A Modulated Model Predictive Control Scheme for a Two-Level Voltage Source Inverter

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***Abstract*—Traditional finite-set model predictive control (FS-MPC) techniques are characterized by a variable switching frequency which causes noise as well as large voltage and current ripple. In this paper a novel predictive control strategy with a fixed switching frequency for a voltage source inverter called as modulated model predictive control (M2PC) is proposed, with the aim of obtaining a modulated waveform at the output of the converter. The feasibility of this strategy is evaluated using simulation results to demonstrate the advantages of predictive control, such as fast dynamic response and the easy inclusion of nonlinearities. Finally, a modified strategy is proposed in order to naturally reduce the common mode voltage. The constraints of the system are maintained but the performance of the system in terms of power quality is improved when compared to FS-MPC.**

NOMENCLATURE

Variable	Description	
v_{dc}	DC-voltage	
i_{dc}	DC-current	
$\mathbf{v}$	Load voltage	$[v_a\ v_b\ v_c]^T$
$\mathbf{i}$	Load current	$[i_a\ i_b\ i_c]^T$
$\mathbf{i}^*$	Load current reference	$[i_a^*\ i_b^*\ i_c^*]^T$
R	Load resistor	
L	Load inductor	
T_s	Sampling time	

I. INTRODUCTION

Thanks to technological advances and the emergence of faster microcontrollers that are capable of more powerful calculations, predictive control has emerged as an alternative modulation method for power converter applications [1]. This technique is a very intuitive concept that is easy to implement and performs well considering numerous restrictions. The technique can compensation for downtime or nonlinearities in the system, offers a flexible control method and is easily extendible for different applications [1]–[5]. However, there are some issues which constitute a disadvantage of this control method. One of the main drawbacks of the FS-MPC methods are that the control can choose only from a limited number of valid switching states because of the absence of a modulator. This generates noise as well as large voltage and current ripples. The variable switching frequency produces a spread spectrum, decreasing the performance of the system in terms of power quality [6]–[10].

In [11] the discrete space vector modulation is extended to be used with predictive control, where virtual vectors are considered in the control algorithm which are synthesized through an external modulator, obtaining constant switching frequency and an improved performance. Similar results are obtained in [12], where traditional PI controllers were substituted by a predictive controller but with a conventional modulation technique. In [7], [13] a deadbeat predictive controller is proposed in order to determine the duty cycle for the PWM pulses for a given reference current over the entire speed range of operation of a switched reluctance machine. In [14] a predictive controller is proposed with a cost function that includes the current error and additionally a penalization term which is used to control the switching frequency. In [6], [9], [15] the switching behaviour of PWM with triangular carriers is used to propose a predictive method with a fixed switching period which is divided into smaller evaluation steps to obtain improved performance for different power converter topologies.

Different solutions have been proposed in the literature [8], [16], [17] which allow the operation at fixed switching frequency. However they result in complicated expressions for the switching time calculations and they are not intuitive as it is very complicated to introduce other objectives into the cost function. In order to solve these problems, this paper proposes a new solution which allows operation at a fixed switching frequency while maintaining the advantages of predictive control. The proposed method emulates the implementation of space vector modulation (SVM) with a linear PI controller. Using a suitable modulation scheme in the cost function minimization of the predictive algorithm for a selected number of switching states to generate the duty cycles for two active vectors and the two zero vectors which are applied to the converter using a given switching pattern.

II. TOPOLOGY AND MATHEMATICAL MODEL OF THE VOLTAGE SOURCE INVERTER

The topology of a voltage source inverter (VSI) is shown in Fig. 1. One restriction for the correct operation of this converter is to ensure that the two switches in each leg must operate in a complementary mode in order to avoid short-circuiting the DC-source.

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As a result, only eight possible switching states are allowed from which the line-to-line output voltages and DC-link current are generated (Table I and Table II).

