Two Effective Spectrum-Shaped FCS-MPC Approaches for Three-Level Neutral-Point-Clamped Power Converters

Xinliang Yang, Xiaodong Liu, Zhenbin Zhang⋆
School of Electrical Engineering
Shandong University
Jinan 250061, China
zbz@sdu.edu.cn

Cristian Garcia, José Rodríguez
Facultad de Ingenieria
University Andres Bello Chile
Santiago 8370146, Chile
jose.rodriguez@unab.cl

***Abstract*—Unlike pulse width modulation (PWM) based approaches, the spectra of classical finite control set model predictive control techniques spreads uniformly across a wide frequency range for power converters, which makes the design of their filters particularly difficult. An effective method to achieve spectra similar to those of PWM for two-level power converters is the so-called model predictive period control (MPPC) approach, which makes the frequency of the converter's output voltage quasi-fixed by adding a constraint on the switching frequency. In terms of output voltage change, voltage-state-change (VSC) is more relevant than switch-state-change (SSC) because the output voltage change is unequal to that of SSC for multi-level power converters. In this work we propose two different control techniques, namely, switch-state-change (SSC-MPPC) and voltage-state-change based model predictive period control (VSC-MPPC), for 3L-NPC power converters. Simulation data confirm that, i) both approaches achieve current spectra similar to those of PWM-based solutions, ii) both of them achieve quasi-fixed switch frequency, which simplifies the heat sink design, however, VSC-MPPC practically operates with half of the reference frequency for 3L-NPC converter, iii) SSC-MPPC outperforms the VSC-MPPC approach in terms of power quality and neutral point voltage regulation but consumes much more switching losses especially for high level power systems.**

***Index Terms*—Fixed switching frequency, spectrum analysis, inverters, Finite control set (FCS), model predictive control (MPC), pulse width modulation (PWM).**

I. Introduction

Model predictive control (MPC) has emerged as a promising control technique during last decade in a wide range of fields, such as power converter systems and motors [1]–[3]. Among different researched MPC strategies, the finite control set MPC (FCS-MPC) gradually stands out for its discrete characteristics which are more relevant to working state of converters, especially facing multiple non-linear objectives and system constraints. FCS-MPC makes optimal choice at each sampling instant by choosing least cost function which is calculated for all potential switch states.

Without special constraint, variable switching frequency shows up in FCS-MPC, causing the spectra of output current and voltage widely and uniformly distributed and spread in frequency domain. It can be even half of the sampling frequency at most, leading to huge energy losses of semiconductors. Appropriate filter designs become more difficult and there may be unexpected resonance excitation.

To solve this issue, several methods have been proposed; they can be classified in two categories, i.e., modulator-based solutions, e.g., [4], [5] and non-modulator-based solutions, e.g., weighting penalization [6], sliding window [7], and notch filter [8]. However, both categories have limitations, e.g., the former sacrifices inherent characteristics of FCS-MPC including faster transient response and the flexible structure, while the latter group does not always guarantee the same spectrum quality as that achieved by the modulator-based solutions.

Recently, another method based on the so-called model predictive period control (MPPC) concept was proposed for a two-level voltage source power converter [9], achieving a quasi-fixed frequency pattern, good current tracking performance and extremely similar spectra of current and voltage with pules width modulation (PWM) strategy. However, its optimality dubious; the half bridge voltage state is more relevant to the output voltage of multi-level power converters, but the difference between the switch-state-change (SSC) and voltage-state-change (VSC) frequencies is minimal when they operate on a two-level inverter.

