Adaptive Selective Harmonic Elimination Model Predictive Control for Three-Level T-Type Inverter

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ABSTRACT In this work, an adaptive selective harmonic elimination model predictive control (ASHE-MPC) method for a 3L-T type inverter is proposed. This algorithm is based on model predictive control (MPC), introduces adaptive selective harmonic elimination (ASHE) algorithm, and performs digital delay compensation through two-step prediction. Compared with the harmonic suppression strategies based on PI or PR controller, ASHE-MPC significantly improves the current loop bandwidth, speeds up the dynamic response, and greatly increases the harmonic order that can be eliminated. Compared with the harmonic suppression strategies based on the deadbeat model predictive control (DB-MPC), ASHE-MPC can eliminate low-order harmonics caused by multiple factors (including dead-time and grid background harmonics), and can easily eliminate multiple harmonics (5th−31th in this paper). The proposed ASHE-MPC method for the first time achieves adaptive selective harmonic elimination in model predictive control. The ASHE-MPC method is novel, simple and efficient. A three-level T-type grid-connected inverter for dead-time compensation is used as an example to verify the feasibility of this method.

INDEX TERMS Model predictive control, adaptive selective harmonic elimination, current loop bandwidth, dynamic response.

I. INTRODUCTION
In recent years, distributed grid-connected power generation based on renewable energy sources such as wind energy and solar power has received increasing attention and has become a research focus. Harmonics has been considered as a major problem in grid-connected generation of new energy. According to IEEE Std. 929—2000 and IEEE Std. 519-1992 standards [1], [2], the total harmonic distortion (THD) of the current fed into the power grid is limited to less than 5% and each harmonic is limited to a certain range. Therefore, in order to meet the above standards, appropriate current control strategies need to be studied to suppress current harmonics.

For grid-connected inverters with L-type or LCL-type filters, the low-order harmonics (usually 5th, 7th, 11th, 13th ...) in the grid current are large due to the influence of dead time and grid background harmonics. These lower-order harmonics cannot be eliminated by the L-type or LCL-type filter. Therefore, appropriate current control strategies must be developed.

In order to eliminate or suppress the low-order harmonics of the current, many methods including the following have been proposed.

A. HARMONIC SUPPRESSION STRATEGY BASED ON INTERNAL MODEL PRINCIPLE (IMP)
IMP means that if you want to well cancel the external disturbance or track the reference input signal, the feedback loop of the system needs to include a dynamic model that is the same as the external input [3]. IMP states that a linear feedback system can have perfect anti-interference ability at a certain frequency if and only if the controller gain is infinite at that frequency. Based on IMP, many harmonic suppression strategies have been developed including: harmonic suppression strategies based on multiple PI controllers with coordinate transformations (called as PI-IMP) [4], harmonic suppression strategies based on PR controllers with multiple resonant controllers (called as PR-IMP) [5]–[7], and harmonic suppression strategies based on repetitive control (called as RC-IMP) [8], [9].
According to the IMP, the PI controller can track the DC reference due to its high gain at zero frequency. The disadvantages of PI-IMP are as follows: Multiple coordinate transformations bring a large computational burden to the processor, and the use of a low-pass filter will introduce a phase delay; with the increase of the harmonic order to be suppressed, the PI controller-based current loop cannot provide a sufficiently high bandwidth, which results in a very low harmonic order that can be suppressed; at the same time, a small current loop bandwidth results in a slow dynamic response.

According to the IMP, the PR controller can produce a very high gain at a specified frequency, thus perfectly tracking the sinusoidal reference of the corresponding frequency. PR-IMP does not require a large number of coordinate transformations, but it also has the disadvantages of PI-IMP. In addition, digital implementation of multiple resonant controllers is quite difficult [10].

Repetitive control puts the repetitive signal generator as an internal model in a closed-loop system, which can completely track the periodic reference signal or suppress the periodic disturbance signal, and achieve extremely low steady-state error. The dynamic response of the repeat control is very slow. Repeated control is sensitive to grid frequency fluctuations.

In summary, the above three IMP-based harmonic suppression strategies have the following disadvantages: current loop bandwidth is small, dynamic response is slow, the number of harmonics that can be suppressed is small, digital implementation of the controller is difficult, and control strategies are very sensitive to grid frequency fluctuations.