The DC-link current i_{dc} can be determined as a function of the inverter switches and the output currents $\mathbf{i}$:

$$i_{dc} = \left[\begin{array}{ccc} S_1 & S_3 & S_5 \end{array} \right] \mathbf{i} \tag{1}$$

The output voltage can be synthesized as a function of the inverter switches and the DC-link voltage v_{dc} as:

$$\mathbf{v} = \left[\begin{array}{c} S_1 \\ S_3 \\ S_5 \end{array} \right] v_{dc} \tag{2}$$

From Fig. 1, the continuous model of the converter is:

$$\mathbf{v} = L\frac{d\mathbf{i}}{dt} + R\mathbf{i} \tag{3}$$

From eq. (3) it is possible to obtain a discrete time model, assuming that the variables keep constant during a sampling time T_s:

$$\mathbf{i}^{k+1} = \left(1 - \frac{RT_s}{L}\right)\mathbf{i}^k + \frac{T_s}{L}\mathbf{v}^k \tag{4}$$

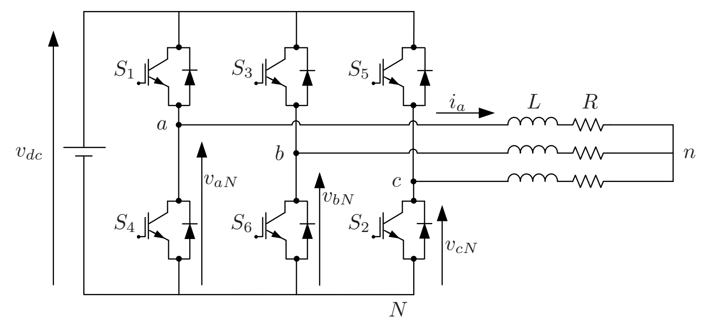

Fig. 1. Topology of the voltage source inverter.

TABLE I
VALID SWITCHING STATES OF THE VSI

$State$	S_1	S_2	S_3	S_4	S_5	S_6
1	1	1	0	0	0	1
2	1	1	1	0	0	0
3	0	1	1	1	0	0
4	0	0	1	1	1	0
5	0	0	0	1	1	1
6	1	0	0	0	1	1
7	1	0	1	0	1	0
8	0	1	0	1	0	1

TABLE II
OUTPUT LINE-TO-LINE VOLTAGES AND CURRENTS OF THE VSI

$State$	v_{ab}	v_{bc}	v_{ca}	i_{dc}
1	v_{dc}	0	$-v_{dc}$	i_a
2	0	v_{dc}	$-v_{dc}$	$i_a + i_b$
3	$-v_{dc}$	v_{dc}	0	i_b
4	$-v_{dc}$	0	v_{dc}	$i_b + i_c$
5	0	$-v_{dc}$	v_{dc}	i_c
6	v_{dc}	$-v_{dc}$	0	$i_a + i_c$
7	0	0	0	0
8	0	0	0	0

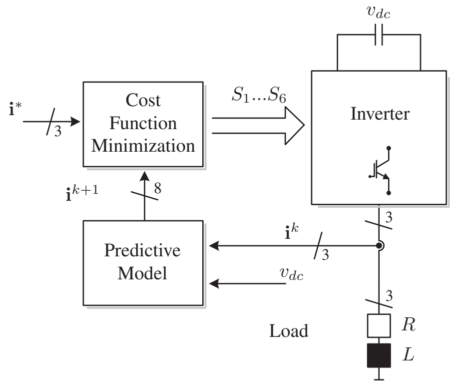

Fig. 2. Classic predictive current control method.

III. CLASSIC PREDICTIVE CURRENT CONTROL METHOD

Predictive current control is a well known method which uses the finite number of possible switching states that can be generated by the power converter and the mathematical model of the system. With this information it is possible to predict the behaviour of the variables for each switching state. Each prediction is evaluated with respective to its reference in a cost function and the switching state that generates the minimum value of this evaluation is selected to be applied in the next sampling time.