In this work, we closely investigate the influence of SSC and VSC frequencies on the MPPC approach and further propose two effective spectrum-shaped FCS-MPC methods, namely, SSC-MPPC and VSC-MPPC for grid-tied 3L-NPC power converters. For this paper, "switching" means VSC or SSC while discuss the corresponding strategies and the "switch" represents the real switches. The effectiveness of the proposed

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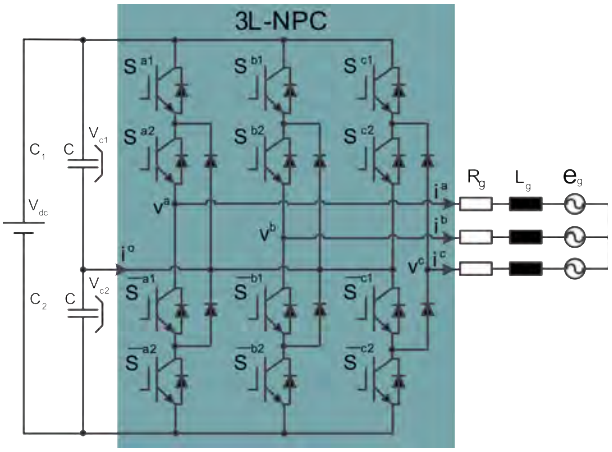

Fig. 1: Simplified electrical circuit of a grid-tied 3L-NPC converter with RL filter connected to an ideal grid.

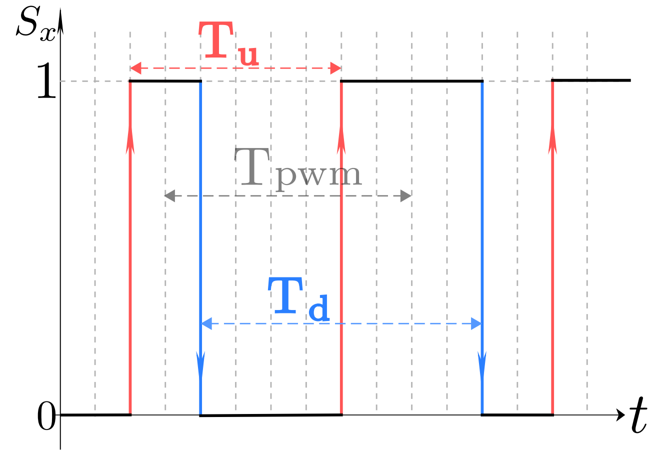

Fig. 2: Period definition comparison between $\mathrm{T_u}$,$\mathrm{T_d}$ for MPPC and $\mathrm{T_{pwm}}$ for PWM control.

methods is verified and compared with the conventional FCS-MPC strategy through simulation results.

II. Discrete Converter Model

A three-level grid-tied NPC converter is chosen for the implementation of the different strategies; it is depicted in Fig. 1.

A. 3L-NPC Power Converter

For $x \in \{a, b, c\}$ and $i \in \{1, 2\}$, the upper and lower switches are denoted, respectively, as S^{xi} and $\overline{\mathrm{S}}^{xi}$. The relation between the switch state and the half bridge voltage state (V_x) is defined as

$$V_x := \mathcal{G}(S^x) = \begin{cases} P & \text{if} : S^{x1} = 1 \wedge S^{x2} = 1 \\ O & \text{if} : S^{x1} = 0 \wedge S^{x2} = 1 \\ N & \text{if} : S^{x1} = 0 \wedge S^{x2} = 0. \end{cases} \quad (1)$$

It is worth mentioning that VSC is sufficient and unnecessary condition of SSC because of redundant switch states corresponding the same voltage vector, which means SSC-MPPC has more relaxation in trade-off process than VSC-MPPC.

In the condition of enough high sampling frequency, the Forward Euler approximation ($\frac{d}{dt}x(t) \approx \frac{x[k+1]-x[k]}{T_s}$) is utilized on the derivative of grid current, the discrete equation to define the system in $(\alpha\beta)$ frame is summarized as

$$i(k+1) = \left(1 - R_g \frac{T_s}{L_g}\right) i(k) + \frac{T_s}{L_g}(v(k) - e(k)) \quad (2)$$

$$V_o(k+1) = V_o(k) - \frac{T_s}{C}(i_{abc})^{\top} |V_{abc}|, \quad (3)$$

where $i_{abc}{}^{\top} = (i_a, i_b, i_c)$, $C = C_1 = C_2$ denotes the DC-link capacitance, R_g and L_g denote filter resistance and inductance, $v = (v_\alpha, v_\beta)^{\top}$ and $i = (i_\alpha, i_\beta)^{\top}$ are the output voltage and current, $e = (e_\alpha, e_\beta)^{\top}$ is the grid voltage. T_s is sampling period and V_o is the DC-link voltage difference.

