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Modified FCS-MPC algorithm for five-leg voltage source inverter

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ABSTRACT

This paper represents a test of a modified algorithm to minimize the cost function in the traditional finite control-set model predictive current control (FCS-MPC) to control the (five-leg) DC voltage input inverter. A Matlab/Simulink description of a system presents a certain deviation limits between the reference and the actual measured phase currents, also the model implements a load current limitation. The algorithm picks out a proper switching state, which makes the lower error value between the wanted and the prognosticated currents; the proposed technique sets the chosen switching state as a driving signal to the ten switches. The modified program eliminates the switching combination with error values above the requested ones. Thereafter the system response enhanced by lowering the overshoots. The rigidness of the model is examined by using a step change in reference signals.

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1. INTRODUCTION

In recent years, many applications in AC machines require a higher number of supply phases. This can be accomplished by power electronics drives. The multi-phase AC drives supplied from more than three phase voltage source inverters which, controlled by various methods. The former introduction of five-leg DC voltage input inverter driving a multi-phase induction motor was proposed by Ward and Harer in 1969 [1-4]. Predictive control spread widely in the past years and it proved the superiority over the other PWM techniques [5-14].

The essence of this strategy of control based on the system parameters model, to forecast the next act of the specified variables, later the controller employs this prediction with the aid of optimization procedure to obtain the most suitable control commands. Many advantages is gained by implementing the MPC and make this strategy suitable in power electronics converters control, this because its easiness to acquire, the major drawback of this choice is the need for a high speed computers due to the considerable figure of mathematical calculations.The finite current set technique (FCS-MPC) is one of the main outcome of the predictive control since it employs one close control loop (load current), to calculate the minimum error between the predetermined reference and the measured current to predict the next control action. In this work, a modified algorithm is used by adding defined error, and maximum current constraints to the cost function which responsible of produce the required commands is presented to drive the five-leg DC voltage input inverter.

2. FIVE-LEG VSI MODEL

The structure of this type of inverters is illustrated in Figure 1; the inverter has ten IGBT switching elements numbered from one to ten the two IGBT's in the same leg must not conduct in the same time to prevent short-circuiting the battery source. This inverter has (25=32) switching states. The load voltage totally relies upon each switching state combination; these switches links the two Battery terminals to the load. This work handles a load with R-L filter; the new strategy can be likewise extended to manage various loads and filters. The underlying advance of surmising the mathematical model of the inverter is by delineating the dependence of the load voltages on the exchanging signal requests.

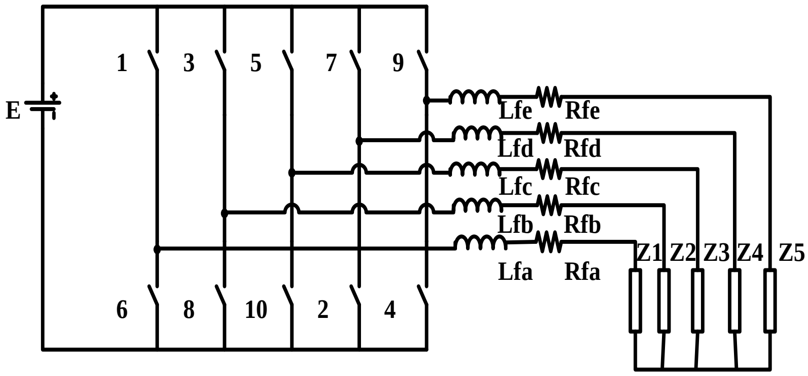


Figure 1. 5-leg VSI

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \\ v_{dn} \\ v_{en} \end{bmatrix} = \begin{bmatrix} S_1 \\ S_3 \\ S_5 \\ S_7 \\ S_9 \end{bmatrix} .E \tag{1}$$

from Figure 1. The inverter terminal voltages are:

$$\left.\begin{array}{l} v_{an}=R_{ta} i_{oa}+L_{fa}\frac{di_{oa}}{dt} \\ v_{bn}=R_{tb} i_{ob}+L_{fb}\frac{di_{ob}}{dt} \\ v_{cn}=R_{tc} i_{oc}+L_{fc}\frac{di_{oc}}{dt} \\ v_{dn}=R_{td} i_{od}+L_{fd}\frac{di_{od}}{dt} \\ v_{en}=R_{te} i_{oe}+L_{fe}\frac{di_{oe}}{dt} \end{array}\right\} \tag{2}$$