This control method has been extendedly implemented in different converter topologies and applications such as: DC/AC converters, AC/DC converters and AC/AC converters [1]. The block diagram of this control strategy is shown in Fig. 2 and this algorithm can be summarized as:

1) The value of the current reference $\mathbf{i}^*$ is defined and the load current $\mathbf{i}^k$ is measured.
2) For each valid switching state of the converter, the load current for the next sampling instant $\mathbf{i}^{k+1}$ is predicted by using the mathematical model of the converter as indicated in eq. (4).
3) A cost function g is considered to evaluate the error between the reference and its respective prediction value for each valid switching state of the converter. In this particular case, only the error between the load current references and the prediction values is considered and thus the cost function is defined as

$$g(k+1) = \left(\mathbf{i}^* - \mathbf{i}^{k+1}\right)^2 \tag{5}$$

4) The switching state that generates the minimal cost function value is selected to be applied to the converter in the next sampling time.

IV. PROPOSED MODULATED MODEL PREDICTIVE CONTROL

In space vector modulation (SVM), it is possible to define each available vector for the VSI in the $\alpha-\beta$ plane as shown in Fig. 3. It is possible to define six sectors which are given by two adjacent vectors, being the first sector the one between vector $\mathbf{v}_1$ and vector $\mathbf{v}_2$, which correspond to the voltage

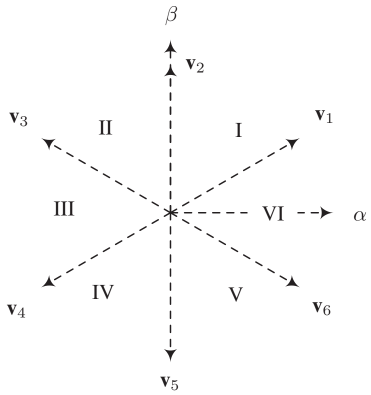

Fig. 3. Available vectors for the VSI.

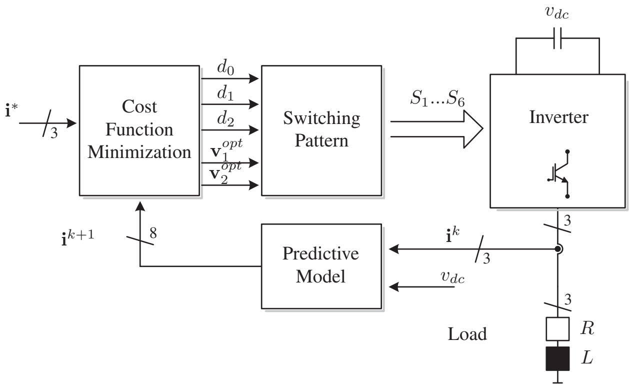

Fig. 4. Proposed modulated model predictive current control scheme.

generated by switching state number 1 and switching state number 2, respectively, based on eq. (2) and Table I. The proposed method is shown in Fig. 4 and is the same idea as the classical predictive control method as it uses the same prediction of the load current indicated in eq. (4). Moreover the proposed technique evaluates the prediction of the two active vectors that conform each sector at every sampling time and evaluates the cost function separately for each prediction. The cost function g is evaluated for each case and is the same as the one considered for the classical predictive method. For example, for sector I, the first prediction and cost function g_1 is evaluated for vector $\mathbf{v}_1$ and the second prediction and cost function g_2 is evaluated for vector $\mathbf{v}_2$. Each prediction is evaluated based on eq. (4) and the only change is in respect to the calculation of the load voltage $\mathbf{v}$. The duty cycles for the two active vectors are calculated by solving:

$$\begin{aligned} d_0 &= K/g_0 \\ d_1 &= K/g_1 \\ d_2 &= K/g_2 \\ d_0 + d_1 + d_2 &= T_s \end{aligned} \quad (6)$$

where d_0 correspond to the duty cycle of a zero vector which is evaluated only one time. By solving the system of eq. (6), is possible to obtain the expression for K and the expressions

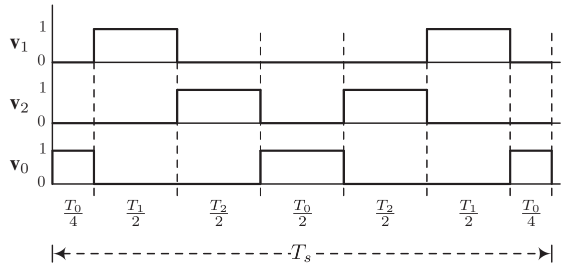

Fig. 5. Switching pattern for the optimal vectors.