III. Proposed VSC-MPPC and SSC-MPPC Strategies

Thinking of the converter as an output voltage source for the load, the fluctuating of output voltage introduces the different component in frequency domain. Therefore, imitating the pwm type strategies, MPPC aims to fix the switching frequency by adding a relevant constraint into the cost functinon . Emerging difficulties are that, i) the frequency definition is based on a prior period, but conventional FCS-MPC has no memory. ii) FCS-MPC cannot predict the centers of the switching cycles, which makes old criteria for the period definition of PWM strategy unusable, iii) the so-called switching frequency has uncertainty including VSC frequency and SSC frequency while they are equal with each other for 2-level inverters and the former one is more relative to output voltage fluctuating

To address these problems, as illustrated in Fig. 2, MPPC perceives averaged time between similar switching behaviors including rising up (T_{u}) and falling down (T_{d}) as period ($T = \dfrac{T_{\mathrm{u}} + T_{\mathrm{d}}}{2}$). Additionally, an integer K is utilized to count sampling periods, thus providing the required record of prior periods.

A. Switching Period Estimation of SSC and VSC

In SSC-MPPC, switch states are transferred from the half bridge voltage states as per Eq. 1. It is sufficient for the cost function to consider only six switch states because the lower switches' T_{d} and T_{u} are equal to the upper ones' T_{u} and T_{d}, respectively.

As for VSC-MPPC, the half-bridge voltage states have negative values while the lower two switches are both conducting, which makes binary logical calculation inapplicable. To address this issue, we utilize the absolute value $|V|$ to make half-bridge voltage states occur only between zero and $\dfrac{V_{\mathrm{dc}}}{2}$. However, at the same time, it means no constraint is applied to the voltage polarity; there would be the situation illustrated in Fig. 3, eve though a constant frequency of VSC is achieved from the view of the controller, the frequency of

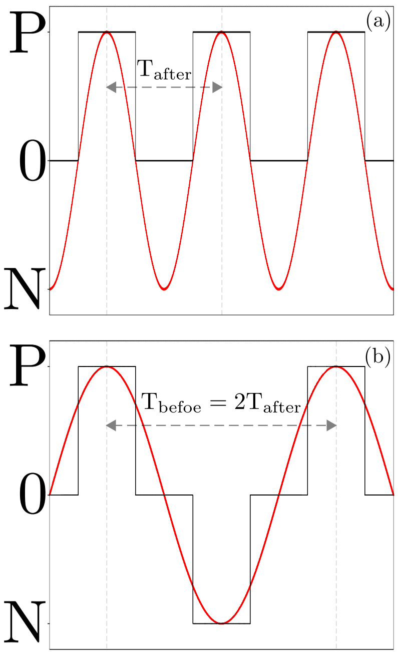

Fig. 3: Fundamental wave (a) after and (b) before absolute value operation.

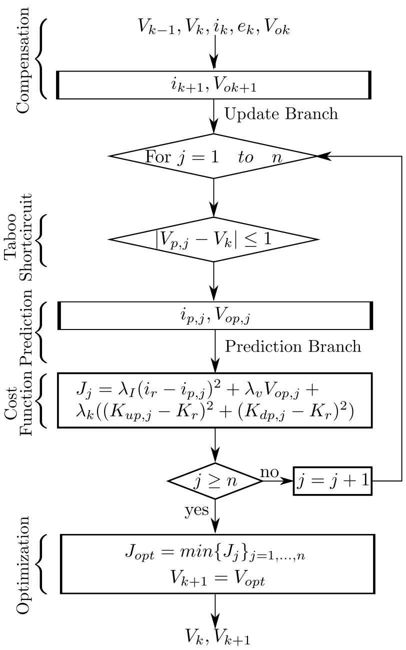

Fig. 4: Flow chart of the whole strategy for SSC- and VSC-MPPC.

