Finite Control Set Model Predictive Control for LCL-Filter-Based Grid-Tied NPC Inverter

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Abstract—Recently, finite control set model predictive control (FCS-MPC) has been successfully used in the two-level grid-tied inverter with LCL filter. This method can be also adopted for the three-level inverter. However, the DC link capacitor voltages of three-level inverter need to be balanced. This paper presents a new implementation using FCS-MPC for a grid-connected neutral-point-clamped (NPC) inverter with LCL filter in stationary qdf frame, which is capable to balance the DC link capacitor voltages, damp the oscillation caused by the LCL filter, and generate a sinusoidal grid-injected current by adopting the multivariable control. Simulation model is built to verify the performance of the proposed modified control method under stiff and weak grid, distorted grid voltage and unbalanced grid voltages conditions.

Keywords—finite control set model predictive control (FCS-MPC); grid-connected NPC inverter; LCL filter; multivariable control

I. INTRODUCTION

With the increasing popularity of distributed renewable energy system, applications for grid-connected inverters have a great importance in fields like distributed generation, energy storage systems, etc.[1]-[3]. In these applications, using three-level inverter can reduce current ripples, decrease switching power losses, and obtain the smaller output inverter common mode voltages in contrast to its two-level equivalent [4]. Aside from these several advantages, however, it also faces some major limitations including neutral point voltage balancing and robustness against the parameter uncertainties, etc.

Selection of a suitable control strategy is vital to solve these problems and obtain good quality grid-injected current. Therefore, it is extremely significant to study control strategy of a grid-tied NPC inverter. Some linear and nonlinear control strategies have been proposed for this inverter to solve these problems, e.g. proportional-integral (PI) control, proportional-resonance (PR) control, sliding mode control (SMC), passive-based control (PBC) and model predictive control (MPC), etc [5]-[7].

MPC is a kind of model-based optimal control strategy. It is widely used in process control area. With rise of the computing power of digital signal processors (DSP), MPC appears as an attractive alternative for the control of power electronics due to its fast dynamic response and flexible control scheme that allows the easy inclusion of system constraints and nonlinearities [8]. Due to these various advantages, MPC has been implemented in different power converter topologies such as voltage source inverter [9], rectifier and inverter (ac-dc-ac) system [10], direct matrix converter [11] and indirect matrix converter [12], etc. Although several variants of MPC have been developed within power electronics, the FCS-MPC approach has become the best known. In this control, a system model is used to predict the system behavior using the present states and the control action. The control objectives of FCS-MPC can vary considerably according to the application. For example, the voltage or current for inverter systems. The basic principle of the FCS-MPC is to construct a multi-objective optimization cost function in order to judge the inverter’s states and determine the appropriate switching combinations. Specifically, the switching states that can result in the minimum cost function will be chosen and applied in the next switching cycle [13].

Recently, FCS-MPC has been successfully used in two-level grid-tied inverter with LCL filter [13]. This method can be also adopted for the three-level inverter. However, the DC link capacitor voltages of three-level inverter need to be balanced. Extra algorithm is used to balance voltages of DC link capacitor for the three-level inverter in [14]. Based on the control method for two-level inverter in [13], the proposed modified FCS-MPC strategy for the grid-tied NPC inverter in this paper adopts one of the MPC features: multivariable control in one cost function. One model of the LCL filter is applied to predict future behavior of the state variables: inverter current, capacitor voltage and grid current. Another model of capacitor at DC link is employed to predict the future DC link capacitor voltages. Then, the four variables are considered into a cost function to control the system. The modified control method can achieve the effects of balancing the DC link capacitor voltages, damping the oscillation caused by LCL filter and providing a sinusoidal grid-injected current.

The remainder of this paper is organized as follows. In Section II, mathematical model of grid-connected NPC inverter with LCL filter is presented. The proposed modified FCS-MPC method is described in Section III. Then, simulation results are documented in Section IV, where the performance of the modified method are analyzed under stiff and weak grid, distorted grid voltage and unbalanced grid voltage conditions. Finally, conclusions are given in Section V.