for the duty cycles for each vector are given as:

$$\begin{aligned} d_0 &= T_s g_1 g_2/(g_0 g_1 + g_1 g_2 + g_0 g_2) \\ d_1 &= T_s g_0 g_2/(g_0 g_1 + g_1 g_2 + g_0 g_2) \\ d_2 &= T_s g_0 g_1/(g_0 g_1 + g_1 g_2 + g_0 g_2) \end{aligned} \quad (7)$$

With these expressions, the new cost function, which is evaluated at every sampling time, is defined as

$$g(k+1) = d_1 g_1 + d_2 g_2 \quad (8)$$

The two vectors that minimize this cost function are selected and applied to the converter at the next sampling time. After obtaining the duty cycles and selecting the optimal two vectors to be applied, a switching pattern procedure, such as the one shown in Fig. 5, is adopted with the goal of applying the two active vectors and two zero vectors [18]. A similar idea has been first proposed for a three-phase active rectifier and a seven-level converter in [19], [20] respectively and now it is extended to a three-phase voltage source inverter.

V. Results

In order to validate the effectiveness of the proposal method, simulation results were carried out in both steady and transient conditions. These results are compared with the results obtained with the classical predictive control implementation. The simulation parameters are shown in Table III. In order to have a reasonable comparison between both predictive methods, a higher sampling time T_s is considered for the classical predictive controller, $T_s = 1/60000$ [s], while a $T_s = 1/20000$ [s] is defined for the proposed predictive method.

TABLE III
SIMULATION PARAMETERS

Variables	Description	Value	p.u.
S	Nominal power	166 [kVAR]	
V_b	Line-line base voltage	380 [V]	1
I_b	Base current	252 [A]	1
Z_b	Base impedance	0.87 [Ω]	1
L_b	Base inductance	2.8 [mH]	1
C_{dc}	DC-link capacitor	3700 [μF]	1
R	Load resistance	0.30 [Ω]	$0.35Z_b$
L	Load inductor	301.26 [μH]	$0.11L_b$
T_s	Sampling time	50 [μs]	
f_s	Switching frequency*	20 [kHz]	
	Simulation step	1 [μs]	

* for the proposal predictive control scheme

A. Results in Steady State

Fig. 6 shows simulation results in steady state for the classical predictive controller implementation and Fig. 7 the same results for the proposed predictive controller. In both cases it is observed a very good tracking of the load current $\mathbf{i}$ to its respective references $\mathbf{i}^*$ which are established as the nominal value (1 [p.u.]) and with a reference frequency of 50 [Hz]. It is possible to observe that the load current ripple for the proposed predictive scheme is slightly lower than the classical predictive method. This can also be seen in Fig. 7b which has a more sinusoidal load voltage v_{an} with respect to the load voltage than in Fig. 6b. As shown in Fig. 8, the classical predictive control strategy presents a spread spectrum over the frequency range where it is difficult to identify the switching frequency.

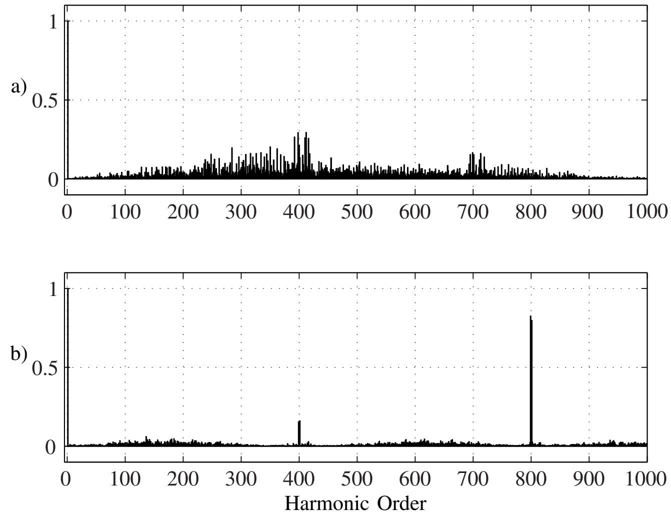

Fig. 8. FFT analysis for the load voltage v_{an}: a) classical predictive control; b) proposed modulated model predictive control scheme.

