Mitigating $dv/dt$ Stress Caused by the Line-line Voltage Polarity Reversal in Model Predictive Controlled VSI Drives

Ameer Janabi, Shukai Wang, Jacob Buys, and Bingsen Wang

Electrical and Computer Engineering Department
Michigan State University
East Lansing, USA

janabiam@msu.edu; wangshuk@msu.edu; buysjaco@msu.edu; bingsen@egr.msu.edu

Abstract—This paper deals with a particular problem in the conventional finite set model predictive control (FS-MPC) method in VSI drives. When FS-MPC is experimentally implemented, the controller chooses any one of the eight available voltage vectors. Therefore, if the controller selects any of the far states, simultaneous switching events among the inverter legs occur. This causes line-line voltage polarity reversal (LLVPR) with the voltage change twice the value of the DC-link voltage. The fast LLVPR combined with the reflected wave by the motor cable can damage the insulation of the stator winding. In this letter, the problem of LLVPR in electric drives with FS-MPC is described, and the solution to this issue is proposed. Experimental results to validate the proposed method are shown.

I. INTRODUCTION

In recent years, finite set model predictive control (FS-MPC) has been proposed as an alternative to the conventional control of power converters and drives [1]. The FS-MPC uses a model of the system to predict the future behavior for a given finite-set of possible actuations. The actuation that minimizes the control objective is selected. The algorithm is repeated every sampling time with considering the new measured states. Several applications of this controlling principle are summarized in [2].

The predictive model enumerates all the possible voltage vectors and selects the one that minimizes the objective function. Simultaneous switching among the inverter legs occurs every time the controller chooses one of the nonadjacent voltage vectors with respect to the present voltage vector. During this type of events, motors that are fed by long cables suffer from high over-voltage due to the line-line voltage polarity reversal (LLVPR). During LLVPR a direct transition from $V_{dc}$ to $-V_{dc}$ or the reverse in the line-line voltage takes place. Due to the reflected-wave phenomenon, such a transition will generate a very high voltage at the motor winding terminals, especially when the motor leads are long [3].

Therefore, voltage reversal is problematic in many PWM-VSI drives. It can occur in SVPWM and SPWM when the inverter operates at the limit of the linear region before the overmodulation and at the border of each sector. A customized solution presented [4] and [5] in the case of SVPWM. However, this comes with the cost of limiting the modulation index.

To this time LLVPR problem has never been addressed in model predictive control case despite the popularity of FS-MPC in the research area.

In this paper, a new model predictive control algorithm is presented that allows only one switch to turn-on and one switch turn-off at each end of the sampling time. The line-line voltage reversal is successfully prohibited as shown in the simulation and the experimental results.

II. CONVENTIONAL MODEL PREDICTIVE CONTROL

The predictive current control scheme using MPC is shown in Fig. 1, and it consists of the following steps:
1- measurement of the load currents;
2- prediction of the load currents for the next sampling instant for all possible switching states;
3- evaluation of the cost function for each prediction;
4- selection of the switching state that minimizes the cost function;
5- application of the new switching state.

In the case of current control, the cost function is defined as the error between the reference current and the predicted currents for a given switching state, and it is expressed as

$$g = |i^*_{\alpha} - i^p_{\alpha}| + |i^*_{\beta} - i^p_{\beta}|$$

(1)

where $i^*_{\alpha}$ and $i^*_{\beta}$ are the real and imaginary parts of the reference current vector, respectively, and $i^p_{\alpha}$ and $i^p_{\beta}$ are the real and imaginary parts of the predicted load current vector $i^p_{(k+1)}$, respectively. The predicted load current vector is calculated...
Fig. 2: Simulation results of the (a) conventional MPC method and (b) proposed MPC method.

Fig. 3: Total harmonic distortion of the load current for both the conventional MPC and the proposed MPC.

Fig. 4: The total number of actuation by the inverter per fundamental cycle.

using a discrete-time model of the load, which is a function of measured currents $i_{k}(k)$, inverter voltage $v_{k}(k)$, and load back electromotive force (EMF) $e$, and it is expressed as:

$$i_{k+1}^{p} = (1 - \frac{RT_s}{L})i_{k} + \frac{T_s}{L}(v_{x}(k) - e(k))$$  \hspace{1cm} (2)$$

where $R$ and $L$ are the load resistance and inductance, respectively, $T_s$ is the sampling time, $e$ is the estimated back EMF, and $x$ is the index of the voltage vector. As the MPC chooses the voltage vector that minimizes $g$, the line-line voltage reversal can occur during the steady-state operation and leads to $\frac{dv}{dt} = 2V_{dc}$ in the line-line voltage as shown in Fig. 2a. Note that during a small transient, the simultaneous switching occurs in all of the three legs of the inverter with six switches of the inverter at the same time. To overcome this shortcoming in the MPC controller, we propose the following algorithm.