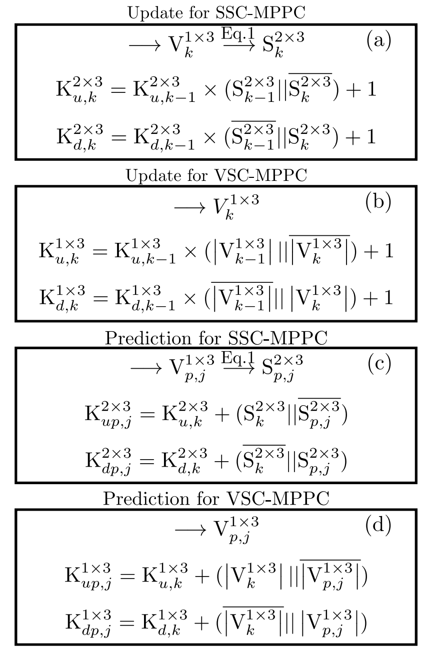

Fig. 5: Different branch components for SSC-MPPC and VSC-MPPC.

the fundamental wave component decreases to half its original value.

B. Cost Function

Along with the current tracking term J_{I} and voltage balance term J_{V}, switching frequency constraint can be indirectly added into the cost function as follows:

$$
\begin{aligned}
J_{\mathrm{T}} &= ((T_{\mathrm{u}} - T_{\mathrm{r}})^2 + (T_{\mathrm{d}} - T_{\mathrm{r}})^2)\lambda_{\mathrm{T}} && (4)\\
&= ((K_{\mathrm{u}} - K_{\mathrm{r}})^2 + (K_{\mathrm{d}} - K_{\mathrm{r}})^2)\lambda_{\mathrm{K}}, && (5)
\end{aligned}
$$

where $\lambda_{\mathrm{K}} = \lambda_{\mathrm{T}} {\mathrm{T}_{\mathrm{s}}}^2$, T_{r} is the reference switching period, and integers K_{u} and K_{d} represent how many sampling periods the switch state stays constant, declining float number computation burden.

C. Implementation

Fig. 4 illustrates the whole strategy, which contains the extra steps presented in Fig. 5 including prediction and update of switching period. The superscripts represent the matrix dimensions, such as $\mathrm{V}^{1\times3} = [V_a, V_b, V_c]$, $\mathrm{K}_u^{1\times3} = [K_{u,a}, K_{u,b}, K_{u,c}]$. Along with the inclusion of a compensation delay, the two-step change of the half bridge voltage is prohibited so as to prevent a short circuit. https://www.overleaf.com/project/5f19eaee3cd06600013aa21e In the update branch of VSC-MPPC, $\mathrm{V}^{1\times3}$ represents three half-bridge voltage states, K_u and K_d are increased by +1 if no commutation takes place and reset to 1 when the corresponding voltage steps up or down. $|\mathrm{V}_{k-1}|\,||\overline{|V_k|}$ and $\overline{|\mathrm{V}_{k-1}|}||\,|\mathrm{V}_k|$ become zero only when an up or down edge takes place, respectively. The prediction branch is different in that K_u and K_d stay constant instead of resetting to 1 when a commutation occurs.

As for SSC-MPPC, $\mathrm{S}^{2\times3}$ is a 2 by 3 matrix corresponding to six upper switches as explained in Sec. III-A. As Fig. 5 illustrates, $\mathrm{K}_u^{2\times3}$ and $\mathrm{K}_d^{2\times3}$ come from $\mathrm{S}^{2\times3}$, which is transferred from the voltage state matrix $\mathrm{V}^{1\times3}$ as per Eq. 1.

