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Model Predictive Control for Quasi-Z Source Inverters with Improved Thermal Performance

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***Abstract*—The quasi-Z source inverter (qZSI) is one of the most promising power electronics converter topologies suitable for renewable energy applications. However, as a high-order system, its control is challenging. Recently, the model predictive control (MPC) with several advantages has been applied to the qZSI, where the switching behaviors (counts) are not yet optimized. This paper thus exposes a switching-count-reduction scheme for the MPC used in the qZSI. In the proposed scheme, an optimal switching vector is selected through a multi-parameter optimization, which enables reducing switching counts and thus lowering the thermal stress on the power devices. Simulations have been performed to validate the proposal, which is also benchmarked with several conventional MPCs and the PWM-based control.**

Keywords—Model predictive control (MPC), quasi-Z-source inverter (qZSI), thermal stress, switching count

I. INTRODUCTION

The quasi-Z-source inverter (qZSI) has become a promising alternative for renewable energy applications due to several advantages, such as the capability to boost or buck in a single converter stage, improved inverter reliability due to the immunity to shoot-through and open states, continuous input current, and low inrush current [1]. Prior-art work also presented the difficulties in the control of the qZSI, i.e., the pulsating DC-link control [2] and non-minimum phase phenomena in transients [3]. In this sense, it is difficult to maintain the stability of the entire system with a step change in the output reference. For instance, as known, power devices are considered to be the most fragile components in a power converter system, and an important cause of aging and failures of these devices is the thermal cycling [4], [5]. However, only limited research has focused on reducing the thermal cycling for power converters, where the overall system efficiency is degraded [6], [7].

Nowadays, the MPC is becoming more and more widely applied in power electronic systems [8], [9]. The finite control set-MPC (FCS-MPC) is an MPC method that applies the control decision directly to the converter switches without any modulation schemes [10]. Recently, the MPC is integrated in the ZSI family for controlling both DC side and AC side. Up to date, several papers focusing on the qZSI control with the FCS-MPC can be found in the literature, and most of them use the MPC to deal with nonlinearities and to control the DC-link boost voltage and the AC output current [11]-[15]. In [13], a discrete-time average MPC for the qZSI was proposed to improve the performance in terms of fast dynamics and high accuracy in steady state at a constant switching frequency. In [14], an MPC approach for the qZSI was presented to improve the dynamics, where a cost function that considers the qZSI inductor current, the DC capacitor voltage, and the three-phase AC output currents was used. In [15], another MPC was presented with a simplified cost function to reduce the computation. Indeed, the MPC is very powerful control strategy that uses the model of the qZSI to fulfill multiple control objectives with high dynamic performance, and a simplified design process. However, the thermal and reliability performance of the qZSI with a MPC approach is have not been explored.

This paper aims to reduce the thermal stress of a qZSI with a MPC strategy. A modified FCS-MPC with reduced commutations is proposed and applied. This paper uses a cost function that includes the number of commutations in addition to the qZSI capacitor voltage and the three-phase output currents. With the proposed method, the cost function only has two weighting factors, simplifying the entire design. Including switching counts in the cost function reduces the average switching frequency according to the thermal stress of power devices of the qZSI, and thus the overall thermal performance is improved. In addition, a comparative simulation study of the proposed technique and several conventional MPCs and the PWM-based controller has been provided.

II. PROPOSED MPC FOR QZSI

In this paper, the MPC is applied to the qZSI as shown in Fig. 1. The system consists of a quasi-Z-source network, a three-phase conventional inverter bridge and a resistive-inductive (RL) load. The three-phase inverter has a total of 15 valid switch configurations, and these states are distributed as 8 non-shoot-through (Non-ST) states, and 7 shoot-through (ST) states as shown in Table I. During the Non-ST state, the inverter is controlled in the same way as a conventional voltage source inverter (VSI). The ST state occurs when both switches in one phase leg are turned on simultaneously.