III. PROPOSED MODEL PREDICTIVE CONTROL

A simple solution to avoid the $2V_{dc}$ line-line voltage reversal is to restrict the selection of the optimal voltage vector such that only one switch turns-on and one switch turns-off at the end of each sampling interval $T_s$. This can be implemented by using the following steps:

1- Measurement of the load currents;

2- Based on the previous switching state, construct the available finite-set. The available finite-set includes the switching states that require no simultaneous switching. For instance, if the previous switching state $\{S_1, S_2, S_3\}$ is $\{1, 0, 0\}$ the available switching states in the next sampling interval are the following: $\{1, 0, 0\}$, $\{1, 1, 0\}$, $\{1, 0, 1\}$, or $\{0, 0, 0\}$;

3- calculate the voltage vectors that correspond to the available switching states from point 2. This can be easily done by the following formulation:

$$v_1 = \frac{2}{3}V_{dc}(S_1 + \alpha S_2 + \alpha^2 S_3)$$

$$v_2 = \frac{2}{3}V_{dc}(S_1 + \alpha S_2 + \alpha^2 S_3)$$

$$v_3 = \frac{2}{3}V_{dc}(S_1 + \alpha S_2 + \alpha^2 S_3)$$

$$v_4 = \frac{2}{3}V_{dc}(S_1 + \alpha S_2 + \alpha^2 S_3)$$
where $\alpha = \exp(-j \frac{2\pi}{3})$ and $\bar{S}$ is the inverted $S$. Not that the number of available states is always four, which takes half of the computational effort required by the conventional MPC;  

4- Now we successfully constructed the finite-set based on the previous state, the resulting future current for each voltage vector is calculated based on equation (2);  

5- The predicted values of the future currents are substituted in the cost function based on equation (1);  

6- The switching state that corresponds to the voltage vector that minimizes the cost function value of $g$ is selected.

The algorithm from 1 to 6 repeated in the next sampling interval. Fig. 2b shows the simulation results for the proposed MPC method. For the same test conditions, the proposed MPC shows superior performance over the conventional MPC. The LLVPR does not take place in the steady-state performance and the maximum line-line $\frac{dv}{dt}$ is successfully limited to $V_{dc}$.  

On the other hand, it is a just question to ask how much the proposed MPC method affects the THD of the load current and the number of actuation required to follow the reference current? Fig. 3 shows a comparison between the THD of the conventional MPC and the proposed MPC. On average the THD of the proposed method is less than 4%, which is larger than the THD of the conventional MPC by less than 2%. More importantly, the THD of both the proposed MPC and the conventional MPC is about the same when the $M_I$ is within the range of 0.8 to 1. Since most of the machine drive operate at this high $M_I$ range, the proposed method shows no concerning effect to the THD of the load current.  

Fig. 4 shows the total number of actuation required by the six inverter switches to track the sinusoidal reference of the load current. Even though the sampling time is 10 µs, the average switching frequency in both methods is around 5 kHz. When the modulation index is within the range of 0.8 to 1 the number of actuation is about the same. Which also serve to prove that at high modulation ranges, the proposed method offers the avoidance of line-line voltage reversal without any sacrifice of the THD performance or the energy spent to track the reference current.  

IV. EXPERIMENTAL RESULTS  

The experimental tests have been carried out on a three-phase voltage source inverter drive system. The DC-link voltage is 100 V, the load resistance is 5 Ω, the load inductance is 2 mH, and sampling time 10 µs. The result of the conventional MPC method is shown in Fig. 5a, and the result of the proposed MPC method is shown in Fig. 5b. To differentiate between the two waveforms, a zoom-in image is provided in Fig. 5c for the conventional MPC. The $2V_{dc}$ voltage reversal can occur during the steady-state operation. This drawback is successfully avoided in the proposed MPC as shown in Fig. 5d where the maximum line-line voltage reversal is equal to $V_{dc}$. Furthermore, the THD of the load current of both methods is less than 3% and the switching frequency of the converter remain very close to the switching frequency of the conventional MPC.  

The experimental result during a transient change from 8 A to 5 A are shown in Fig. 6a and b. During this small step change, the conventional MPC controller chooses to go from the state 011 to the state 100. This requires switching of all of the six inverter switches at the same time as shown in Fig. 6c,
causing a risk of a DC-link short circuit. This shortcoming is highly unsafe in medium-high and high power inverters. On the other hand, the proposed MPC shows that during the same step change, the inverter chooses one of the adjacent states that require no simultaneous switching of the inverter legs as shown in Fig. 6d. Furthermore, the tracking capability of the proposed MPC does not jeopardize by restricting the finite-set.

V. CONCLUSION

This paper highlights a significant drawback in the conventional MPC method that is the line-line voltage reversal. Line-line voltage reversal can damage the insulation of the phase winding in the machine. The reason behind this problem is explained, and a practical solution is proposed. The proposed solution can reduce the line-line voltage $\frac{dv}{dt}$ from $2V_{dc}$ to $V_{dc}$. The proposed solution validated via simulation and experimental tests.

REFERENCES