B. HARMONIC SUPPRESSION STRATEGY BASED ON ADAPTIVE FEEDFORWARD CANCELLATION (AFC)

Unlike the IMP-based harmonic suppression strategy, the adaptive feedforward cancellation (AFC) method eliminates interference by always adding negative values to the input of the system. Since interference is usually unknown, adaptive information is required to obtain the interference information. In this paper, harmonics are considered as a sine wave disturbance, so an adaptive algorithm is needed to obtain the coefficients of the Fourier series of the sine signal.

In [11], adaptive filters were used to extract harmonics, and multiple resonance controllers were used to suppress harmonics. The use of multiple resonant controllers has the disadvantages previously described. An adaptive selective harmonic elimination (ASHE) algorithm was proposed in [12], which realized the elimination of multiple harmonics. However, the current loop bandwidth is small because the PI controller is used in [12]. When the number of harmonics to be eliminated is large, the system will become unstable as the harmonic order to be eliminated becomes larger.

C. HARMONIC SUPPRESSION STRATEGY BASED ON SHEPWM

In high-power applications, SHEPWM technology can precisely eliminate selected harmonics at very low switching frequencies [13]–[15]. However, in actual implementation, there are some problems with SHEPWM technology. The prior equation used to solve the switching angle of SHEPWM is a non-linear transcendental equation, and the real-time solution of the switching angle is difficult. SHEPWM is an open-loop modulation strategy, and factors such as dead-time and grid background harmonics can cause poor control results. The implementation of SHEPWM requires a high sampling frequency to reduce the quantization error of the switching angle. The dynamic response of SHEPWM is very slow.

SHEPWM is generally used in high-power applications. Since the experiment in this paper is carried out on a low-power (20KW) machine, there is no additional discussion on the method of SHEPWM.

In summary, the control method based on traditional linear controllers (PI, PR, etc.) will cause a small number of harmonics to be eliminated due to the small current loop bandwidth, and the dynamic response of this control method is slow. In order to achieve fast dynamic response and suppress low-order harmonics, some scholars use model predictive control (MPC). As we all know, MPC has fast dynamic response. Deadbeat model predictive control (DB-MPC) is a broad and mature control method in MPC. Reference [16] introduces the theory and implementation of DB-MPC. In [17], a model predictive control was proposed to compensate for the effect of dead-time. The method only considered the suppression of low-order harmonics caused by dead-time, and could not suppress the low-order harmonics caused by other factors. An observer-based model predictive control method was proposed in [18]. The observer based on Kalman filter is designed to estimate harmonic interference. Similarly, only grid background harmonics are considered and other factors are ignored. In addition, the addition of Kalman filter makes the control method very complicated, and the actual implementation is quite difficult. Only simulation results are given in [18]. In [19], a finite set model predictive control (FSMPC) based on sliding discrete Fourier transform (SDFT) was proposed to achieve the suppression of low-order harmonics. However, the method has a large calculation burden, and the number of harmonics to be eliminated is limited (because FSMPC causes even harmonics in the current).

This paper proposes an adaptive selective harmonic elimination model predictive control (ASHE-MPC) method. The ASHE algorithm has the advantage of frequency adaptability, even if the grid frequency fluctuates, it can achieve a good harmonic suppression effect. In the case that many harmonics need to be eliminated, the implementation of the ASHE algorithm is very simple. The ASHE algorithm can not only eliminate low-order harmonics caused by dead-time, but also low-order harmonics caused by grid background harmonics. MPC aims to increase the bandwidth of the current loop. On the one hand, high bandwidth results in fast dynamic response. On the other hand, high bandwidth can increase the number of harmonics that can be eliminated and further improve current quality. According to the author’s
investigation, there are few existing studies on harmonic elimination of MPC. In addition, the use of ASHE algorithm for harmonic elimination in MPC is proposed for the first time in this paper, and no previous research has proposed this method.

The content of this paper is organized as follows: In Section II, the system model is presented. Then, the principle and implementation of MPC are shown in Section III. In Section IV, the principle and implementation of ASHE algorithm based on PI controller are presented. The proposed ASHE-MPC method is presented in Section V. Section VI gives the simulation results. Section VII gives the experimental results and Section VIII summarizes the conclusions.

