^* - i_d(k+2)| + |i_q^* - i_q(k+2)| \tag{6}$$

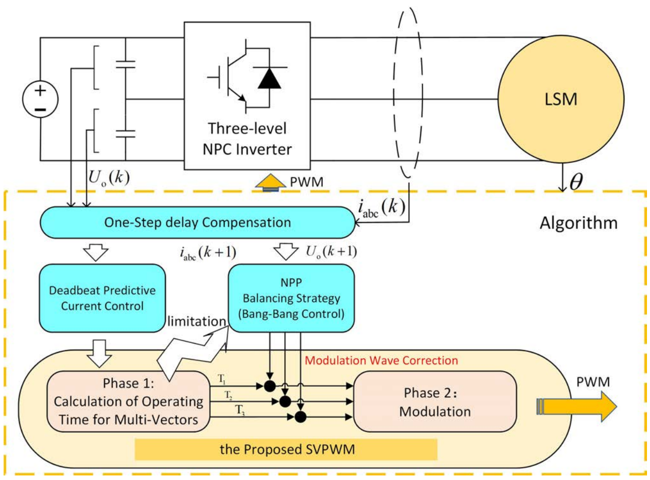

Fig. 5: Control program of the proposed MPC method

3.1 The Deadbeat Current Control

The deadbeat current control method has added a modulation control scheme, which can achieve voltage control vectors with adjustable amplitude and phase through the synthesis of multiple vectors.

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This is beneficial for selecting the optimal control vector under any operating condition. The comparison of its control range with traditional predictive control is shown in Fig.6

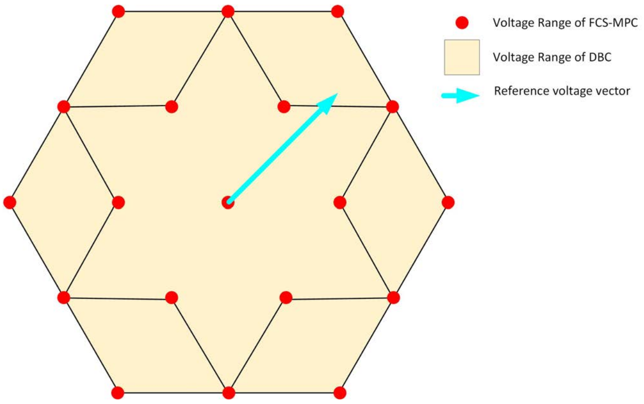

Fig. 6: Comparison between Deadbeat Control and Finite Set Predictive Control

Deadbeat predictive control can achieve ideal voltage vector tracking. The reference voltage vector can be obtained through the voltage-current equations

$$\begin{cases} u_d^{ref} = \frac{L_d}{T} i_{d,ref} - (\frac{L_d}{T} - R) i_{d(k)} \\ \qquad -\omega_c L_q i_{q(k)} \\ u_q^{ref} = \frac{L_q}{T} i_{q,ref} - (\frac{L_q}{T} - R) i_{q(k)} \\ \qquad +\omega_c (L_d i_{d(k)} + \Psi_f) \end{cases} \tag{7}$$

3.2 NPP Balance Strategy

As mentioned above, the balance of neutral point potential(NPP) is related to the neutral point current. Different voltage vectors result in different neutral point currents. It is worth noting the influence of redundant small vectors on the neutral point potential. As shown in the Tab.1 below, the redundant small vectors that have the same control effect on current can have opposite effects on the neutral point current. We can utilize this property to achieve neutral point potential balance.

Tab. 1: The Influence of Redundant Small Vectors on neutral point current

Positive Small Vector	i_o	Negative Small Vector	i_o
POO	$-i_a$	ONN	i_a
PPO	i_c	OON	$-i_c$
OPO	$-i_b$	NON	i_b
OPP	i_a	NOO	$-i_a$
OOP	$-i_c$	NNO	i_c
POP	i_b	ONO	i_b

In order to better utilize the influence of redundant small vectors on the NPP, this study adopts a six-sector approach instead of the traditional four-sector approach,as fig.7. Increasing the number of sectors can further enhance the precision of the output voltage and improve control effectiveness. Additionally, this paper proposes an active NPP balancing strategy, as shown in Fig.8, which introduces an adjustment factor T_0. This factor is used to dynamically correct the modulation wave based on real-time measurements of the three-phase currents and the bus capacitor voltage. With this method, even when there is a significant initial deviation in the neutral point potential, rapid balancing can be achieved without compromising the effectiveness of current control.

