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Simple finite-control-set model predictive control method for reducing common mode voltage in a three phase two-level voltage source inverter

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ABSTRACT

The common mode voltage (CMV) causes many issues and negatively affects the performance of the power system in a hybrid electric vehicle HEV. Therefore, this paper suggests a simple method for mitigating the common mode voltage CMV in a two level three phase voltage source inverter VSI with RL load. Hence, the technique chosen for this purpose is based on model predictive control. Otherwise, when compared to the standard method, this simple method can successfully mitigate CMV while also improving harmonic performance by lowering the total harmonic distortion THD. The purpose of this paper is reducing THD and CMV simultaneously utilizing only non-zero vectors. According to simulation results obtained by MATLAB-Simulink, this simple solution reduced CMV to $\frac{\pm V_{dc}}{6}$ and THD from 3.49% to 3.39 % (10 % improvement) compared with the standard method, which mitigates CMV using the cost function.

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1. INTRODUCTION

Due to the steady increase in population, the need to use transport, primarily cars, has increased. The high number of vehicles leads to pollution and negatively affects the environment [1]. A successful solution to reduce CO2 from the atmosphere is using a hybrid electric vehicle (HEV), which uses two energy sources. HEV combines an electric motor with an internal combustion engine (ICE) [2], [3].

HEVs rely heavily on power electronics, which results in electromagnetic compatibility (EMC) significant problems. One of the most severe issues is electromagnetic interference (EMI) [4]. However, high-frequency switching operations in power electronic devices have increased the dynamic performance of ac motor drives while also causing unexpected issues for example, conducted perturbations in the voltage inverter. Both common-mode or differential-mode, are often caused by fast switching transients of power switches creating strong *dv/dt* and *di/dt* [5].

Common mode voltage (CMV) is known to cause winding insulation breakdown, fault activation of current detector circuits, and leakage currents to damage motor bearings in power drives [6]. Furthermore, flowing common mode currents in HEVs generate radiated EMI emissions propagated between the inverter, batteries, and motors. As a result, the EMI noises emitted affect nearby vehicles [7]. Therefore, it is necessary to find mitigation techniques of the common-mode voltage to solve this problem and avoid costly equipment failures in the industry.

One of the popular suggested methods for the mitigation of CMV is pulse width modulation (PWM) techniques. Owing to their ability to control the amplitude and frequency of the voltage source inverter VSI output voltage, PWM techniques are becoming increasingly popular in modern applications [8]. Thoroughly, many PWM-based CMV reduction strategies for three phase voltage-source inverters have been reported in the literature [8]–[13]. RCMV-PWM algorithms can be classified into three groups: remote state PWM (RSPWM) algorithms [10], active zero state PWM (AZSPWM) algorithms [9], and near state PWM (NSPWM) algorithms [13].

Another advanced technique which we will focus on in our paper is model predictive control. Owing to its simplicity, model predictive control (MPC) is a powerful and efficient method for controlling power inverters. It requires many calculations compared to traditional control PWM methods, but today's fast microprocessors have made it possible to implement for VSI converters. Due to the discrete nature of VSI converters which have a finite number of switching states, the finite control set MPC (FCS-MPC) can easily design the MPC algorithm [14]–[18]. Many researchers have proposed MPC that reduces CMV for various types of three-phase voltage-source inverters (VSIs) [19], [20], [21]–[34].

Despite the fact that many studies avoided using zero vectors to reduce CMV which raises THD, THD has received little attention. Therefore, this article presents a new simple method based on MPC to decrease the CMV in a three phase VSI and improve the harmonic performance. The proposed method uses only active vectors and replaces the zero vector by the two suitable active vectors. This paper is divided into five sections: an introduction, section 2 describing conventional MPC, section 3 explaining the proposed FCS-MPC method, section 4 discussing simulation results using MATLAB-Simulink of the three-phase VSI with RL load and section 5 concluding the paper.