II. SYSTEM MODEL DESCRIPTION

The topology of the 3L-T type grid-connected inverter is shown in Fig. 1. \( e_{ga}, e_{gb} \) and \( e_{gc} \) are grid voltages, \( i_a, i_b, \) and \( i_c \) are grid currents, \( V_{dc} \) is the voltage of the DC source. The \( L \) filter can be modeled as series of an inductance \( L \) and a parasitic resistance \( R \).

**FIGURE 1. 3L-T type grid-connected inverter.**

Let the integer variables \( S_a, S_b, S_c \in \{1, 0, -1\} \) denote the switch positions in each phase leg. \( S_x = 1(x \in \{a, b, c\}) \) means that the devices \( S_{x1} \) and \( S_{x2} \) of phase \( x \) are closed while the devices \( S_{x3} \) and \( S_{x4} \) are opened, and the output voltage is \( V_{dc}/2 \). \( S_x = 0(x \in \{a, b, c\}) \) means that the devices \( S_{x2} \) and \( S_{x3} \) of phase \( x \) are closed while the devices \( S_{x1} \) and \( S_{x4} \) are opened, and the output voltage is 0. \( S_x = -1(x \in \{a, b, c\}) \) means that the devices \( S_{x3} \) and \( S_{x4} \) of phase \( x \) are closed while the devices \( S_{x1} \) and \( S_{x2} \) are opened, and the output voltage is \(-V_{dc}/2\). Considering all valid switching states, the 3L-T type inverter generates a total of 27 switching states. The switching vectors of the 3L-T type inverter is shown in Fig. 2.

**III. THE PRINCIPLE AND IMPLEMENTATION OF MPC**

As a 3L-T type inverter is used in this paper, multiple targets including grid current and mid point voltage need to be controlled, and it is difficult for deadbeat model predictive control (DB-MPC) to control multiple targets simultaneously.

A new method of DB-MPC for a three-level NPC inverter was proposed in [21], but the neutral-point voltage was not controlled. In [22], a neutral-point voltage balancing method for a three-level NPC inverter based on DB-MPC was proposed. However, the traditional PI controller is used to control the current.

Generally, the control target of MPC is current. In order to achieve additional control of the neutral point voltage, the neutral point voltage control method based on the OVI algorithm in [20] is adopted in this paper. The OVI algorithm will not be explained more here, because this paper mainly studies current harmonics, and the neutral point voltage is not the main research target.

The mathematical model of the system in \( \alpha - \beta \) coordinate is

\[
L \frac{di}{dt} = U - Ri - e_g
\]

where \( e_g \) is the grid voltage vector, \( i \) is the grid current vector, \( U \) is the output voltage vector of the inverter. By Euler discretization, the discrete prediction model (2) can be obtained from (1), where \( T_s \) is the sampling period and \( k \) is a discrete time index.

\[
i^{p}(k+1) = (1 - \frac{RT_s}{L})i(k) + \frac{T_s}{L}[U(k) - e_g(k)]
\]

To compensate for the delay, a two-step prediction is required. The second step prediction is shown in (3).

\[
i^{p}(k+2)=(1-\frac{R T_s}{L})i^{p}(k+1)+\frac{T_s}{L}[U(k+1)-e_g(k+1)]
\]

where \( e_g(k+1) = e_g(k) \), because the grid frequency (50Hz) is much smaller than the sampling frequency, the grid voltage can be regarded as a constant at a sampling interval. In the second step prediction, the 27 switching vectors are traversed so that 27 current prediction vectors \( i^{p}(k+2) \) are obtained.

The optimal inverter output voltage \( U_{opt}(k+1) \) is obtained by selecting the smallest cost function. The cost function is defined as follows,

\[
g_t = ||i^{p}(k+2) - i^{p}(k+2)||^2
\]

where \( i^{p}(k+2) \) is the reference value of current at \( k+2 \) instant, \( i^{p}(k+2) \) is the predicted value of current at \( k+2 \) instant.