II. MATHEMATICAL MODEL OF GRID-CONNECTED NPC INVERTER WITH LCL FILTER

The schematic diagram of the proposed modified FCS-MPC method for grid-connected NPC inverter with LCL
The output voltage vector of NPC inverter can be described as a complex space vector in $a\beta$ stationary reference frame:

$$v_{a\beta}(n) = \begin{cases} 
0, & n = \{0,1,2\} \\
\frac{1}{3}U_d e^{j\alpha(n-1)}, & n = \{3,4,\ldots,14\} \\
\frac{\sqrt{3}}{3}U_d e^{j\alpha(n-2)}, & n = \{15,16,\ldots,20\} \\
\frac{2}{3}U_d e^{j\alpha(n-2)}, & n = \{21,22,\ldots,26\} 
\end{cases}$$

(1)

Using the Clarke’s transformation, the dynamic model in $a\beta$ stationary reference frame of LCL filter can be expressed as:

$$\frac{dx}{dt} = Ax + Bv_{a\beta} + B_d v_{g\alpha\beta}$$

(2)

where

$$x = \begin{bmatrix} i_{a\beta} \\ i_{g\alpha\beta} \\ u_{a\beta} \end{bmatrix},$$

$$A = \begin{bmatrix} 0 & 0 & -1/L_2 \\
0 & 0 & 1/L_2 \\
1/C & -1/C & 0 \end{bmatrix}$$

(4)

$$B = \begin{bmatrix} 1/L_1 \\ 0 \\ 0 \end{bmatrix}^T$$

(5)

$$B_d = \begin{bmatrix} 0 \\ 1/L_2 \\ 0 \end{bmatrix}^T$$

(6)

Next, a discrete-time model of the LCL filter is obtained from (2) for a sampling time $T_s$ and is expressed as:

$$x(k+1) = Ax(k) + Bv_{a\beta}(k) + B_d v_{g\alpha\beta}(k)$$

(7)

where matrices $A_1, B_1, B_2$ are

$$A = e^{AT}; B_1 = \int_0^{T_s} e^{AT} B_d d\tau; B_2 = \int_0^{T_s} e^{AT} B_d d\tau$$

(8)

The dynamic process of the DC link capacitor voltage can be described by the capacitive differential equation. The value of the capacitors voltage derivation can be approximated as

$$\frac{dv_{xc}(k+1)}{dt} \approx \frac{v_{xc}(k+1) - v_{xc}(k)}{T_s}$$

(9)

Where $x = 1,2$.

Then, the predicted values of the DC link capacitors voltage are calculated as follows:

$$v_{xc}(k+1) = v_{xc}(k) + \frac{1}{C_x}i_{xc}(k)T_s$$

(10)

Where $i_{xc}$ is the current of DC link capacitor. The current of DC link capacitor depends on the switching state and value of output current of the inverter, and it can be calculated by the following expression.

$$i_{xc}(k) = i_{a\beta}(k) - H_{11}i_a(k) - H_{12}i_b(k) - H_{13}i_c(k)$$

$$i_{ga}(k) = i_{dc}(k) + H_{21}i_a(k) + H_{22}i_b(k) + H_{23}i_c(k)$$

(11)

Where $i_{dc}$ is the current of DC source and $H$ is decided by the switching state.

$$H_{1y} = \begin{cases} 
1, & S_y = ”1” \\
0, & otherwise 
\end{cases}$$

$$H_{2y} = \begin{cases} 
1, & S_y = ”0” \\
0, & otherwise 
\end{cases}$$

(12)

Where $y=a,b,c$.

The switching state of $y$ phase of the inverter is shown in Table II. (e.g. the meaning of $y1$ is the first switch of the $y$ phase)

<table>
<thead>
<tr>
<th>$S_1$</th>
<th>$S_{11}$</th>
<th>$S_{12}$</th>
<th>$S_{13}$</th>
<th>$S_{14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

(13)
The performance and effectiveness of the proposed modified FCS-MPC algorithm for a grid-connected NPC inverter with an LCL filter are evaluated using MATLAB/Simulink model. System performance is mainly analyzed under stiff and weak grid, distorted grid voltage and unbalanced grid voltages conditions.

### 4. Simulation Results

The performance and effectiveness of the proposed modified FCS-MPC algorithm for a grid-connected NPC inverter with an LCL filter are evaluated using MATLAB/Simulink model. System performance is mainly analyzed under stiff and weak grid, distorted grid voltage and unbalanced grid voltages conditions.

### 4.1 Under the Stiff Grid Condition

Fig. 3 shows the steady grid voltage and current under the stiff grid condition. It is shown in the figures that the output grid-injected currents of inverter with LCL filter are sinusoidal with lower distortion and it is illustrated that the overall behavior of the system is improved compared with LCL filter.