2. RESEARCH METHOD

2.1. The load model

The schematic representation of the inverter is provided by Figure 1. To ensure the continuity of alternating output currents I_a, I_b, and I_c, switches S_1 and S_4, S_3 and S_6, S_5 and S_2 must be complementary two by two. Only eight different switching states can generate line-to-line output voltages and DC-link current. A load used in this paper is given by (1):

$$V(t) = Ri(t) + L\frac{di(t)}{dt} \tag{1}$$

Where L and R are load inductance and resistance, respectively:
V(t) and i(t) are voltage and the current, which are defined as (2):

$$V(t) = \frac{2}{3}[V_{an}(t) + aV_{bn}(t) + a^2V_{cn}(t)] \tag{2}$$

$$i(t) = \frac{2}{3}[i_a(t) + ai_b(t) + a^2i_c(t)] \tag{3}$$

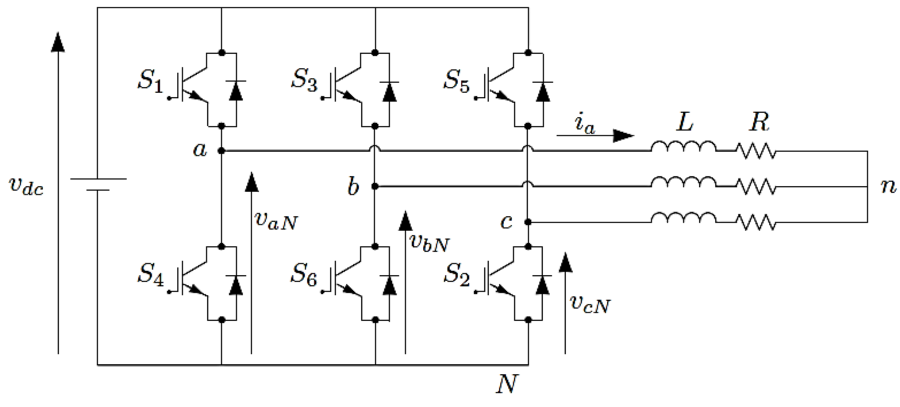

Figure 1. The voltage source inverter VSI topology

2.2. The discrete-time model

The future value of the load current can be predicted using a discrete-time equation of the load current (1). The derivative di/dt is approximated by (4):

$$\frac{di}{dt} \approx \frac{i(k)-i(k-1)}{T_s} \quad (4)$$

After replacing (4) in (1), we get the following calculation for the load current:

$$\text{i(k)} = \frac{1}{RT_s+L}[Li(k-1)+T_s v(k)] \quad (5)$$

If the sample time is short enough and the load is primarily inductive, RTs can be ignored. The future load current can be calculated by moving the discrete-time forward one step in (6):

$$i(k+1) = \frac{1}{RT_s+L}[Li(k)+T_s v(k+1)] \quad (6)$$

Voltage vector selection, in (7) is evaluated in the predictive algorithm for each of the seven possible voltage vectors, yielding seven different current predictions, as indicated in Figure 2. At the next sampling instant, the voltage vector with the closest predicted current to the expected current reference is applied to the load. Therefore, the vector with the lowest quality function will be selected. The general model predictive control scheme is given by the Figure 3.

$$\text{g} = |i_\alpha^*(k+1) - i_\alpha(k+1)| + |i_\beta^*(k+1) - i_\beta(k+1)| \quad (7)$$

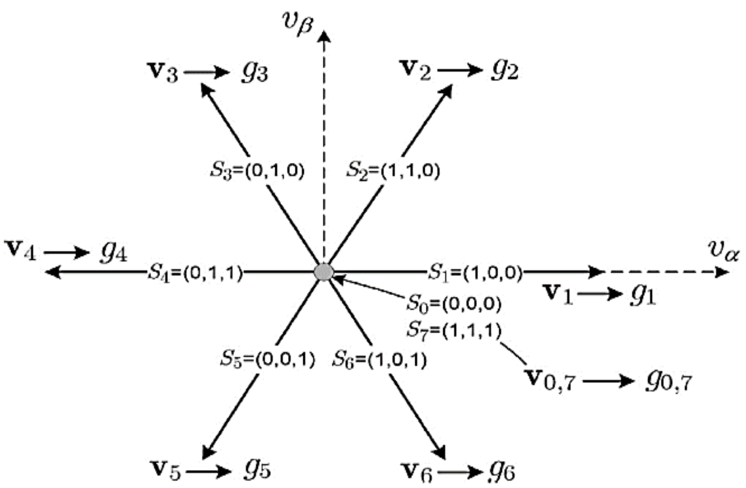

Figure 2. Voltage vectors (VV), with switching states and cost functions [35]

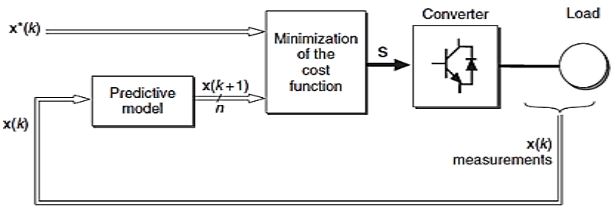

Figure 3. MPC scheme for power converters [36]

The following steps can be used to summarize this strategy:

– Reference currents at the end of the following sample time; $i_\alpha^*(k+1)$ and $i^*_\beta(k+1)$ are determined by an outer control loop at the end of the current sample time, and the load current $i_\alpha(k)$ and $i_\beta(k)$ are measured.