Next, the neutral-point voltage balance is achieved by the OVI Method proposed in [20]. The OVI Method is used to generate the optimal offset voltage value \( U_{offset} \). The optimal offset voltage value \( U_{offset} \) is added to the optimal inverter output voltage \( U_{opt}(k+1) \) to generate the final reference voltage \( U_{ref} \). Finally, \( U_{ref} \) is modulated by the
SVM algorithm [23], [24]. The overall control block diagram of DSVM-MPC is shown in Fig.3.

FIGURE 3. The overall control block diagram of MPC.

IV. THE PRINCIPLE AND IMPLEMENTATION OF AHSE ALGORITHM BASED ON PI CONTROLLER

In this section, the ASHE algorithm is described in detail as follows. As shown in Fig.4, the current loop uses a PI controller. $U_{ref}$ is the reference voltage, and $G_p(s)$ is the transfer function of the plant. In this paper, $G_p(s) = 1/(Ls+R)$. The target of the control scheme is to filter the harmonic interference component $U_{ASHE}$ from the main input $d$ (signal to be filtered). Due to the uncertainty of interference, an adaptive algorithm needs to be found to estimate the interference value. The least mean square (LMS) adaptive algorithm is used for harmonic interference estimation due to its simplicity and efficiency.

FIGURE 4. The control block diagram of ASHE algorithm based on PI controller.

The adaptive selective harmonic elimination algorithm based on LMS is shown in Fig.5 [25]. According to the Fourier transform theory, a periodic signal can be expressed as the sum of a series of sine terms. Assume that the harmonic interference signal is

$$d_{is}(k) = A_0 \cos(\omega_0 kT_s) + B_0 \sin(\omega_0 kT_s) \quad (5)$$

The target of the LMS algorithm is to continuously update the harmonic weight coefficients $W_c(k)$ and $W_s(k)$ to ensure that $W_c(k) = A_0$ and $W_s(k) = B_0$. The LMS algorithm is given by (6) [25].

$$W(k+1) = W(k) + 2\mu \varepsilon(k)X(k) \quad (6)$$

where $\mu$ is the adaptation gain constant. Generally, $\mu$ is a small positive number. In this article, the value of $\mu$ is in the range of 0.05-0.8. $W(k) = [W_c(k), W_s(k)]^T$, $X(k) = [\cos(\omega_0 kT_s), \sin(\omega_0 kT_s)]^T$. $\varepsilon(k)$ is the estimation error. When $G_p(s)$ is taken into the ASHE algorithm, $\varepsilon(k) = i(k)$ is obtained, as shown in Fig.5.

According to the above description of the ASHE algorithm, Fig.6 shows the overall control block diagram of the adaptive selective harmonic elimination algorithm based on PI controller (ASHE-PI). Fig.6 (a) shows the control block diagram of a single frequency adaptive selective harmonic elimination. The ASHE algorithm is easily extended to the case when multiple harmonics need to be eliminated. The control block diagram of multiple frequency ASHE (MF-ASHE) is shown in Fig.6 (b).

FIGURE 6. The overall control block diagram of ASHE-PI method. (a) The control block diagram of a single frequency adaptive selective harmonic elimination. (b) The control block diagram of MF-ASHE.

V. THE PROPOSED ASHE-MPC METHOD

In this paper, a 3L-T type inverter is used. Both the grid current and the neutral-point voltage need to be controlled, which is difficult to achieve under DB-MPC. The proposed method uses MPC as described in Section III to achieve fast and effective control of grid current and neutral-point voltage. Compared with PI controller, MPC greatly increases the bandwidth of the current loop, which provides a guarantee for eliminating higher order harmonics.

As described in the previous section, there are few methods for low-order harmonic suppression in model
predictive control, especially in three-level inverters. Existing methods only compensate for harmonics caused by a specific factor (such as dead-time or grid background harmonics), and their applicability is low. In addition, the existing observer-based or SDFT-based harmonic suppression strategies become more complex and difficult to implement as the number of harmonics that need to be eliminated increases.

In order to make up for the shortcomings of the existing schemes, this paper proposes an adaptive selective harmonic elimination model predictive control (ASHE-MPC) method. In order to embed the ASHE algorithm into the MPC control, we use the ASHE-PI method as a starting point for description.