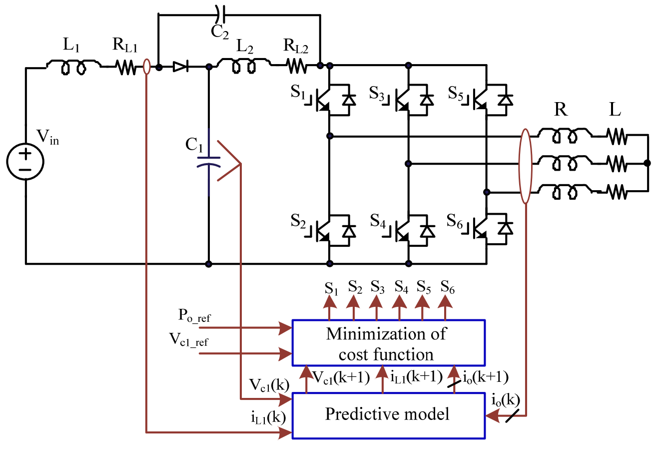

Fig. 1. Overall control structure of the qZSI with MPC.

TABLE I. SWITCHING STATES OF THE QZSI

Switching state		S_1	S_2	S_3	S_4	S_5	S_6
Non -ST state	Null state	1	0	1	0	1	0
		0	1	0	1	0	1
	Active state	1	0	0	1	0	1
		1	0	1	0	0	1
		0	1	1	0	0	1
		0	1	1	0	1	0
		0	1	0	1	1	0
		1	0	0	1	1	0
ST state		1	1	0	0	0	0
		0	0	1	1	0	0
		0	0	0	0	1	1
		1	1	1	1	0	0
		0	0	1	1	1	1
		1	1	0	0	1	1
		1	1	1	1	1	1

It is important to notify that many of these states are redundant as they produce the same output voltage vector. The two null states and 7 ST states can be simplified into one switch configuration for each. Thus the controller computation time can be significantly reduced since only 8 switching configurations. It is necessary to evaluate the selection of the optimal voltage vector.

Fig. 1 shows the overall control structure of the qZSI with a MPC. In the MPC implementation, the actual values of the input inductor current, the qZSI capacitor voltage, and the AC output currents are measured at t_k. Based on these values, the predicted capacitor voltage and inductor current during the ST state and non-ST state can be obtained as

During ST states:

$$v_{c1}(k+1)= v_{c1}(k)+\frac{T_s}{C_1}i_{L1}(k+1) \tag{1}$$

$$i_{L1}(k+1)=\frac{L_1 i_{L1}(k)+T_s \cdot v_{c1}(k)}{L_1+R_{L1}\cdot T_s} \tag{2}$$

During non-ST states:

$$v_{c1}(k+1)=v_{c1}(k)+\frac{T_s}{C_1}(i_{L1}(k+1)\text{-}i_{inv}(k+1)) \tag{3}$$

$$i_{L1}(k+1)=\frac{L_1 i_{L1}(k)+T_s(v_{in}\text{-}v_{c1}(k))}{L_1+R_{L1}\cdot T_s} \tag{4}$$

where T_s is the sampling period, v_{c1} is the voltage of the capacitor C_1, and i_{L1} is the current of the inductor L_1 with R_{L1} being its internal resistance. Considering a *RL* load, the load current at t_{k+1} can be predicted according to the following

$$i_o(k+1)=\frac{T_s\cdot V_o(k+1)+L\cdot i_o(k)}{L+R\cdot T_s} \tag{5}$$

The above (i.e., Eq. (1)-(5)) can be used to form the conventional FCS-MPC for the qZSI, as shown in Fig. 1. The variables in the ST and non-ST states are then predicted with the measured present variables. Then, the optimization during which the optimal switching state is chosen is performed to minimize the cost-function. Clearly, the performance of the FCS-MPC is affected by the cost function. The cost function used in [14] consists of three weighted factors as given in (6), where λ_i , λ_{vc} , λ_{iL} are the corresponding weighting factors and α, β represents the α *or* β-axis component, respetively.

The MPC offers high flexibility to manage several control objectives without adding significant complexity. For example: if the control objective changes, only the cost function must be adapted accordingly. Thus, it is possible to obtain the desired electrical and thermal behavior of the qZSI system by including electrical and thermal stress related information in the system model, and defining the cost function.