TABLE IV
THD ANALYSIS

Variables	THD Value Method I	THD Value Method II
i_α	2.3%	1.3%
i_β	2.3%	1.3%
v_{an}	173.2%	170.2%

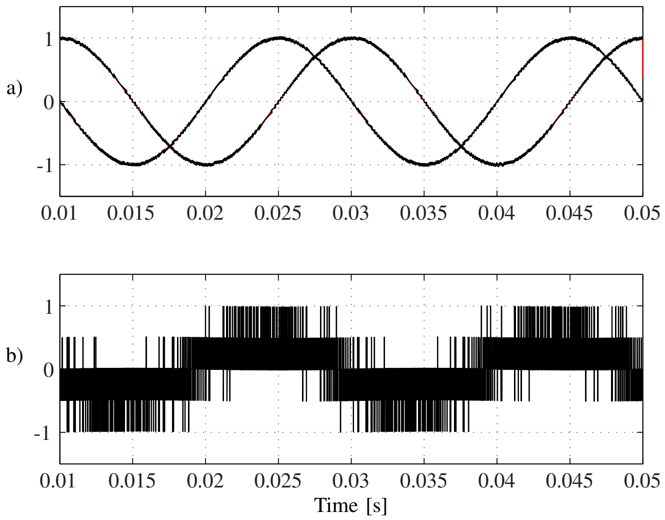

Fig. 6. Simulation results classical predictive control method: a) load current references and measured [pu]; b) load voltage [pu].

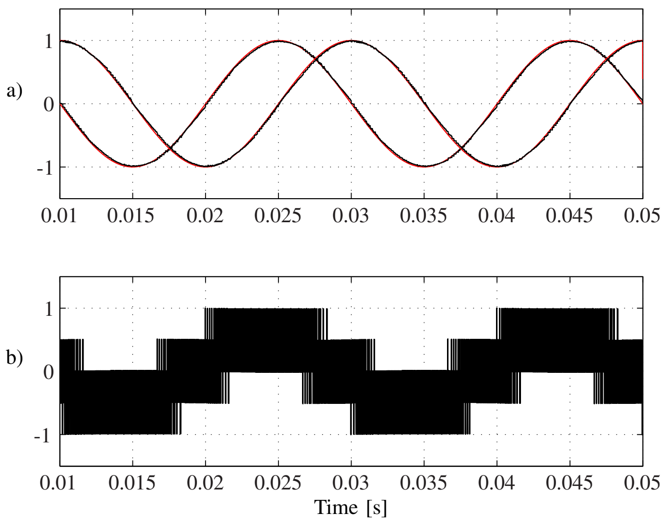

Fig. 7. Simulation results proposed modulated model predictive control scheme: a) load current references and measured [pu]; b) load voltage [pu].

On the other hand, for the proposed predictive control method, the load voltage presents a fixed switching frequency which is located around harmonic number 400 (400×50 [Hz] = 20 [kHz]). Table IV shows that a reduced THD in both currents and voltage is obtained with the proposed method. It is important to highlight that in order to have a similar THD value in the classical predictive method it is necessary a higher sampling time with respect to the proposed method.

B. Results in Transient Condition

In order to demonstrate the performance of the proposed strategy in terms of dynamic response, transient state analysis is done for both methods. Fig. 9 shows results for the classical predictive method and Fig. 10 shows the same results for the proposed method. A step change in the load current reference $\mathbf{i}^*$ from 1 [p.u.] to 0.6579 [p.u.] is applied at instant $t = 0.03$ [s]. In both cases it is observed a very good dynamic response and again lower load current ripple is observed for the proposed predictive controller scheme. One interesting issue is observed for the classical predictive controller, where a reduction in the switching frequency is obtained when a lower load current reference is applied and thus a variable switching frequency is present. On the other hand, for the proposed predictive scheme a constant switching frequency is observed in despite of the load current reference applied.

