2023 5th International Conference on Power and Energy Technology (ICPET) | 979-8-3503-3967-3/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICPET59380.2023.10367520

Total Harmonic Distortion Reduction Method of Improved Finite Control Set Model Predictive Control for Single-Phase Inverter with Twisted Parameter

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***Abstract*—The single-phase inverter is a commonly used DC/AC converter in the industrial field. Due to its fast dynamic performance and the ability to handle multiple constraints, Finite Control Set-Model Predictive Control (FCS-MPC) is capable of effectively tracking the current of single-phase inverters. However, the implementation of FCS-MPC is characterized by high computational demand, time delay, and a requirement for high model accuracy. In order to address these challenges, this study proposes a twisted parameter FCS-MPC method that artificially twists the model parameters. This method aims to reduce Total Harmonic Distortion (THD) as compared to the one-step delay compensation FCS-MPC. By ensuring accurate tracking of the single-phase inverter, this method can effectively save computational time. The study utilizes simulations to uncover the impact of model parameters on the THD of the grid current. It is discovered that reducing the control parameters of inductance can lead to a reduction in THD of the current. The simulation results demonstrate that, within a certain range, reducing the control parameters of inductance can effectively enhance the quality of the grid current without an increase in the number of switch operations. Furthermore, this method outperforms the delay compensation method by offering a lower computational burden, smaller prediction error, and lower switch loss.**

***Keywords*—twisted parameter, total harmonic distortion, Finite control set-model Predictive control, single-phase inverter**

I. Introduction

A. Overview

The control strategy of an inverter has a direct impact on its operation and performance. Given the wide range and intricate nature of inverter applications, researchers have dedicated considerable efforts to exploring and enhancing its control technology in recent years [1-3]. In general, the control objectives for single-phase inverters can be defined as achieving a low level of total harmonic distortion (THD) in the output current, minimal computational complexity, and resilience to interference [4].

Model Predictive Control (MPC) can not only solve the nonlinear problems of the system but also control multiple constraints while ensuring control performance requirements. According to whether there is a modulation unit, MPC can be divided into two categories: Continuous Control Set-MPC (CCS-MPC) and Finite Control Set-MPC (FCS-MPC) [5]. Among them, FCS-MPC can transform the expected output signal of the system into discrete control signals, directly control the switch state of the switch device with this signal, and integrate the target optimization and the switch state decision-making process into one step, the process is simple and clear, and pulse width modulation is not required. These significant advantages make it a hot topic in inverter control research [6-7]. However, in practical applications, FCS-MPC faces challenges such as large computation, easy susceptibility to parameter sensitivity and computation delay [8-9].

B. Related Works and Motivation

Conventional FCS-MPC needs to make n predictions in one control cycle and obtain the optimal switch state by calculating the cost function n times, where n is the total number of valid switch states of the inverter, and the selection process of the optimal vector is complex, resulting in a large computational burden [10]. In [11], the computational burden is reduced by merging control objectives. In [12], an event-triggered model predictive control is proposed, which triggers model predictive control only when the state of the power converter exceeds a preset threshold, with the advantages of a small computational burden and low switch losses. In [13], a space vector balancing predictive current control is proposed, which can reduce the number of switch states to be evaluated.

Digital control has the problem of delay generally, and a high computational burden will inevitably exacerbate the problem of delay. Due to the large amount of computation of the FCS-MPC optimization process, the calculation time is longer than the sampling time. There will be a delay between the moment when the grid current is sampled and the moment when the new switch state is applied, leading to oscillations of the grid current around its reference value and increasing the current ripple. Based on this, a delay compensation method is proposed which can reduce the impact of delay on the prediction of the grid current [14]. In [15], a delay compensation method based on dead-beat control is proposed, which uses two-step prediction to compensate for the delay, but this also increases computation.

This work is supported by the Central Universities under Grant 20720220071 and 20720220084.

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FCS-MPC is a model-based control strategy, and its control performance largely depends on the accuracy of the model parameters. Due to the saturation degree of the magnetic circuit, temperature, and other environmental changes, the actual circuit parameters are dynamic, which will cause parameter mismatch issues. The impact of the load parameters of the inverter FCS-MPC on the prediction effect of the load current, and concludes that the effect of the load inductance on the prediction effect is greater than that of the load resistance [16]. To compensate for system disturbances caused by parameter mismatches, compensation methods based on online parameter identification models using the extended state observer (ESO) [17], recursive least-squares (RLS) [18], and extended Kalman filter (EKF) [19] can be employed to estimate model parameters and reduce prediction errors caused by parameter mismatches. In [20], to solve the problem of model parameter sensitivity, a method combining data-driven and iterative learning is proposed, but a large number of iterations increase the computational burden of the controller.