A possibility to reduce the thermal stress of semiconductors is to control the losses in the semiconductor devices. It is well known that the power losses in any semiconductor can be mainly expressed as the sum of the switching losses and conduction losses. The switching losses are the product of switching energies of the device and the switching frequency.

To reduce the thermal stress on the power devices, the number of commutations needs to be directly reduced. A simple approach is to modify the cost function in (6). A term that covers the number of switches changes should be added. Then, the cost function for the switching counts is obtained as

$$g_n=\lambda_n\cdot n=\lambda_n\cdot\sum_{i=1}^{6}|S_i(k)\text{-}S_i(k\text{-}1)|^2 \tag{7}$$

where n is the number of switches when the switching state S(k) is applied and λ_n is the weighting factor. Based on (6) and (7), the resulting cost function for the proposed FCS-MPC is expressed as in (8).

According to (4), the future inductor current $i_{L1}(k+1)$ has the same value during non-ST states, unlike the future values for the capacitor voltage and load current which are varying with all the states. Thus, to reduce the computations, the inductor current is taken as a key factor in selecting the unique ST state for the qZSI in this paper. With this technique, the proposed algorithm has much lower computational burden than the conventional MPC algorithm [15]. Consequently, the cost function for the proposed algorithm will include only three terms with two weighting factors for the capacitor voltage and switching counts.

$$g(x)=\lambda_i\left(\left|i_{\alpha_{ref}}(k+1)\text{-}\ i_{\alpha_o}(k+1)\right|+\left|i_{\beta_{ref}}(k+1)\text{-}\ i_{\beta_o}(k+1)\right|\right)+\lambda_{vc}\left|v_{c_{ref}}(k+1)\text{-}\ v_{c1}(k+1)\right|+\lambda_{iL}\left|i_{L_{ref}}(k+1)\text{-}\ i_{L1}(k+1)\right| \tag{6}$$

$$g(x)=g_i(k+1)+g_c(k+1)+g_n=\left|i_{\alpha_{ref}}(k+1)\text{-}\ i_{\alpha_o}(k+1)\right|+\left|i_{\beta_{ref}}(k+1)\text{-}\ i_{\beta_o}(k+1)\right|+\lambda_{vc}\left|v_{c_{ref}}(k+1)\text{-}\ v_{c1}(k+1)\right|+\ g_n \tag{8}$$

The control structure of the proposed FCS-MPC method is shown in Fig. 2. As can be seen, there are several control objectives. First, the output current should accurately track its reference value derived from the output power reference. The inductor current reference is calculated based on a power balance equation. In addition, the capacitor voltage should be regulated along its reference trajectory. Moreover, the thermal stresses of power devices are kept relatively low, which can be achieved indirectly by controlling the switching counts. Finally, the optimal control action (i.e., the switching state) is chosen by minimizing errors, reducing computational burden, and lowering switching counts. The selection process of the optimal switching states in each sampling time step is depicted in Fig. 3.

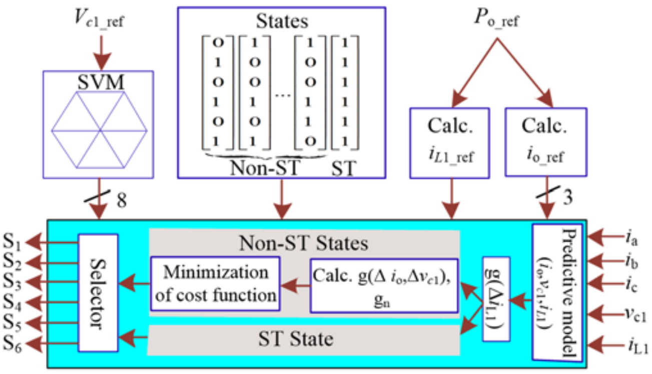

Fig. 2. Detailed control structure of the proposed FCS-MPC method.