- The system model (6) is used to predict the output current at the end of the following sample time; $i_\alpha(k+1)$ and $i_\beta(k+1)$.
- For all appropriate switching states, the cost function (7) determines the error between reference currents and predicted load currents at the end of the following sample time. The suitable voltage vector (VV) that minimizes the error function is chosen for the next sample time.

For reducing the common mode voltage, another term should be added to the cost function as defined in:

$$g = |i_\alpha^*(k+1) - i_\alpha(k+1)| + |i_\beta^*(k+1) - i_\beta(k+1)| + \lambda_{cm}|V_{cm}^P| \quad (8)$$

V^p_{cm} is the expected common-mode voltage for the various switching states and is treated as a secondary control goal; it can be reduced by adequately tuning the weighting factor λ_{cm} [36].

2.3. Proposed model predictive control

In principle, the proposed method for reducing CMV is based on the conventional MPC method. Table 1 shows all of the 2L-possible VSI's voltage vectors, as well as the CMV voltage, which is defined as:

$$V_{n0} = V_{cm} = \frac{V_{dc}}{6}(S_a + S_b + S_c) \quad (9)$$

From Table 1, we note that CMV reaches its maximum value when using zero vectors. Therefore, using the cost function (8) to avoid zero vectors is a good solution. However, when the zero vectors are removed, the THD increases.

We look for a method to reduce CMV while maintaining the power system's harmonic performance (decreasing THD). The idea is to replace the zero vectors selected by the cost function (7) with the appropriate active (non-zero) vectors, as shown in Figures 4. The two next neighbor vectors of the preceding vector are used to replace the zero vectors for equal times $\frac{T_s}{2}$, as shown in Table 2.

The current prediction computation (6) and the cost function calculation (7) are executed seven times in the standard MPC: for six active vectors and one zero vector. The proposed method follows the same steps as the standard method, but the zero vector is not chosen this time. The flow diagram Figure 5 shows that when the zero vector is chosen, the new method replaces it with the two next neighbor vectors of the previously selected non-zero vector.

Table 1. Common mode voltage for each voltage vectors

Voltage Vectors VV	Switching Function	CMV
V_0	(-1,-1,-1)	$-\frac{V_{dc}}{2}$
V_1	(+1,-1,-1)	$-\frac{V_{dc}}{6}$
V_2	(+1,+1,-1)	$+\frac{V_{dc}}{6}$
V_3	(-1,+1,-1)	$-\frac{V_{dc}}{6}$
V_4	(-1,+1,+1)	$+\frac{V_{dc}}{6}$
V_5	(-1,-1,+1)	$-\frac{V_{dc}}{6}$
V_6	(+1,-1,+1)	$+\frac{V_{dc}}{6}$
V_7	(+1,+1,+1)	$\frac{+V_{dc}}{2}$

Table 2. Active vectors which replace the zero vector

Previous vector V(k)	Vectors replacing the zero vector
V_1	$V_2 + V_3$
V_2	$V_3 + V_4$
V_3	$V_4 + V_5$
V_4	$V_5 + V_6$
V_5	$V_6 + V_1$
V_6	$V_1 + V_2$

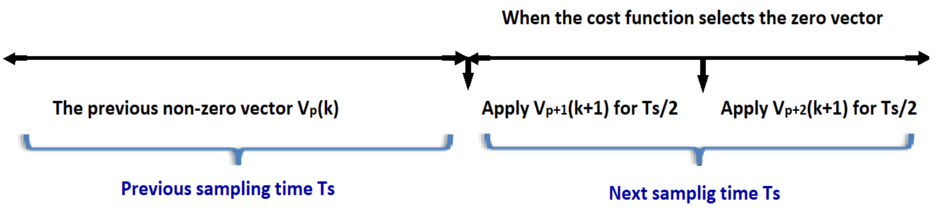

Figure 4. Replacement of the zero vector with the previous vector's opposite vector