C. Discussion

As mentioned in [6] and [10], if the FS-MPC controller is evaluated and the control is applied at every sampling time

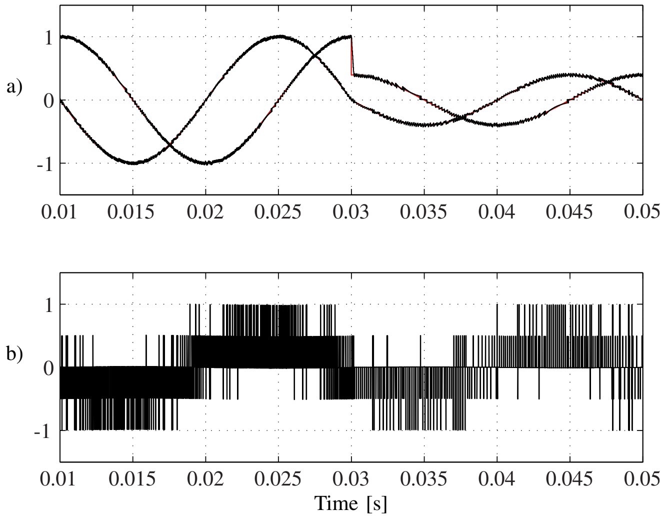

Fig. 9. Simulation results classical predictive control method: a) load current references and measured [pu]; b) load voltage [pu].

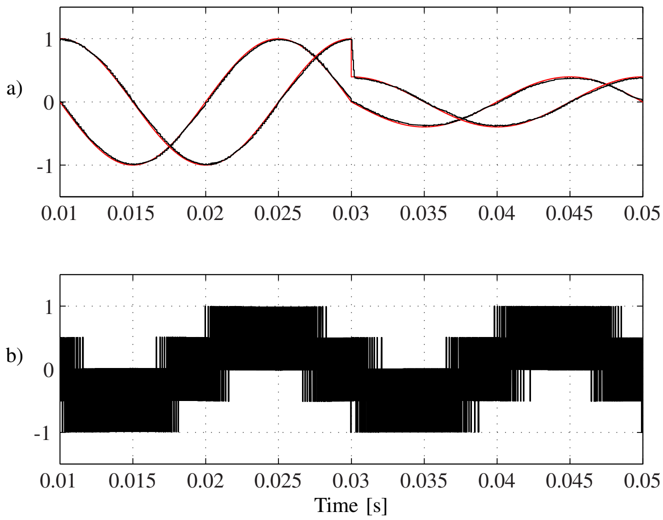

Fig. 10. Simulation results proposed modulated model predictive control scheme: a) load current references and measured [pu]; b) load voltage [pu].

(which means that only one output voltage vector is applied during the whole sampling period), the resulting switching frequency becomes variable where the maximum switching frequency occurs for a reference that is equivalent to a duty cycle of a 0.5 and decreases as the references moves away from a 0.5. Thus, in order to have a high switching frequency for every reference the control algorithm has to be evaluated at a higher rate than the switching frequency. This issue has been addressed in Fig. 9 where it is shown that the switching frequency varies when the reference varies. Additionally, it is necessary to consider a high sampling time in order to obtain an almost similar average switching frequency respect to the switching frequency.

With the proposed technique it is possible to eliminate one of the main disadvantages of predictive control: variable switching frequency. By considering a modulated model predictive control scheme it is possible to consider the use of two active vectors and the two zero vectors during each sampling period. The operation at fixed switching frequency produces less ripple and a more concentrated spectrum, which is reflected in an improvement in the performance of the system.

VI. Proposed Modification for the Modulated Model Predictive Control

In this section it is proposed a modification of the model predictive control presented previously. This modification consists in to replace the application of zero vectors by two adjacent active vectors in order to reduce naturally the common mode voltage. For this, is used the duty cycle obtained for the zero vectors and this duty cycle is applied but now considering the two other adjacent active vectors and applying a switching pattern as the one shown in Fig. 11. With this modification, the common mode voltage is naturally reduced.