IV. Simulation Results

Simulations results using the proposed tow spectrum-shaped strategies are presented in this section. System parameters are listed in Table. I. To make the comparison fairer, the average switching frequency of conventional FCS-MPC is regulated to about F_{r1} by simple penalization on switching.

A. Steady-State Performance

As illustrated in Fig. 6(a) and (c), VSC-MPPC presents higher ripples at peak current and a higher averaged total harmonics distortion value (THD_{avg}). As Fig. 6(b) and (d) present, the half-bridge voltage shows monopolar-PWM modulation-like behaviors especially for VSC-MPPC.

The current spectra are illustrated in Fig. 7, where the fundamental frequency is 50 Hz. Besides the similar spectra distribution to that of the PWM strategy, the centers of the high-frequency components are slightly higher than the multiples of the reference switching frequency. Fig. 7(b) has an extra peak centered at about half of the reference value $F_{r2} = 4$kHz (explained in III-A for the Fig. 3).

Instead of Averaged Sliding Window measurements for frequency, Fig. 8 shows that the real switching frequency for a single switch fluctuates around the reference value F_{r1} under SSC-MPPC control but around half of F_{r2} under VSC-MPPC control, and the former one's frequency tracking

TABLE I: Simulation Parameters

Load resistor	Load inductor	DC-link voltage	Sampling frequency	Ref.switching frequency	Ref.current magnitude	Ref.current frequency	Weight factors
R [Ω]	L [mH]	V_{dc} [V]	F_s [kHz]	F_{r1}, F_{r2} [Hz]	I_r [A]	ω_r [Hz]	λ_I, λ_k,λ_v [-]
0.156	8	800	80	4000,4000	24	50	100,10,38

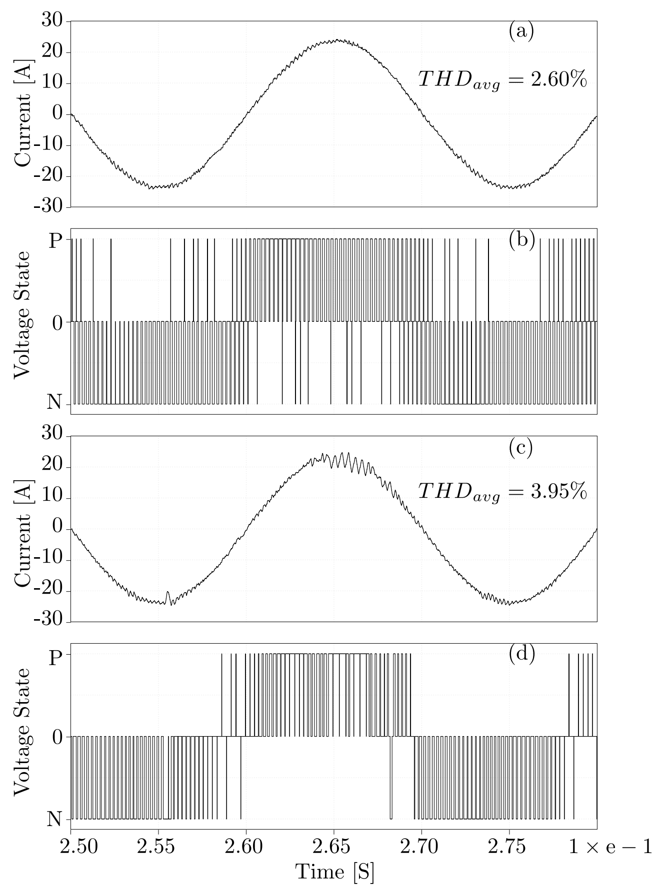

Fig. 6: Simulation results for phase A: (a) load current and (b) inverter voltage for SSC-MPPC, (c) load current and (d) inverter voltage for VSC-MPPC.