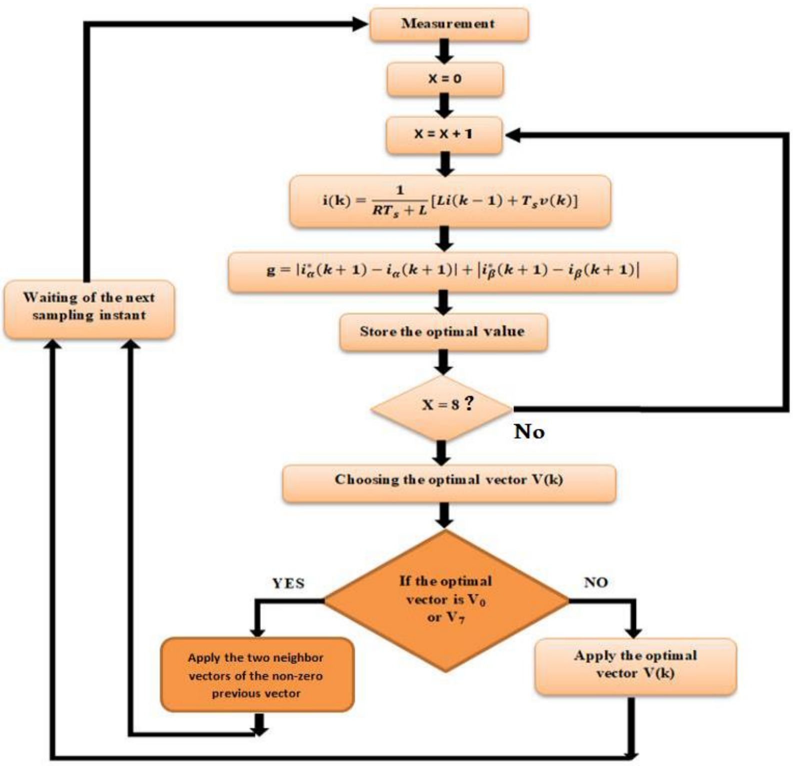

Figure 5. Flow diagram of the proposed MPC

3. RESULTS AND DISCUSSION

This section describes the simulation of CMV mitigation in a three-phase inverter with RL load. The proposed MPC-based technique is evaluated in comparison to standard MPC with and without CMV reduction. This Method uses only active vectors and avoids using zero vectors, since zero vectors are the source of CMV high values. The following parameters are used in the Matlab-Simulink simulation: T_s=25 µs, I_{ref} (peak) =10 A, L=10 mH, R=10 Ω, f=50 Hz, V_{dc}=520 V. Figures 6, 7, 8 show the simulation of the output current i_a(t) and its FFT analysis and the common mode voltage V_{cm}(t) in the VSI.

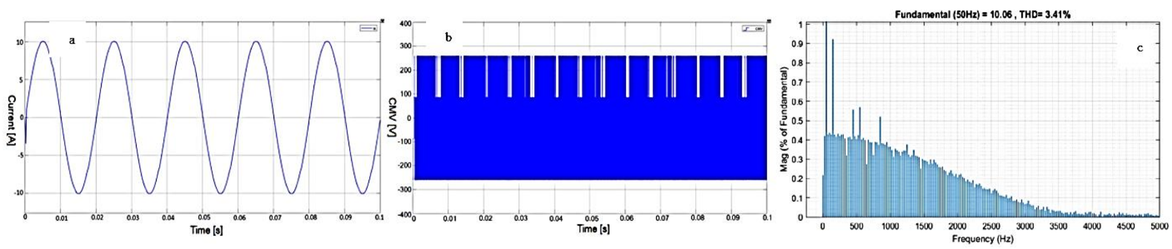

Figure 6. Standard MPC using cost function (7): (a) output current i_a (t), [A]; (b) V_{cm} (t), [V] (the common mode voltage); (c) FFT analysis of the output current i_a(t)