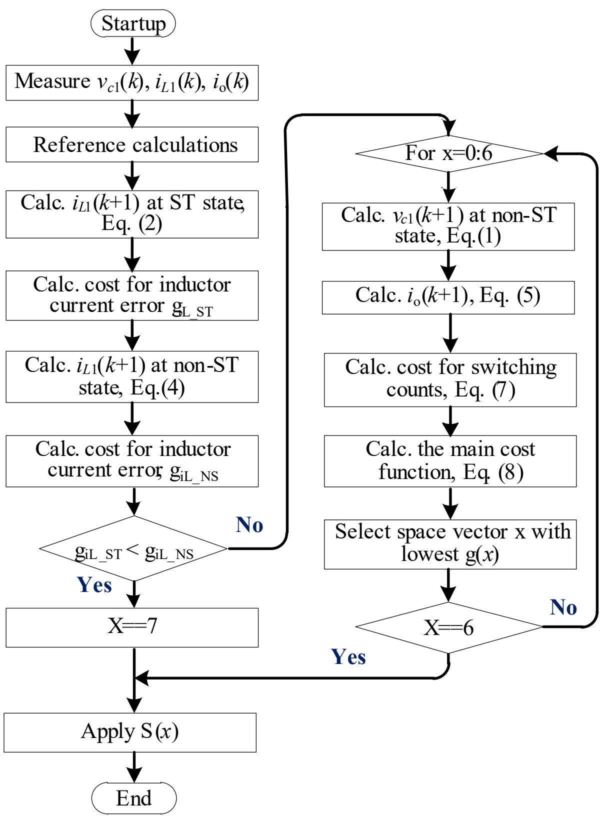

Fig. 3. Flow chart of the proposed FCS-MPC algorithm.

III. Simulation Results

To evaluate the performance of the proposed MPC scheme for the qZSI, simulations have been conducted. A comparison between the proposed FCS-MPC and the previous MPC algorithms (as in[14] and [15]) and the classical PWM-based control method (as in [16]) is carried out to assess the performance. Table II lists the parameters of the system used in the simulation. Based on the desired output power (P_{o_ref} =10 kW) The peak value for the output current reference i_{o_ref} is set to 40 A, while the input inductor current reference is set to 32 A. The peak output current reference values, and the RL load, the desired peak value of the output voltage can be calculated. The capacitor voltage reference should be larger than the calculated peak output voltage. In this paper, in order to ensure a sinusoidal waveform of the output current and to prevent the interacting between the dc and ac sides, the capacitor voltage reference is chosen to as 400 V. An FS50R12KT4 power module is employed. The pulse width modulation carrier frequency of the classical PWM-based control is set to 5 kHz to ensure the same number of commutations with the proposed MPC algorithm. The estimation of the junction temperature of the switches are done according to the thermal model and the losses in the PLECS software. The ambient temperature is set to 50 °C.

The MPC controller is different from the PI controller since there is no modulator and no linear controller. The weighting factors allow to tune the behavior of the control. Table III lists the weighting factors obtained using trial and error method.

Simulation results for both DC side and AC side of qZSI during steady-state operation are shown in Fig. 4. It is obvious that the capacitor voltage oscillates around 400 V which is the reference value for the capacitor voltage. Also, the inductor current and output current track each reference current during operation.

TABLE II. QZSI System Parameters.

Parameters	Symbol	Value
Input dc voltage	V_{in}	310 V
qZSI inductance	L_1, L_2	2 mH
qZSI inductor resistance	R_{L1}, R_{L2}	0.1 Ω
qZSI capacitor	C_1, C_2	400 µF
Load inductance	R	4 Ω
Load resistance	L	2 mH
Sample time	T_s	50 µs

TABLE III. Weighting Factors

Cost functions	λ	Value [14]	Value [15]	Value Proposed
Inductor current error	λ_{iL}	1	--	--
Output current error	λ_i	2	1	1
Capacitor voltage error	λ_{vc}	2	2	4
Commutation number	λ_n	--	--	0.3