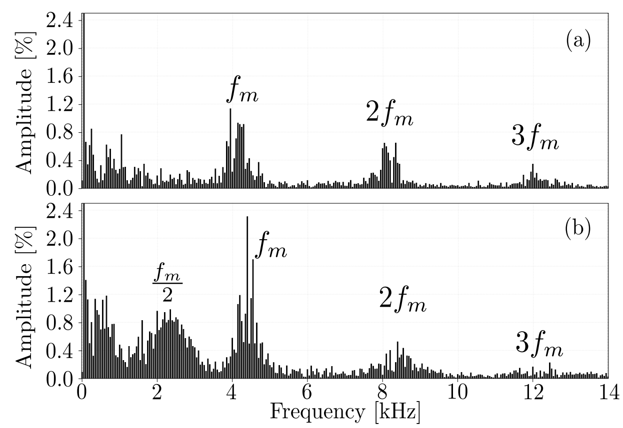

Fig. 7: Load current spectra (a) SSC-MPPC, (b) VSC-MPPC.

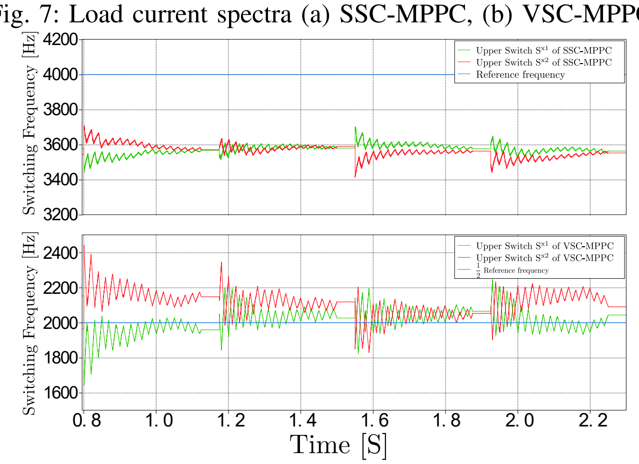

Fig. 8: Real switching frequency of a single switch for SSC-MPPC and VSC-MPPC.

performance is more accurate and the later one has bigger amplitude of the ripples. It means both of them maintain quasi-fixed frequency and uniform switching losses, which simplifies the heat sink design. Compared with SSC-MPPC, there is a obvious advantage that VSC-MPPC could reduce much switching losses while achieving the same approximately equal equivalent PWM carrier frequency, much lower frequency of real switches and qualified THD value.

So the reason why VSC-MPPC has comparatively more ripples for peak current and worse THD value is that, i) the real switching frequency is lower, which means less tracking correction for current, ii) VSC is the sufficient and unnecessary condition of SSC(see II-A), iii) while the wanted current slope is high, the half-bridge voltage is more possibly P or 0 to maintain the current rising or falling trend; but when the slope is low, with the constraint of switching frequency still existing, to retain the current almost constant, there would be more possibility that the voltage states N more frequently happen without long-horizon prediction, in another word, the optimal half-bridge voltage state for one controlling period is not the optimal one for period control, and the same process in reverse slope situation.

B. Transient State Performance

Very fast response is an advantageous property that is desirable to maintain in FCS-MPC. Fig. 11 shows the results

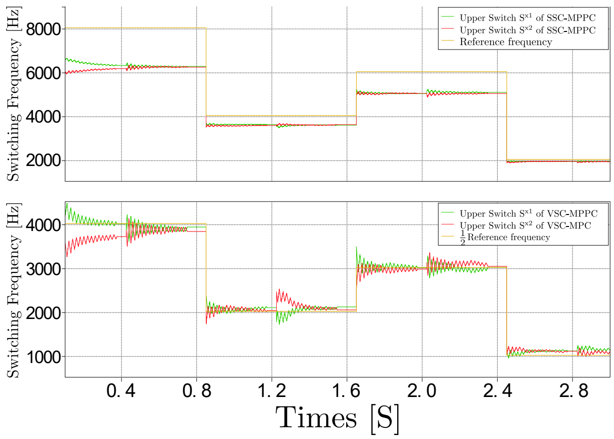

Fig. 9: Transient of switching frequency step: (a) SSC-MPPC, (b) VSC-MPPC.