Previous research on parameter mismatch focused on the situation where the actual value of circuit parameters changed and did not match the nominal value, and then eliminated the negative impact of parameter mismatch on control performance, but inevitably increased the computational burden of the controller and did not consider the input value of circuit parameters in the controller's influence on control performance. This study artificially distorted the input value of circuit parameters in the FCS-MPC controller, under the condition that the actual value of circuit parameters is the same as the nominal value and is known, to explore the law of the influence of control parameters and actual circuit parameter mismatch on control performance.

C. Main Contributions

The main contributions lie in three aspects.

- Comprehensively analyzes and studies the parameter mismatch problem of single-phase bridge inverter FCS-MPC, discovers the regularity and phenomenon of the controller inductor input parameters affecting the current THD that have not been discovered before, and breaks through the limitations of the previous parameter mismatch problem research perspective.
- Proposes a scheme to artificially twist the control parameters, which can replace the delay compensation method and provide new ideas for research to alleviate the computational burden, reduce load current ripple, and improve control performance. It not only does not increase the number of switch actions but can also reduce current ripple.
- Conducts simulation experiments on the artificially adjusted control parameter method under different switch frequencies and current reference values verifies the proposed method, and summarizes the follow-up research branches.

D. Outline

The rest of this article is organized as follows. Section II constructs a model of the single-phase inverter and analyzes the control strategy of conventional FCS-MPC for the single-phase inverter. The reasons for the delay problem in FCS-MPC are presented, and the principle of the delay compensation method is introduced in Section III. Section IV explains the proposed twisted parameter method. Section V verifies the effectiveness of the twisted parameter method through simulation experiments. Finally, Section VI concludes this paper.

II. Modeling

A. System Description

This paper studies single-phase inverters as the control object of FCS-MPC. As shown in Fig. 1, where U_{dc} is the equivalent DC voltage source, L is the filter inductor, R is the line resistance, u_{ab} is the inverter output voltage, i is the grid current, and e represents grid voltage. According to Kirchhoff's law, the grid current can be described as

$$L\frac{di}{dt}+Ri=u_{ab}-e \tag{1}$$

The predictive grid current can be discretized as (2) based on the Euler's method.

$$i_p(k+1)=(1-\frac{RT_s}{L})i(k)+\frac{T_s}{L}(u_{ab}(k)-e(k)) \tag{2}$$

where T_s is control period, $i(k)$, $u_{ab}(k)$, and $e(k)$ are respectively the measured grid current, inverter output voltage, and grid voltage at t_k.

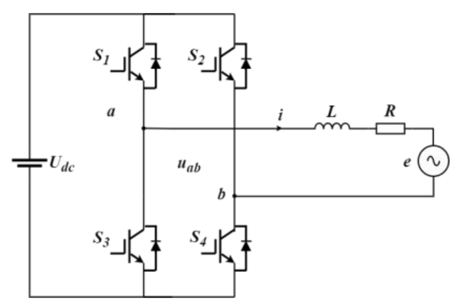


Fig. 1. Single-phase inverter topology

B. Operation Principle of FCS-MPC

The control strategy of conventional FCS-MPC is shown in Fig. 2. The single-phase bridge inverter has four combinations of switch states, each corresponding to a voltage vector u_{ab}. Among them, two switch state combinations correspond to the same vector u_{ab} and combined with (2), three different predicted current values i_p can be obtained.

To achieve accurate tracking of current reference, the cost function can be expressed as

$$g=|i_p(k+1)-i_r(k+1)| \tag{3}$$

where $i_r(k+1)$ is the reference current at t_{k+1}, with the same frequency and phase as the grid voltage.

The control strategy of FCS-MPC involves selecting the switch status corresponding to the voltage vector u_{ab}, which minimizes the cost function through exhaustive enumeration.

This is done to control the next control cycle, enabling the output current to follow the reference current.