According to Fig.6, we can replace the PI controller with the MPC controller to obtain the ASHE-MPC method. The most important point is that the output of the MPC controller is the inverter output voltage value \( U(k+1) \), so the corresponding \( U_{\text{ASHE}} \) must also be the value at \( k+1 \) instant, that is, \( U_{\text{ASHE}}(k+1) \). Therefore, the input of the ASHE algorithm must also be the current at \( k+1 \) instant, that is, \( i(k+1) \).

Through the above analysis, the control block diagram shown in Figure 7 is obtained.

![FIGURE 7. The control block diagram of ASHE-MPC method.](image)

According to Fig.7, the next question is how to obtain the actual current \( i(k+1) \). This paper presents two methods to obtain \( i(k+1) \).

One simple approach is to approximate the value at \( k+1 \) instant by using known values from a few previous sampling instants. In numerical mathematics, Lagrange extrapolation is usually used. The Lagrange extrapolation formulas of order 1, 2 and 3 for the calculation of \( i(k+1) \) are shown in (7), (8) and (9) respectively.

\[
i(k+1) = 2i(k) - i(k-1) \quad (7)
\]

\[
i(k+1) = 3i(k) - 3i(k-1) + i(k-2) \quad (8)
\]

\[
i(k+1) = 4i(k) - 6i(k-1) + 4i(k-2) - 4i(k-3) \quad (9)
\]

The z-domain transfer functions of (7), (8) and (9) can be expressed as

\[
G_1 = \frac{i(k+1)}{i(k)} = 2 - z^{-1} \quad (10)
\]

\[
G_2 = \frac{i(k+1)}{i(k)} = 3 - 3z^{-1} + z^{-2} \quad (11)
\]

\[
G_3 = \frac{i(k+1)}{i(k)} = 4 - 6z^{-1} + 4z^{-2} - z^{-3} \quad (12)
\]

The bode diagrams of \( G_1, G_2 \) and \( G_3 \) under 16KHz sampling frequency are shown in Fig.8 (16KHz is chosen because the sampling frequency in this experiment is set to 16KHz).

Another method of obtaining \( i(k+1) \) is described below. Similar to the first method, we need to find a value approximately equal to \( i(k+1) \). Fortunately, for the MPC controller, since the two-step prediction method is used (to solve the delay problem), the first step prediction provides us with the predicted value of current \( \mathcal{P}(k+1) \), which can be approximated as the actual current \( i(k+1) \). Unlike Lagrangian extrapolation, \( \mathcal{P}(k+1) \) does not introduce high-frequency interference to the system since it is predicted by the system model, which provides the possibility to eliminate higher-order harmonics.

![FIGURE 8. The bode diagrams of \( G_1, G_2 \) and \( G_3 \) under 16KHz sampling frequency.](image)
The research shows that the second method is indeed superior. The harmonic order eliminated by the first method is smaller than that of the second. Therefore, the second method is used as an example to illustrate the proposed ASHE-MPC method.

Fig. 9 shows the overall control block diagram of the ASHE-MPC method. The specific implementation steps are as follows:

1) Sampling to obtain the grid current $i(k)$ and grid voltage $e_g(k)$.

2) Obtain the inverter output voltage $U(k)$ at $k$ instant. It is worth noting that $U(k)$ is obtained by delaying $(U_{opt}(k+1) + U_{offset})$ by one sampling period instead of delaying $U_{opt}(k+1)$ by one sampling period. This is because the target of the ASHE algorithm is to eliminate harmonic interference components from the main input $d$. For MPC, $d = U_{opt}(k+1) + U_{offset}$. This is critical, otherwise it will lead to errors in the proposed method.

3) Substituting $i(k)$, $e_g(k)$, and $U(k)$ into (2) for the first prediction to obtain $i_p(k+1)$.

4) Through the second step of prediction, $i_p(k+2)$ is obtained.

5) Minimize $g_i$ in (4) to get the optimal voltage $U_{opt}(k+1)$.

6) Calculate the offset voltage value $U_{offset}(k+1)$ according to the OVI method proposed in [20].

7) Take the $P(k+1)$ as the input of the ASHE algorithm to obtain the harmonic compensation voltage $U_{ASHE}(k+1)$.