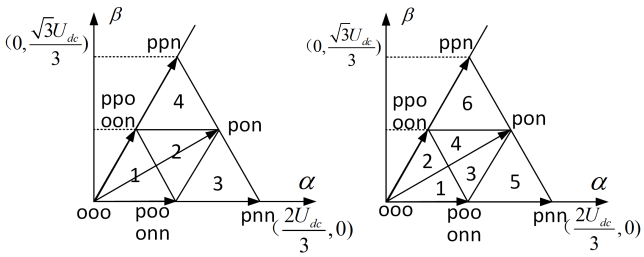

Fig. 7: (a)Four Small Sub-Sectors (b)Six Small Sub-Sectors

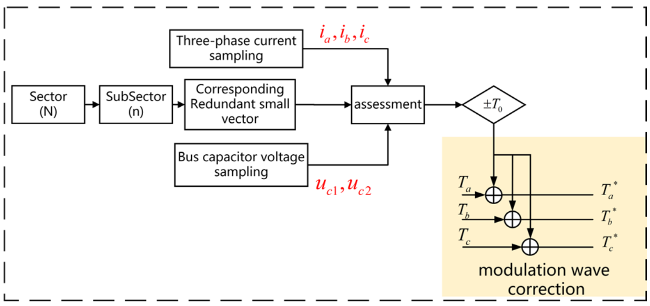

Fig. 8: NPP Balance Strategy

4 Simulation and Result

4.1 Experimental Setup

To validate the effectiveness of the proposed method, experiments were carried out using FCS-MPC and the improved MPC method, respectively. The motor and control parameters are listed in Tab.2. The experiments first analyzed the impact of the weighting factor k in traditional FCS-MPC on the currents and neutral point potential, examining the effect of coupling on multi-objective control. Subsequently, an analysis was conducted on the sensitivity of FCS-MPC to bus voltage utilization.

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Tab. 2: Motor and Control Parameters

DC Voltage U_{dc}	300 V
DC Capacitor C	2250 F
Stator Resistance R	0.0485W
d-axis Inductance L_d	9.5e-3 H
Equivalent Rotor Flux Ψ_f	8.5e-3H
Control Period T_c	100 μs
Adjustment Factor T_0	2μs

Finally, with the same control frequency selected, the proposed improved predictive control method was tested against traditional MPC for comparison. The active balancing strategy of the proposed improved method for the neutral point potential was also verified.

4.2 Experimental Results

4.2.1 Conventional FCS-MPC

As shown in Fig.9, the setting of the weighting factor affects both the fluctuation of the neutral point potential and the quality of the current waveform. If the weighting factor is too large, the amplitude of the neutral point potential fluctuation will decrease, but the total harmonic distortion of the phase current will increase. Conversely, if the weighting factor is too small, the deviation amplitude of the neutral point potential will increase.Therefore, finite set predictive control requires tuning of the weighting factor based on actual operating conditions. In this paper, k=0.08 is selected to achieve a balance among multiple control objectives.

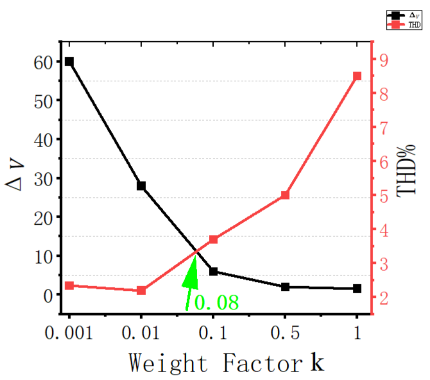

Fig. 9: The Influence of Weighting Factors on Control Effectiveness

4.2.2 The Proposed method

To validate the effectiveness of the proposed improved control strategy, experiments were conducted with id=0,iq varying between 0 and 20A. The current and neutral point potential control performance of the traditional finite set predictive control and the proposed control strategy were compared. As shown in Fig.10, the dynamic performance of both methods is essentially the same. However, in terms of steady-state characteristics, the fluctuation amplitude of the q-axis current for the traditional finite set predictive control is 1A, while the improved model predictive control method reduces it to 0.1A, demonstrating a significant improvement.

In Fig.11, the proposed improved predictive control method achieves a total harmonic distortion of 0.29% in the phase current and a fluctuation amplitude of only 2V in the neutral point potential. Compared to the finite set predictive control in Fig.9, this method not only has significant advantages in current control but also effectively maintains neutral point potential balance. Fig.12 indicates that the proposed predictive control method is less affected by changes in bus voltage utilization, demonstrating good robustness. It achieves better control performance at the same control frequency. Fig.13 shows that the proposed strategy has the ability to actively balance the NPP, eliminating the initial capacitor voltage difference."