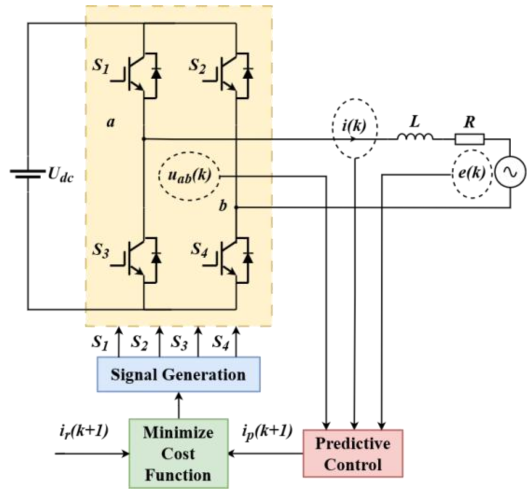
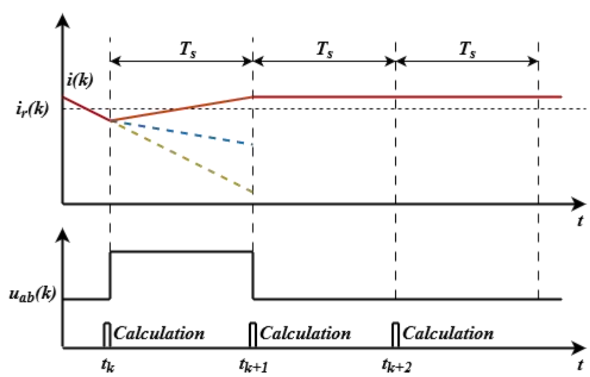


Fig. 2. Control structure of conventional FCS-MPC

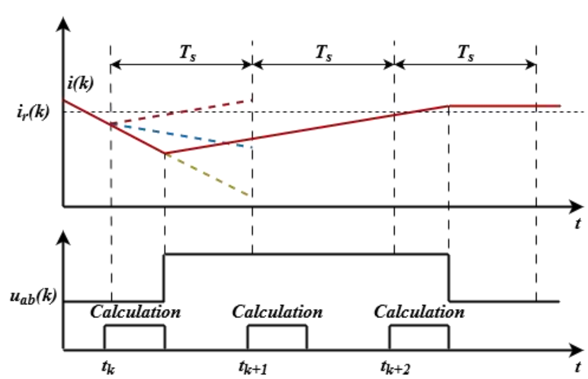
III. Delay Compensation for FCS-MPC

A. Reason for Delay Compensation

Ideally, the controller has zero computation time and there is no delay between the moment of measuring the grid current and applying the new switch state. As shown in Fig. 3(a), the current is measured at t_k, and the cost function corresponding to three voltage vectors is immediately calculated. The switch state that minimizes the cost function is applied at t_{k+1}.



(a) Without delay (ideal case)



(b) With delay (real case)

Fig. 3. Predictive current control operation diagram

However, in practical situations, there is a delay between the moment of measuring the current and applying the new switch state. During this interval, the previous switching state continued to be applied, as shown in Fig. 3(b). This means that the voltage vector selected based on the current measurement at t_k is applied after t_{k+1}, resulting in a deviation of the grid current from the reference value [14].

B. Method of Delay Compensation

To address the problem of low prediction accuracy caused by computation delay, a one-step delay compensation method is adopted on the traditional FCS-MPC, as shown in Fig. 4. The current at t_k and the applied switch state are used to estimate the grid current at t_{k+1}. Based on the estimated grid current at t_{k+1}, the grid current at t_{k+2} is predicted, and the corresponding switch state is applied from t_{k+1} to t_{k+2}.

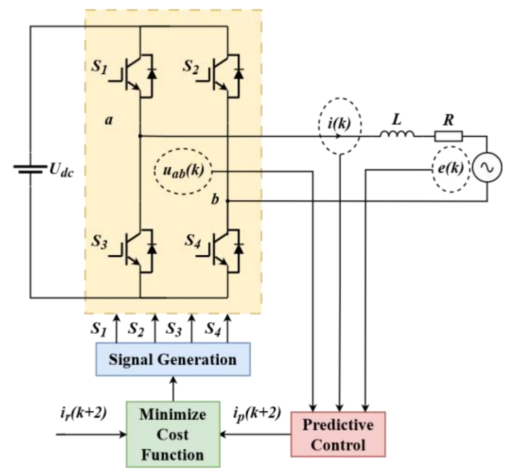


Fig. 4. Control structure of improved FCS-MPC with delay compensation

At t_k, this algorithm estimates the current $\hat{i}(k+1)$ at t_{k+1} as follows:

$$\hat{i}(k+1) = (1-\frac{RT_s}{L})i(k) + \frac{T_s}{L}(u_{ab}(k) - e(k)) \tag{4}$$