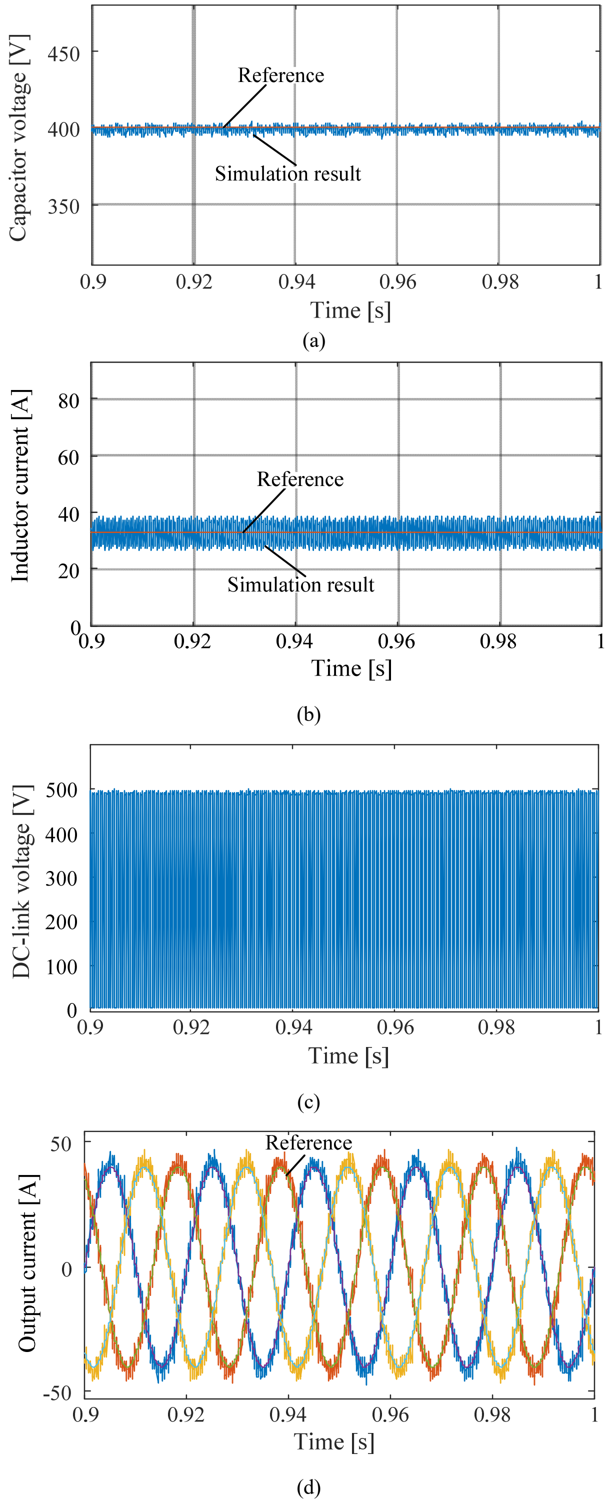

Fig. 4. Simulation results for both DC side and AC side of the qZSI with the proposed MPC control: (a) capacitor voltage, (b) input current, (c) DC-link voltage, and (d) three-phase output currents.

To further explore the effect of weighting factor of switching counts on the system performance, simulations with varying λ_n have performed. This varies the switching frequency. The effect on the maximum junction temperature, junction temperature swing, total harmonic distortion (THD) of the output current are evaluated for each set of λ_n. The impact on switching counts and THD of the output current is shown in Fig. 5. The impact on the junction temperature and its temperature cycle amplitude is shown in Fig. 6. The average switching frequency impact on junction temperature rise and THD of the output current is shown in Fig. 7. A tradeoff between these performance is used to find the optimal λ_n that fulfills the application dependent demands. Nevertheless, a compromise between the thermal performance and THD should be made.

Fig. 8 shows the switching counts and junction temperatures of S1 and S2 of the qZSI with different control methods. The benchmarking results demonstrate that the proposed FCS-MPC technique achieves the lowest junction temperature among the four methods. This is benefited from the reduction of the switching counts (commutation number), as shown in Fig. 8. The reduced thermal loading (i.e., lower junction temperature) thus contributes an improved reliability of the entire system. Furthermore, the output current quality is compared in Fig. 9 in terms of THD. Observations from Fig. 9 show that the proposed FCS-MPC results in a slightly higher THD than the method in [14] and the PWM-based control. This is in agreement with the analysis – a reduction of the switching counts will degrade the current quality.