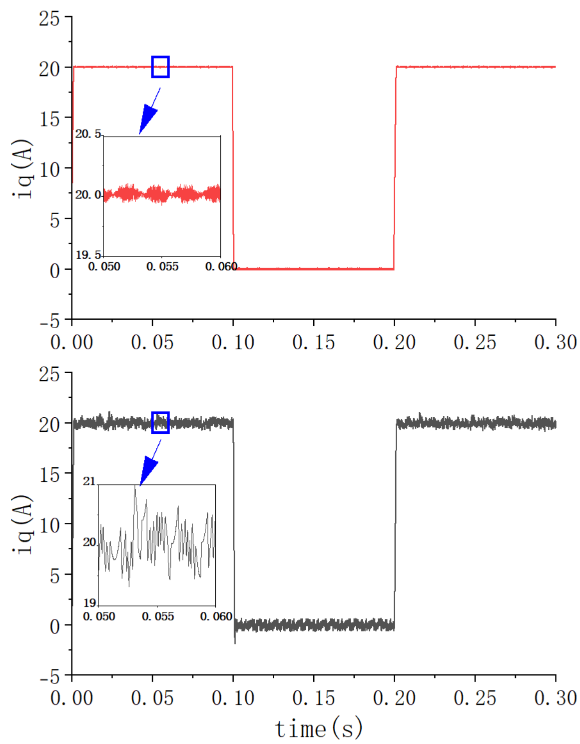

Fig. 10: (a) Convertional FCS-MPC method
(b) Proposed MPC Method

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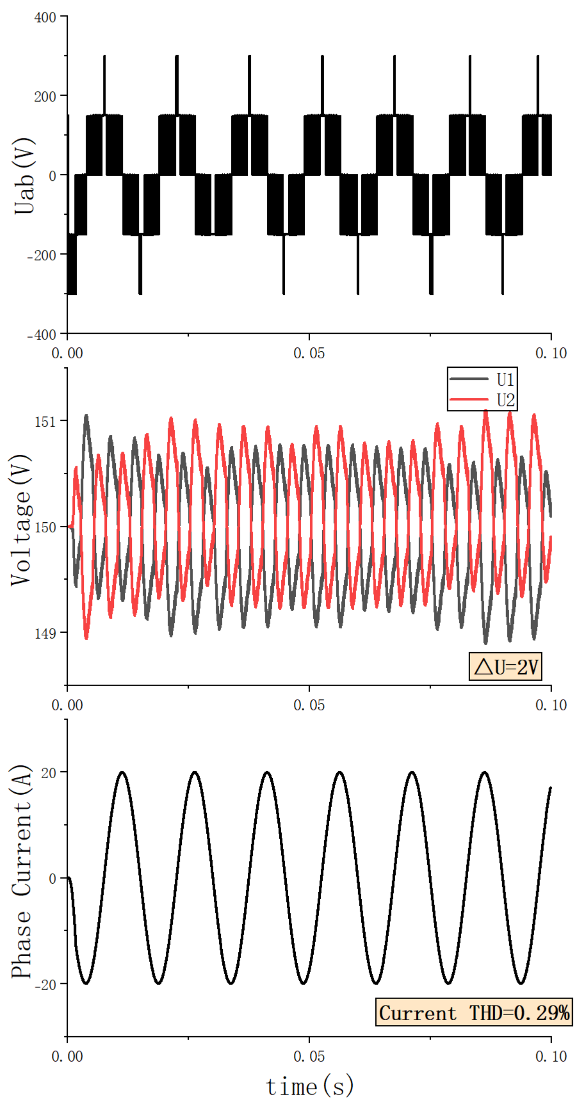

Fig. 11: Steady-State Characteristics of the proposed MPC Method

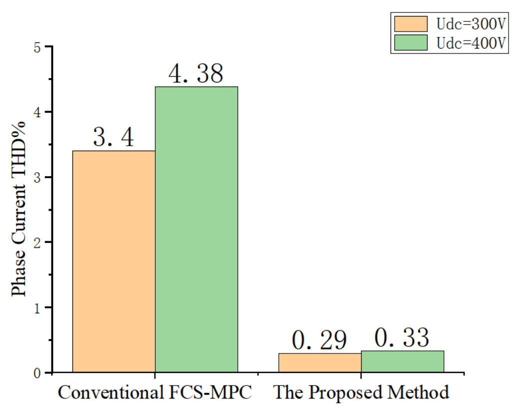

Fig. 12: Comparison of Control Performance Under Different Bus Voltages

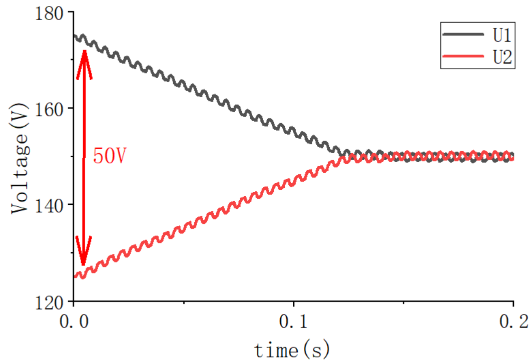

Fig. 13: Active Neutral Point Potential Balancing

5 Conclusion

Traditional finite set predictive control, which uses a discrete control set, is limited by bus voltage utilization and control frequency, resulting in poor current control performance. Moreover, the NPP balancing strategy based on weighting factors is also unable to achieve optimal control for multiple objectives.The proposed improved predictive control strategy achieves optimized current control while eliminating weighting factors, enabling multi-objective optimal control. Simulation experiments have validated the accuracy of the proposed method. The next step will be to validate this method on a real motor platform.

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