8) Calculate the final reference voltage $U_{ref}$, that is, $U_{ref} = U_{opt}(k+1) + U_{offset} - U_{ASHE}(k+1)$. Finally, $U_{ref}$ is modulated by the SVM algorithm.

### VI. THE SIMULATION RESULTS

The simulation has been operated on a three-level grid-connected voltage source inverter. The simulation parameters are shown in Table 1.

In order to verify the effectiveness of the proposed AHSE-MPC method, the simulations were performed with uncompensated dead time without and with ASHE algorithms. In order to highlight the superiority of the AHSE-MPC method over the ASHE-PI method, simulations are also performed on the ASHE-PI method. In all simulations, the sampling frequency was set to 16KHz and the dead time was set to 7μs.

#### A. STEADY-STATE SIMULATION WAVEFORMS WITH 5th AND 7th HARMONICS ELIMINATED

In a three-phase symmetrical system, harmonics mainly exist as the odd non-triples in relation to fundamental. In other words, harmonics mainly exist as 5th, 7th, 11th, 13th...31st, 35th... Simulations are first performed to eliminate a small number of harmonics to ensure that the system is stable.

1) ASHE-PI METHOD

Fig.10 shows the simulation waveforms based on the PI controller without adding the ASHE algorithm. Fig.10 (a) shows the grid current waveform of phase $a$ without the ASHE algorithm. The corresponding THD of the current is shown in Fig.10 (b). It can be clearly seen from Fig.10 that without the ASHE algorithm, there are obvious low-order harmonics in the grid current.

Fig.11 shows the waveform of the 7th harmonic weight coefficient $W_{c7}$. The waveforms of other harmonic weight coefficients ($W_{c5}$, $W_{c7}$) are similar, and are not listed.
Here one by one. As can be seen from Fig.12, the ASHE algorithm can converge quickly. When the ASHE algorithm converges, the selected harmonics are eliminated.

2) ASHE-MPC METHOD

Fig.13 shows the simulation waveforms based on the MPC controller without adding the ASHE algorithm. (a) The waveform of grid current. (b) The THD of grid current.

Fig.13 (a) shows the grid current waveform of phase $a$ without the ASHE algorithm. The corresponding THD of the current is shown in Fig.13 (b). It can be clearly seen from Fig.13 that without the ASHE algorithm, there are obvious low-order harmonics in the grid current.

Fig.14 shows the simulation waveforms after adding the ASHE algorithm under the condition that other system parameters are not changed. Fig.14 (a) shows the grid current waveform of phase $a$ after adding the ASHE algorithm, and the corresponding THD of the current is shown in Fig.14 (b). It can be clearly seen from Fig.14 that after the ASHE scheme is added, the low-order harmonics in the grid current are significantly reduced.

Fig.15 shows the waveform of the 7th harmonic weight coefficient $W_c^7$. Similar to the ASHE-PI method, the harmonic weight coefficient can also quickly converge.
FIGURE 14. The experimental waveforms based on the MPC controller with the ASHE algorithm. (a) The waveform of grid current. (b) The THD of grid current.

FIGURE 15. The waveform of the 7th harmonic weight coefficient $W_{c7}$.

B. DYNAMIC RESPONSE WAVEFORMS WITH 5th AND 7th HARMONICS ELIMINATED

Fig.16 and Fig.17 show the dynamic response waveforms of the two methods when the current command value $i_{q}^*$ steps from 15A to 30A at 0.25s. And $i_{d}^*$ is set to $i_{d}^* = 0$. Under the ASHE-PI method, the dynamic response waveforms of the grid current and $W_{c7}$ are shown in Fig.16. Fig.17 show the corresponding waveforms under the ASHE-MPC method. Obviously, the dynamic response of the ASHE-MPC method is faster, which is the advantage of predictive control. In addition, both methods can finally guarantee the convergence of the ASHE algorithm, which can be seen from $W_{c7}$.

From Fig.10 to Fig.18, comparing the ASHE-PI method and the ASHE-MPC method, it can be seen that both ASHE-PI and ASHE-MPC are good at eliminating selected harmonics, but ASHE-MPC has a faster dynamic response.