The estimated current $\hat{i}(k+1)$ at time t_{k+1} is used as the starting point for predicting the current at t_{k+2}.

$$\begin{aligned} i_p(k+2) = &\left(1-\frac{RT_s}{L}\right)\hat{i}(k+1) \\ &+\frac{T_s}{L}\big(u_{ab}(k+1) - e(k+1)\big) \end{aligned} \tag{5}$$

where $i_p(k+2)$ is the predicted current value at t_{k+2}. The cost function is modified to evaluate the predicted current $i_p(k+2)$ under the influence of the voltage vector $u_{ab}(k+1)$.

$$g = |i_p(k+2) - i_r(k+2)| \tag{6}$$

where $i_r(k+2)$ is the reference current value at t_{k+2}, which has the same frequency as the grid voltage. In the case where the switching frequency is much higher than the grid frequency, it can be assumed that $i_r(k+2) = i_r(k+1)$. The voltage vector $u_{ab}(k+1)$ that minimizes the cost function is selected as the inverter output voltage vector at t_k, and is applied to the next control cycle.

The one-step delay compensation algorithm follows the steps below:

(1) measure the grid current at t_k;

(2) apply the switch status (calculated in the previous cycle);

(3) estimate the current at t_{k+1} based on the applied switch status;

(4) select the switch status that minimizes the cost function;

(5) evaluate the cost function for each predicted switch status;

(6) select the switch status that minimizes the cost function.

To address the delay calculation issue, a one-step delay compensation algorithm is used, in which the predicted current at t_{k+2} is used for the switch switching at t_k. The sampling, calculation, and control are performed step by step, thus solving the problem of a larger current ripple caused by the delay of the optimal voltage vector control relative to the optimization calculation in conventional FCS-MPC. However, the improved FCS-MPC with delay compensation adds a current estimation step, which introduces a new problem of increased computational complexity.

IV. Proposed Twisted Parameter Method

From (5), it is known that during the grid-connected operation of a single-phase inverter, the predicted grid current value i_p is mainly affected by the inductance parameter L and the resistance parameter R. In contrast to previous studies on the robustness of control systems when circuit parameter actual values do not match nominal values, this study focuses on intentionally distorting the input values of circuit parameters in the FCS-MPC controller, causing a mismatch between the control parameters and actual circuit parameter values, and using this parameter mismatch to achieve a positive effect on the predicted current to reduce current THD, instead of using the delay compensation method.

L' and R' the twisted inductance and resistance control parameters respectively, $\Delta L = L' - L$ and $\Delta R = R' - R$ are the amounts of twisted inductance and resistance parameters, $\Delta i_p(k+1) = i_p(k+1) - i_p'(k+1)$ is the current distortion. Assuming there is a delay but no compensation, the twisted inductance and resistance parameters of the FCS-MPC controller are used, and the predicted grid current value is given by:

$$i_p'(k+1) = (1 - \frac{R'T_s}{L'})i(k) + \frac{T_s}{L'}(u_{ab}(k) - e(k)) \quad (7)$$

Subtracting (2) from (7) yields the mathematical expression for the current distortion amount.

$$\Delta i_p(k+1) = \frac{T_s}{LL'}[(\Delta RL - \Delta LR)i(k) + \Delta L(u_{ab}(k) - e(k)] \quad (8)$$

Since the mechanism by which parameter distortion affects current prediction performance is unclear, this study adopts an experimental approach to explore the regularity of the impact of controller inductance input parameters on THD and analyze the positive impact of parameter distortion on current prediction performance guided by experimental results.

V. Experiments and Results

A. Simulation of Twisted Inductance Parameters

Considering the actual operation of a single-phase inverter, a simulation model is established as shown in Fig. 4. A one-step delay compensation is applied under delayed conditions, which is compared with a simulation model without compensation under delayed conditions. The current THD and switch action times are recorded under different reference values of grid current. The model parameters are shown in Table I.

TABLE I. Simulation Parameters

Parameters	Symbols	Values
DC-link voltage	U_{dc}	120V
Grid phase voltage amplitude	e	100V
Grid frequency	f	50Hz
Filter inductance	L	8mH
Load resistance	R	1Ω
Switching period	T_s	50μs

The current THD with one-step delay compensation before and after application is shown in Table II. Experimental results show that the current THD and switch action times decrease after one-step delay compensation, solving the problem of large current ripple caused by the application of optimal voltage vector lagging behind current sampling.