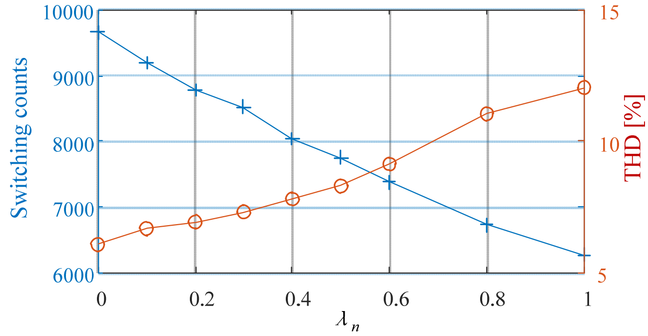

Fig. 5. Tuning of the proposed MPC by varying the λ_n. View on the switching counts versus THD of the output current.

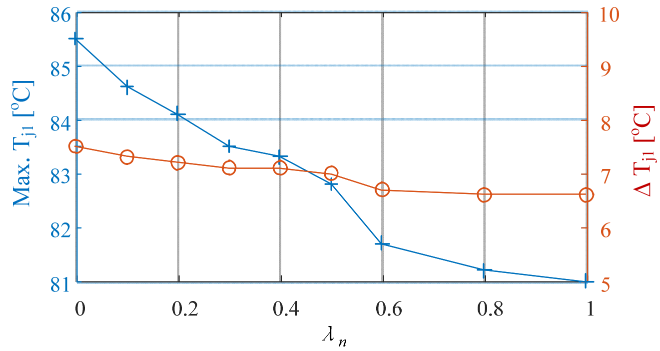

Fig. 6. Tuning of the proposed MPC by varying the λ_n. View on the maximum junction temperature and amplitude of the junction temperature cycle of S_1.

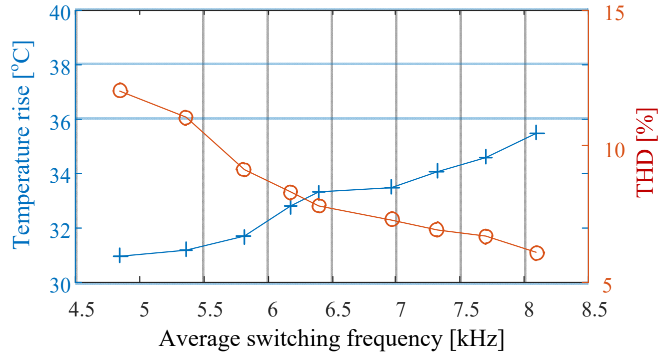

Fig. 7. Tuning of the proposed MPC by varying the λ_n. View on the junction temperature rise of S_1 versus THD of the output current.