C. SIMULATION WAVEFORMS WITH MULTIPLE HARMONICS ELIMINATED

In this simulation, in order to highlight that ASHE-MPC can eliminate higher order harmonics, the harmonics to be eliminated in the ASHE algorithm are set to 5th to 31st, a total of 10 harmonics.

Under the ASHE-PI method, when the harmonic order to be eliminated reaches 23rd, the system cannot be stabilized no matter how the adaptive gain constant $\mu$ is adjusted. This is because the PI controller cannot provide enough bandwidth, which is consistent with the previous analysis.

However, the ASHE-MPC method can eliminate higher order harmonics. Fig.18 (a) shows the current waveform of the ASHE-MPC method with 5th to 31st harmonics eliminated, and Fig.18 (b) shows the corresponding THD of the current. It is clear that the ASHE-MPC method can eliminate higher order harmonics, which results in higher quality current.

D. COMPARISON OF TWO METHODS TO OBTAIN $i(k+1)$

Aiming at the two methods of obtaining $i(k+1)$ mentioned in the paper, simulations are carried out taking the elimination of the 5th to 23rd harmonics as an example. Fig.19 shows the $W_{c7}$ waveforms under the two methods. Obviously, when the harmonic order to be eliminated is large, the first method...
VII. THE EXPERIMENTAL RESULTS

The experiment has been operated on a 20-KW three-level grid-connected voltage source inverter. The experimental parameters are the same as Table 1. The whole control was programmed in DSP model TMS320F28377. The experimental platform is shown in Fig. 20.

In order to verify the effectiveness of the proposed AHSE-MPC method, the experiments were performed with uncompensated dead time without and with ASHE algorithms. In order to highlight the superiority of the AHSE-MPC method over the ASHE-PI method, experiments are also performed on the ASHE-PI method. In all experiments, the sampling frequency was set to 16KHz and the dead time was set to 5μs (The experimental environment is generally worse than the simulation environment, so the dead time is set smaller than that of the simulation).

The experimental platform of this paper uses TMS320F28377 as the main control chip. The chip integrates three digital-to-analog converters (DAC). During the experiment, some parameters (such as \( W_{c7} \)) in the program can be released through the DAC and then observed by an oscilloscope.

A. STEADY-STATE EXPERIMENTAL WAVEFORMS WITH 5\(^{th}\), 7\(^{th}\), 11\(^{th}\), AND 13\(^{th}\) HARMONICS ELIMINATED

In a three-phase symmetrical system, harmonics mainly exist as the odd non-triples in relation to fundamental. In other words, harmonics mainly exist as 5\(^{th}\), 7\(^{th}\), 11\(^{th}\), 13\(^{th}\) ... 31\(^{st}\), 35\(^{th}\) ... Experiments are first performed to eliminate a small number of harmonics to ensure that the system is stable.

1) ASHE-PI METHOD

Fig. 21 shows the experimental waveforms based on the PI controller without adding the ASHE algorithm. Fig. 21 (a) shows the grid current waveform of phase \( a \) without the ASHE algorithm. The corresponding THD of the current is shown in Fig. 21 (b). It can be clearly seen from Fig. 21 that without the ASHE algorithm, there are obvious low-order harmonics in the grid current.
FIGURE 21. The experimental waveforms based on the PI controller without adding the ASHE algorithm. (a) The waveform of grid current. (b) The THD of grid current.

FIGURE 22. The experimental waveforms based on the PI controller with the ASHE algorithm. (a) The waveform of grid current. (b) The THD of grid current.

Fig.22 shows the experimental waveforms after adding the ASHE algorithm under the condition that other experimental conditions are not changed. Fig.22 (a) shows the grid current waveform of phase \(a\) after adding the ASHE algorithm, and the corresponding THD of the current is shown in Fig.22 (b). It can be clearly seen from Fig.22 that after the ASHE scheme is added, the low-order harmonics in the grid current are significantly reduced.

FIGURE 23. The waveform of the 5\(^{th}\) harmonic weight coefficient \(W_{c5}\).

FIGURE 24. The experimental waveforms based on the MPC controller without adding the ASHE algorithm. (a) The waveform of grid current. (b) The THD of grid current.

without the ASHE algorithm, there are obvious low-order harmonics in the grid current.