TABLE II. Delay Compensation Simulation Results

Current reference I_r(A)	THD before compensation (%)	THD after compensation (%)	Number of switches before compensation	Number of switches after compensation
10.00	5.72	5.09	449	341
11.11	5.42	4.72	501	337
12.50	4.56	4.23	441	327
12.90	4.40	4.02	363	309
13.33	4.29	3.59	454	301

B. Simulation of Twisted Inductance Parameters

Under the condition of no compensation for delay and unchanged actual circuit parameters, the inductance and resistance parameters of the FCS-MPC controller are artificially twisted within a certain range, and the change of current THD is tested. The results are shown in Fig. 5.

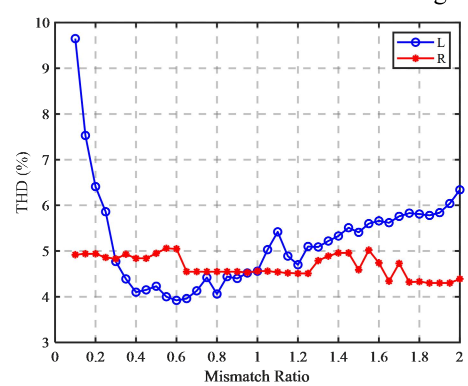
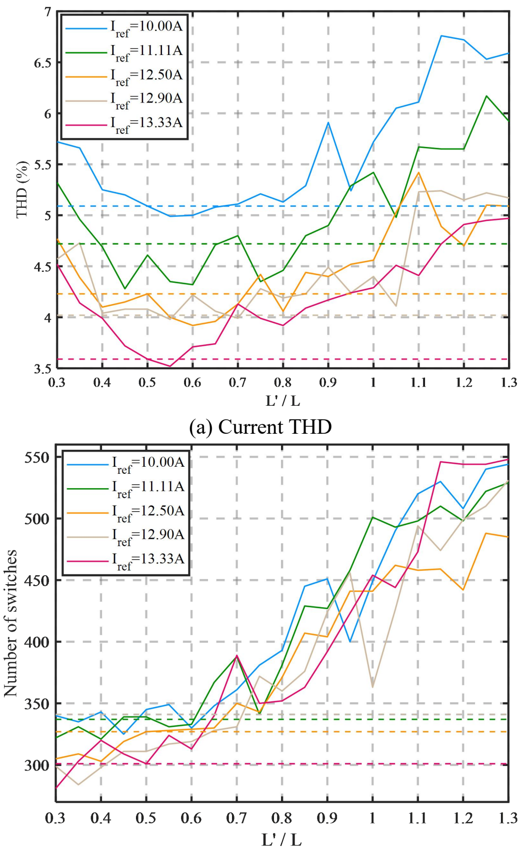


Fig. 5. THD variation diagram after inductance and resistance parameters twist

The experimental results show that the distortion of the resistance parameter in the FCS-MPC controller has little influence on the current THD, while the sensitivity of current THD to the inductance parameter is greater. Subsequent research will focus on the analysis of twisted inductance parameters.

C. Simulation of Twisted Inductance Parameters

The switching frequency was set at 20kHz, and the reference current amplitude from the grid was successively set at 10A, 11.11A, 12.5A, 12.9A, and 13.33A. The effect of twisted inductance parameters in the FCS-MPC controller on the current THD and number of switches was tested, and compared with the effect of one-step delay compensation. The results are shown in Fig. 6(a) and Fig. 6(b). The solid lines in Fig. 6(a) represent the effect of twisted inductance parameters, and the horizontal dashed lines represent the effect of delay compensation.



(a) Current THD

(b) Number of switches

Fig. 6. Results of twisted inductor parameters at 20kHz

It can be seen from Fig. 6(a) that within a certain range, reducing the inductance mismatch ratio L'/L can reduce the current THD, and when the inductance mismatch ratio L'/L is around 0.55, the current THD is even lower than the effect of using one-step delay compensation. It can be seen from Fig. 6(b) that in general, the lower the inductance mismatch ratio L'/L, the fewer the switching frequencies, which are lower than the switching frequencies after delay compensation within a certain range.

The comparison of current waveforms obtained by using the twisted parameter method and delay compensation method is shown in Fig. 7, with the inductance mismatch ratio L'/L set to 0.55.