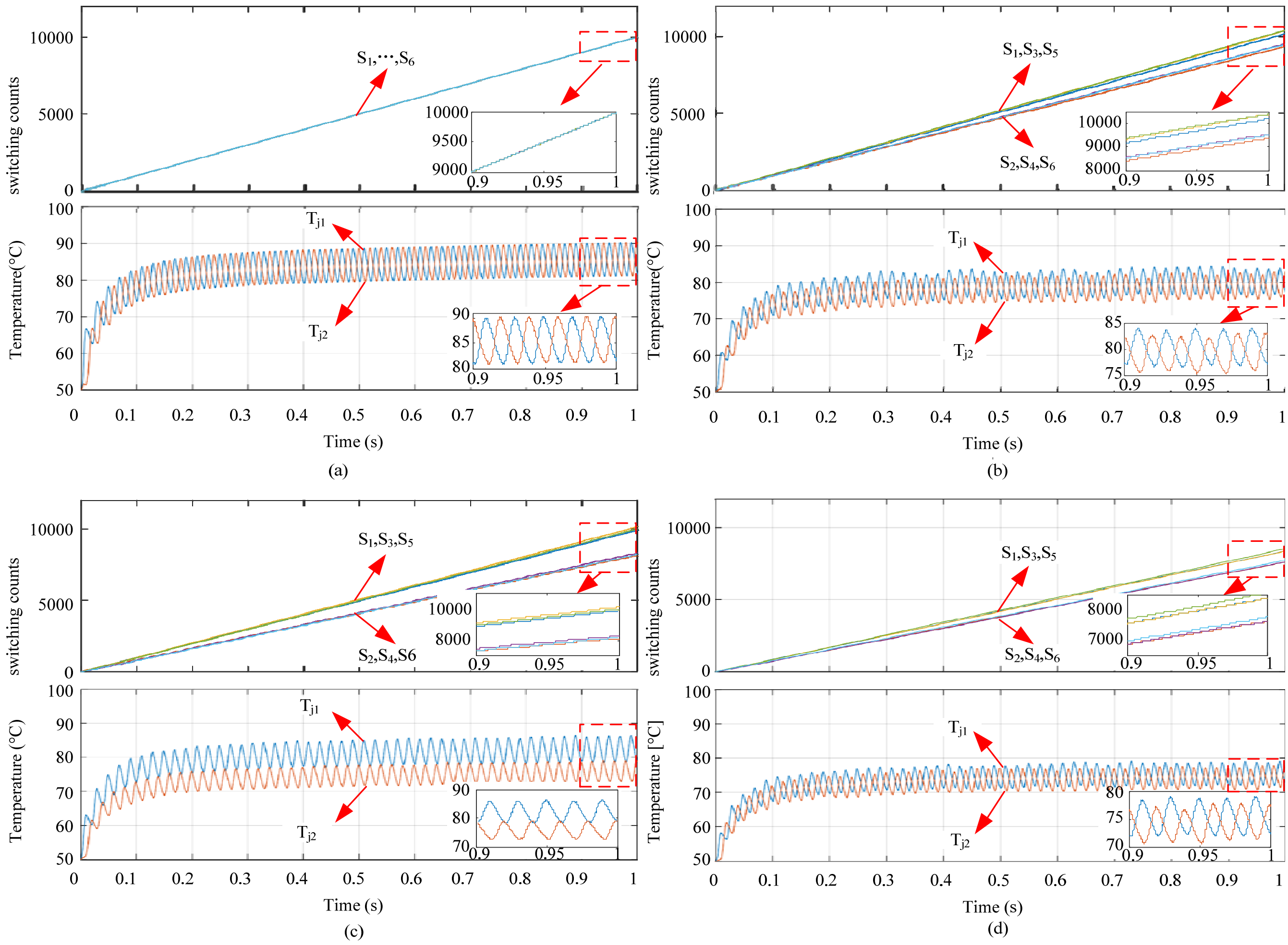

Fig. 8. Simulation results (switching counts and junction temperatures of S1 and S2 in Fig. 1) of the qZSI with (a) PWM-based control, (b) MPC in [14], (c) MPC in [15], (d) Proposed MPC

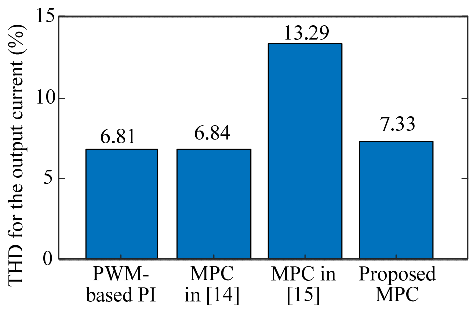

Fig. 9. THD of the output current of the qZSI.

IV. CONCLUSIONS

An FCS-MPC algorithm for the qZSI was proposed in this paper. With the proposed algorithm, a reduction of switching counts and thus the thermal stress on the power devices have been achieved, which leads to an improved reliability. The cost function of the proposed FCS-MPC is simple, where one weighting factor for the capacitor voltage and one weighting factor for the number of commutations that should be tuned. The comparison between the proposed FCS-MPC and other control methods have demonstrated the effectiveness of the proposed solution.

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