In order to demonstrate the performance of the modified strategy transient state analysis is done for both the conventional modulated and the modified methods. Fig. 12 shows results for the modulated model predictive method and Fig. 13 shows the same results for the modified method. A step change in the load current reference $\mathbf{i}^*$ from 1 [p.u.] to 0.6579 [p.u.] is applied at instant $t = 0.05$ [s]. In both cases it is observed a very good dynamic response with low load current ripple but with an important difference in the common mode voltage.

VII. Conclusion

In this paper a new predictive control scheme has been proposed which allows the operation of the converter with a fixed switching frequency while maintaining the advantages of the classical finite-state model predictive control techniques such as fast dynamic response and easy inclusion of nonlinearities. Simulations results demonstrate that this is a viable alternative to avoid linear controllers and performs well in both steady and transient conditions with a good tracking to its references and a reduced ripple. By considering a modification of the applied vectors it is possible to naturally reduce the common mode voltage.

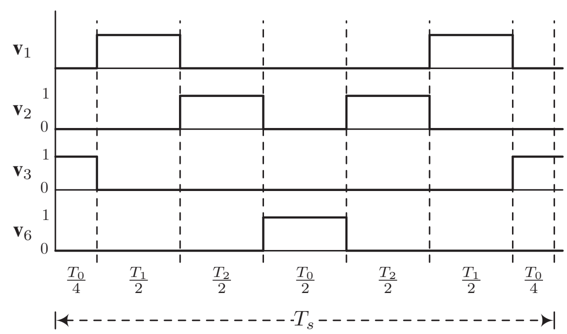

Fig. 11. Switching pattern for the optimal vectors of the modified method.

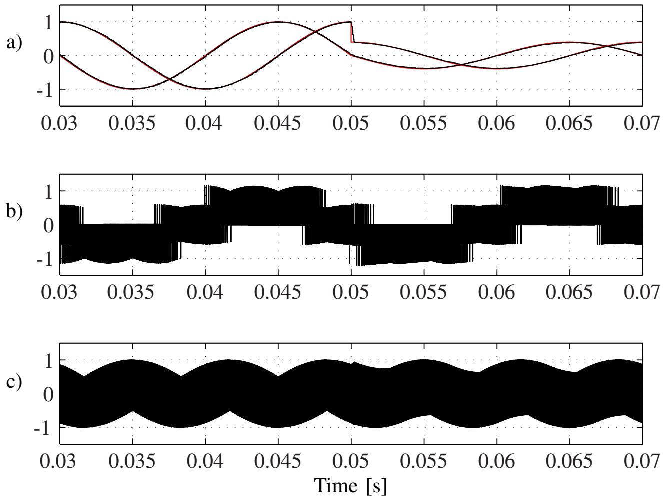

Fig. 12. Simulation results modulated model predictive control method: a) load current references and measured [pu]; b) load voltage [pu]; c) common mode voltage [pu].

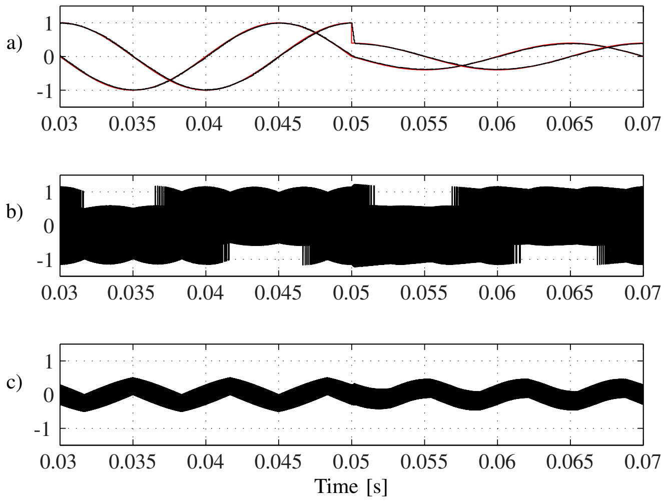

Fig. 13. Simulation results proposed predictive control scheme: a) load current references and measured [pu]; b) load voltage [pu]; c) common mode voltage [pu].

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