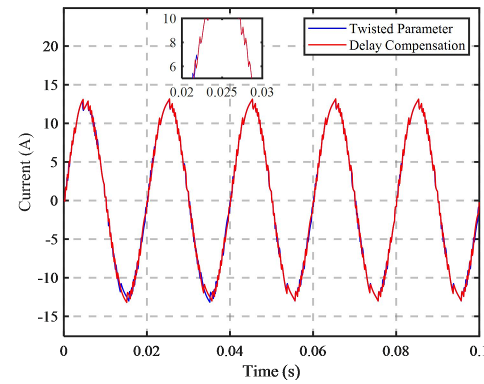
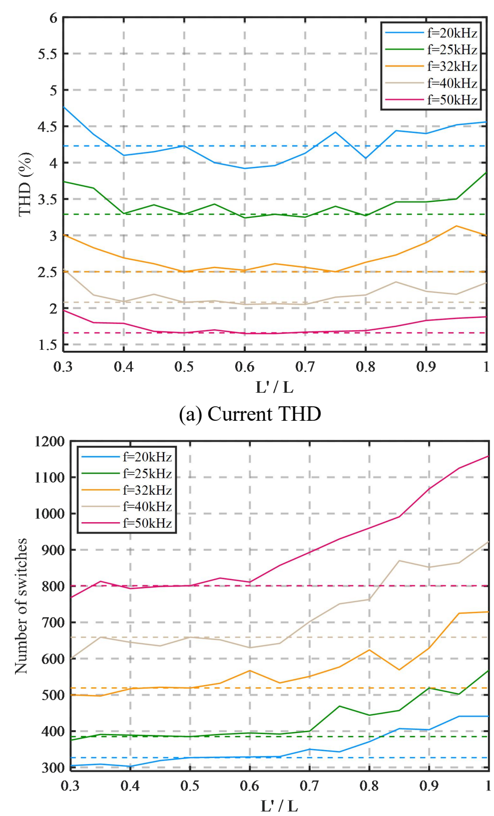


Fig. 7. Comparison of current waveform between twisted parameter method and delay compensation method

It can be observed in Fig. 7 that the current waveforms obtained by the twisted parameter method and the delay compensation method are close to coinciding when L'/L is set to 0.55. When the inductance mismatch ratio L'/L is further reduced to 0.5, the current waveforms obtained by the twisted parameter method and the delay compensation method completely coincide, although the exact mechanism behind this is unknown.



(a) Current THD

(b) Number of switches

Fig. 8. Results of twisted inductor parameters at different switching frequencies

Further simulations were conducted with the reference grid current amplitude set at 12.5A, with the inductance mismatch ratio range narrowed down, and experiments were carried out at switching frequencies of 20kHz, 25kHz, 32kHz, 40kHz, and 50kHz, to verify if the same law exists at different switching frequencies. The current THD and number of switches are shown in Fig. 8(a) and Fig. 8(b), respectively.

The solid lines in Fig. 8 represent the effect of twisted inductance parameters, and the horizontal dashed lines represent the effect of delay compensation. It can be observed in this figure that within certain limits, reducing the ratio of the controller's inductance parameters to their actual values did not increase the number of switching actions, but instead can reduce current THD. When the mismatch ratio $L^{'}/L$ is 0.5, the effect of current THD and switching times is the same as that of the delay compensation method. The control effect is even better than that achieved using the delay compensation method, proving the effectiveness of the proposed twisted parameter method.

VI. CONCLUSION

This paper takes the single-phase bridge inverter control as an example and focuses on the contradiction between the large computational complexity, time delay, and parameter mismatches in the FCS-MPC controller. In-depth analysis and research on the parameter mismatch problem are conducted, breaking through the limitations of traditional research perspectives. This paper discovers some phenomena and laws related to the impact of controller inductance input parameters on grid current THD, which were not previously discovered. A simple and efficient method for artificially twisting control parameters is proposed to replace the one-step delay compensation method, and significantly reduce grid current ripple without increasing the number of switching actions. The research results show that reducing the control parameters of the inductance within a certain range can effectively improve the quality of grid current, while also solving the computational complexity problem introduced by delay compensation method. The next research focus will be on how to find the optimal inductance parameter mismatch ratio based on the impact law of artificially twisted inductance control parameter on grid current THD.

ACKNOWLEDGMENTS

This work was financially supported by the Central Universities under Grant 20720220071 and 20720220084.

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