Fig.25 shows the experimental waveforms after adding the ASHE algorithm under the condition that other experimental conditions are not changed. Fig.25 (a) shows the grid current waveform of phase \(a\) after adding the ASHE algorithm, and the corresponding THD of the current is shown in Fig.25 (b). It can be clearly seen from Fig.25 that after the ASHE scheme is added, the low-order harmonics in the grid current are significantly reduced.

FIGURE 25. The experimental waveforms based on the MPC controller with the ASHE algorithm. (a) The waveform of grid current. (b) The THD of grid current.

2) ASHE-MPC METHOD

Fig.24 shows the experimental waveforms based on the MPC controller without adding the ASHE algorithm. Fig.24 (a) shows the grid current waveform of phase \(a\) without the ASHE algorithm. The corresponding THD of the current is shown in Fig.24 (b). It can be clearly seen from Fig.24 that the waveforms of other harmonic weight coefficients are similar, and are not listed here one by one. As can be seen from Fig.23, the ASHE algorithm can converge quickly. When the ASHE algorithm converges, the selected harmonics are eliminated.
Fig. 26 shows the waveform of the 5th harmonic weight coefficient $W_{c5}$. Similar to the ASHE-PI method, the harmonic weight coefficient can also quickly converge.

**FIGURE 26.** The waveform of the 5th harmonic weight coefficient $W_{c5}$.

### B. DYNAMIC RESPONSE WAVEFORMS WITH 5th, 7th, 11th, AND 13th HARMONICS ELIMINATED

Fig. 27 and Fig. 28 show the dynamic response waveforms of the two methods when the current command value $i_d^*$ steps from 15A to 30A at 2s. And $i_q^*$ is set to $i_q^* = 0$. Under the ASHE-PI method, the dynamic response waveforms of the grid current and $W_{c5}$ are shown in Fig. 27 (a) and Fig. 27 (b), respectively. Fig. 28 (a) and (b) show the corresponding waveforms under the ASHE-MPC method, respectively. Obviously, the dynamic response of the ASHE-MPC method is faster, which is the advantage of predictive control.

**FIGURE 27.** The dynamic response waveforms of the ASHE-PI method. (a) The dynamic response waveform of the grid current. (b) The dynamic response waveform of $W_{c5}$.

**FIGURE 28.** The dynamic response waveforms of the ASHE-MPC method. (a) The dynamic response waveform of the grid current. (b) The dynamic response waveform of $W_{c5}$.

From Fig. 21 to Fig. 28, comparing the ASHE-PI method and the ASHE-MPC method, it can be seen that both ASHE-PI and ASHE-MPC are good at eliminating selected harmonics, but ASHE-MPC has a faster dynamic response.

### C. EXPERIMENTAL WAVEFORMS WITH MULTIPLE HARMONICS ELIMINATED

In this experiment, in order to highlight that ASHE-MPC can eliminate higher order harmonics, the harmonics to be eliminated in the ASHE algorithm are set to 5th to 31st, a total of 10 harmonics.

Under the ASHE-PI method, when the harmonic order to be eliminated reaches 19th, the system cannot be stabilized no matter how the adaptive gain constant $\mu$ is adjusted. The current will exceed the protection value and the machine will stop running. This is consistent with the previous analysis.

However, the ASHE-MPC method can eliminate higher order harmonics. Fig. 29 (a) shows the current waveform of the ASHE-MPC method with 5th to 31st harmonics eliminated, and Fig. 29 (b) shows the corresponding THD of the current. It is clear that the ASHE-MPC method can eliminate higher order harmonics, which results in higher quality current.

**FIGURE 29.** The experimental waveforms based on ASHE-MPC method with multiple harmonics eliminated. (a) The waveform of grid current. (b) The THD of grid current.

### VIII. CONCLUSION

In this paper, an adaptive selective harmonic elimination model predictive control method is proposed to eliminate low-order harmonics in the grid current. The proposed method has advantages such as fast dynamic response, multi-objective optimization, large number of harmonics to be eliminated, and simple implementation, etc. In addition, the proposed method is not only applicable to grid-connected inverters, but also to other power electronics fields such as UPS and motor drive control, etc.

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