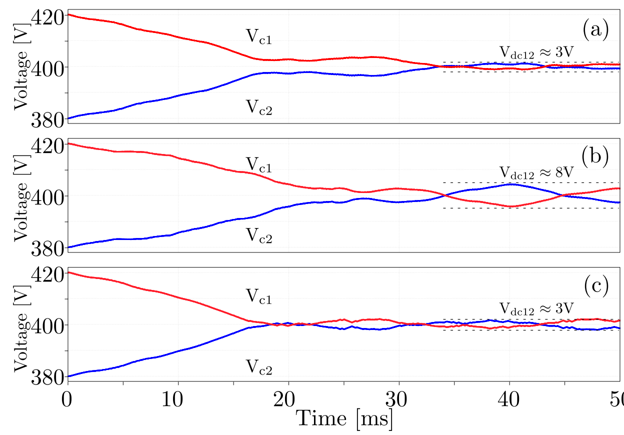

Fig. 10: voltage balance: (a) SSC-MPPC, (b) VSC-MPPC, (c) conventional FCS-MPC.

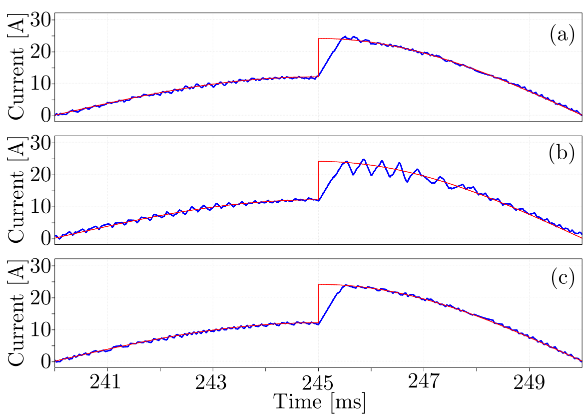

Fig. 11: Transient of current step: (a) SSC-MPPC, (b)VSC-MPPC, (c) FCS-MPC.

of applying instant growing and falling reference switching frequency for both proposed strategies. It can be seen that the hard stepping transition of references witnesses their fast tracking performance without visible difference. However, the accuracy of SSC-MPPC obviously unenough that usually there is a negative tracking error which could be solved by adding a PI control loop [10].

The results of the current reference step test from 12A to 24A at 0.245s both with and without a frequency constraint are illustrated in Fig. 11. It is obvious that more noise exists for the lower current reference value, which is inherent to FCS-MPC. For transient performance, the addition of a frequency constraint makes the control slower, and it takes two and three times longer to reach steady state in SSC-MPPC and VSC-MPPC, respectively. On the other hand, both strategies present overshoot behaviors.

As for the NPC converter, the voltage balance and its need for a fast regulating ability represent another challenge. The process is achieved by setting the initial capacitor voltage difference at about 40V as presented in Fig. 10. Obviously, conventional FCS-MPC has a more balanced performance and spends less time reaching to steady state. Between the two proposed strategies, SSC-MPPC shows a lower voltage difference between two capacitors.

V. Conclusions

This paper proposes different controllers using SSC-MPPC and VSC-MPPC on a grid-tied NPC converter. The main contribution lies in the design of different branches based on basic MPPC (See Fig. 5), including prediction and update branches. Simulation results indicate that both control strategies achieve spectra similar to that of the PWM stategy, but SSC-MPPC has better current tracking (especially at the peak portion) as well as a lower capacitor voltage difference during steady state. In addition, the spectrum of VSC-MPPC has an extra peak component at half the reference frequency because of the lack of constraint on voltage polarity. Both of them achieve uniform losses of each switch, however, VSC-MPPC practically operates with half of the reference frequency for 3L-NPC converter, which means it consumes much less switching losses. Overall, VSC-MPPC is better than SSC-MPPC for spectrum-shaped application especially on high power level systems.

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