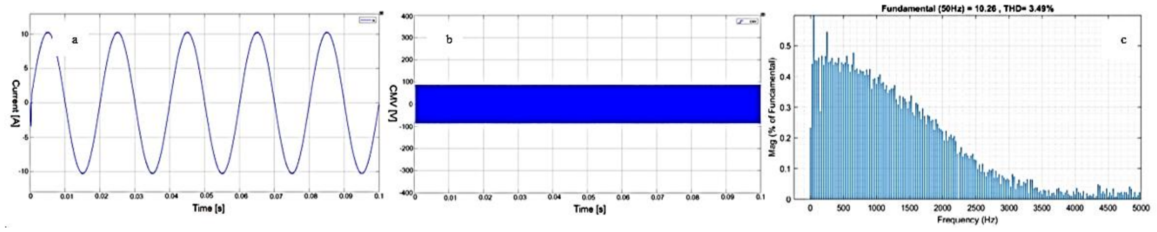

Figure 7. Standard MPC using cost function (8): (a) output current $i_a(t)$,[A]; (b) $V_{cm}(t)$,[V] (the common mode voltage); (c) FFT analysis of the output current $i_a(t)$

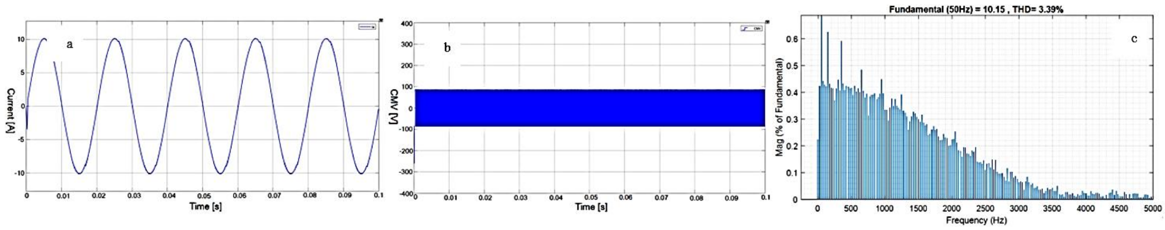

Figure 8. Proposed MPC using cost function (7): (a) output current ia(t), [A]; (b) Vcm(t), [V] (the common mode voltage); (c) FFT analysis of the output current ia(t)

Table 3 shows that the THD increases when we try to decrease the common mode voltage using the cost function (8) (the second method). This increase of THD indicates that avoiding zero vectors had a negative effect on the harmonic performance of the system. The simulation results presented using MATLAB-Simulink shows that the proposed simple method can reduce CMV from $\frac{\pm V_{dc}}{2}$ to $\frac{\pm V_{dc}}{6}$, and decreased THD from 3.49% to 3.39% (10% of improvement).

The CMV mitigation results (Table 3) indicated that the conventional MPC's zero vector selection is the origin of the high CMV value. As a solution, the zero vectors are avoided using the same method by adding a new term to the cost function. However, avoiding zero vectors resulted in a higher THD. As a result, THD must be reduced while CMV is alleviated. The research found that when the zero vector was replaced with the two next neighbor vectors of the preceding active vector (Table 2), the CMV and THD were lowered using the suggested MPC (10% of improvement of THD). The proposed strategy achieves a better THD results than the standard method without CMV mitigation.

Table 3. Comparison between methods used in terms of THD and CMV

Method Used	THD	CMV
Standard MPC without CMV mitigation	3.41%	$\frac{\pm V_{dc}}{2} = 260\ V$
Standard MPC with CMV mitigation	3.49%	$\frac{\pm V_{dc}}{6} = 86.66\ V$
Proposed MPC Method	3.39%	$\frac{\pm V_{dc}}{6} = 86.66\ V$

4. CONCLUSION

A hybrid electric vehicle (HEV), which uses two energy sources, is an effective way to reduce CO2 emissions from the atmosphere. However, because HEVs largely depend on power electronics, they have notable Electromagnetic compatibility (EMC) issues. CMV has been related to electromagnetic interference, winding insulation breakdown, and leakage currents, which have the potential to damage motor bearings in power drives. To solve this problem and avoid costly equipment failures in the future, common-mode voltage mitigation techniques must be developed. This paper proposed a simple FCS-MPC method to mitigate the common mode voltage CMV in a three phase VSI with RL load and compared it to conventional MPC methods. The selection of zero vectors V0 and V7 yields the highest possible value of CMV ($\frac{\pm V_{dc}}{2}$) but eliminating those vectors causes another problem; an increase in total harmonic distortion THD. The proposed method replaces the zero vector chosen by the cost function (7) (which is executed seven times) by the two next neighbour vectors of the previous chosen active vector. This strategy achieved two goals: first, it mitigated the CMV from $\frac{\pm V_{dc}}{2}$ to $\frac{\pm V_{dc}}{6}$. Second, it reduced THD from 3.49% to 3.39% (10% of improvement), which improved the harmonic performance of the system.

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