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**Fig. 2 The flowchart of proposed modified FCS-MPC method**

1) Using the reference grid current vector \( i_{x}^{\text{ref}} \), it is possible to calculate the reference values of the capacitor voltage and inverter current

\[
\begin{align*}
u_{g}^{*} &= v_{g} - L_{c}\omega i_{a}^{*} \\
u_{g}^{*} &= v_{g} + L_{c}\omega i_{b}^{*} \\
\end{align*}
\]

\[
\begin{align*}
i_{a}^{*} &= (1 - CL_{c}\omega^{2})i_{a}^{*} \\
i_{b}^{*} &= (1 - CL_{c}\omega^{2})i_{b}^{*} \\
\end{align*}
\]
filter. Furthermore, as the grid current harmonics spectrums (a phase) depicted in Fig.4, the total harmonic distortion (THD) of grid current is low and the harmonics related with resonance frequency of LCL filter have only a small value. It can greatly prove the validity of the proposed strategy for LCL structure.

Additionally, another aim of the proposed algorithm is to balance the voltage of DC link capacitors. As shown in Fig.5, the voltages of DC link capacitors are accurately balanced with the weighting factor at the beginning and then they are becoming unbalanced with the weighting factor set to zero at 0.05s. Next, if the error of DC link capacitors voltages reaches to 40V, the weighting factor will add to the cost function again. The figure demonstrates that the voltages of the DC link capacitors fluctuate slightly around a value respectively. Thus, it can prove that the control strategy is effective for balancing the voltages of the DC link capacitor.

As shown in Fig.6(a), the reference grid current is set at a value of 12.86 A (peak) and then stepped up to 20A (peak) for each phase at 0.08s, and the simulation result demonstrates that, each phase grid current is accurately tracking the reference value and reaching to its steady state condition in approximately 1ms, far less than a quarter of the fundamental cycle, performing a good dynamic response. And, the voltage of the DC link capacitors are displayed in Fig.6(b), we can find that the waveforms have only a small change and reach to its steady state quickly when the reference grid-injected current changes. Thus, it verifies the feasibility of the proposed control method.
B. Under the Weak Grid Condition

As depicted in Fig.7, it displays the voltage and current waveforms of the point of common coupling (PCC) under the weak grid condition (\(I_g = 5mH\)). We can find that the grid currents have a low THD even adding the additional grid inductance. It is illustrated that the proposed control method is robust against the impact of grid inductance.

![Fig.7: Simulation results under the weak grid condition (\(I_g = 5mH\)).](image)

C. Under the Distorted Grid Voltage Condition

The grid voltage often behaves distorted from sine wave due to nonlinear loads. The proposed control algorithm should be robust enough to cope with this type of disturbance. When the grid voltage is distorted by the 3rd, 5th, 7th, 9th, and 11th harmonics, whose magnitudes with respect to the grid fundamental voltage are 1.2\%, 2.8\%, 1.3\%, 2.4\% and 1.5\%, respectively [5]. As depicted in Fig.8, the grid current behaves a good quality (low THD). And, it behaves the good robustness of the proposed control methods.

![Fig.8: Simulation results under the distorted grid voltage condition.](image)

D. Under the Unbalanced Grid Voltages

The voltage dips is generally caused by the failure of the power grid like short circuit faults, or sudden changes in the load, such as the start of high-power equipment. It can cause many problems in control of the inverter. The performance of grid current under a 30\% single phase (a phase) voltage dips and a 30\% single phase (c phase) voltage rises with a duration of 40ms from 0.03s to 0.07s is displayed in Fig.9. It can be observed that the grid currents are balanced (only relatively small transients at the beginning and the end of the voltage changes).

![Fig.9: Simulation results under the unbalanced grid voltages condition (a phase 30\% dips, c phase 30\% rises).](image)

V. Conclusion

A new implementation using FCS-MPC for a grid-connected NPC inverter with LCL filter has been presented in this paper. Based on the FCS-MPC algorithm for two-level inverter in [13], the proposed method for the grid-tied NPC inverter adopts the multivariable control with the DC link capacitor voltages considered into the cost function, which avoids the extra control algorithm to balance the DC link capacitor voltages. The effectiveness and high performance of proposed control strategy have been verified by using simulations under stiff and weak grid, distorted grid voltage and unbalanced grid voltages conditions.

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