where,
R_{ta}, R_{tb}, R_{tc}, R_{td} , and R_{te} are (a, b, c, d, and e) phase resistances.
L_{fa}, L_{fb}, L_{fc} , L_{fd} and L_{fe} are (a, b, c, d, and e) phase filter inductances.
i_{oa}, i_{ob}, i_{oc} , i_{od} and i_{oe} are the (a, b, c, d, and e) phase load currents.
putting in a matrix form as:

$$v_o=R_t i_o+L_f\frac{di_o}{dt} \tag{3}$$

The instant load current can be calculated from (3) as follows:

$$\frac{di_o}{dt}=\frac{1}{L_f}\left[v_o-R_t i_o\right] \tag{4}$$

3. THE CURRENT CONTROL USING FCS-MPC WITH LEAST CURRENT ERROR AND MAXIMUM CURRENT CONSTRAINTS.

The structure of this control strategy is based on the cost function reduction. This strategy is used widely in power converters employments over the latest years, in light of its straightforward thought, and rapid [14-16]. The key steps, which are carried out in this technique, are as follow:

a) Reading the real actual current at each instant.
b) Creating a reference value dependent on the desired implementation.
c) Finally producing the discrete predictive model based on inverter parameters.

In this work and for tolerable accuracy the discrete structure is constructed by applying first-order approximation to the derivatives [17-25].

$$\frac{di_o}{dt}=\frac{i_o(K+1)-i_o(K)}{T_s} \tag{5}$$

Putting (5) in (4) yields:

$$i_o(K+1)=\frac{T_s}{L_f+R_tT_s}v_o(K)+\frac{L_f}{L_f+R_tT_s}i_o(k) \tag{6}$$

The (32) switching available combination can be handled by the proposed program to calculate vo(K), this will give a (32) various predictions of the next instant io(K +1). The program is designed to selects the right switching combination at k^{th} instant, which, produce the least possible error results from subtracting the estimated actual current and the required reference current value [io*(K +1)- io(K +1)] at the future instant of time (K +1). This switching combination is utilized as a control action to inverter switches.

The cost function (g) governing the process is:

$$\begin{aligned} g(K+1)=&\left\|i_o^*(K+1)-i_o(K+1)\right\| =\left\|i_{oa}^*(K+1)-i_{oa}(K+1)\right\|+\left\|i_{ob}^*(K+1)-i_{ob}(K+1)\right\| \\ &+\left\|i_{oc}^*(K+1)-i_{oc}(K+1)\right\|+\left\|i_{od}^*(K+1)-i_{od}(K+1)\right\|+\left\|i_{oe}^*(K+1)-i_{oe}(K+1)\right\|+ \\ &f1+\ldots+f10 \end{aligned} \tag{7}$$

If the sampling time Ts $\leq$ 20μs extrapolation process is not required [10], so that the desired current at (K) instant= desired current at (K +1) instant [9].

The proposed algorithm define the function (f) which represents the predefined load current boundaries and maximum allowed error. These functions (f_1….f_{10}) are appear as a constraint in the cost function (8), therefor any violation to these constraint, will exclude this cost function value, and the corresponding switching combination from the solution. This can be achieved by enlarging the result of (8).

4. SIMULATION OF THE MODIFIED TECHNIQUE

The 5-leg DC voltage input inverter Matlab/Simulink model using the FCS-MPC technique is clarified in Figure 2. The components used in the simulation are (filter resistor=0.7Ω, filter inductor=15mH, load resistor=10Ω, and switching time=20µsec). The VSI subsystem block, includes of two subsystems block, see Figure 3. The first one is (inverter1), which contains the five-leg inverter. The inverter switches are SEMKRON (SKM50GAL12T4) IGBT type, the switches data (fall time, rise time, and tail time) are used in inverter model (IGBT block). The specifics of (inverter1) are shown in Figure 4.

The MPC subsystem is shown in Figure 5. The main object in this subsystem is the S-function block named (mpcc5) were its inputs are the three-phase desired currents and the actual measured load currents. The M-file program established in this block performs the FCS-MPC modified algorithm. The output of this subsystem is the inverter switching commands as shown in Figure 5. Each output switching state acts as the proper switching combination which produces the optimal cost function value (i.e. least error) at the (K +1) period.

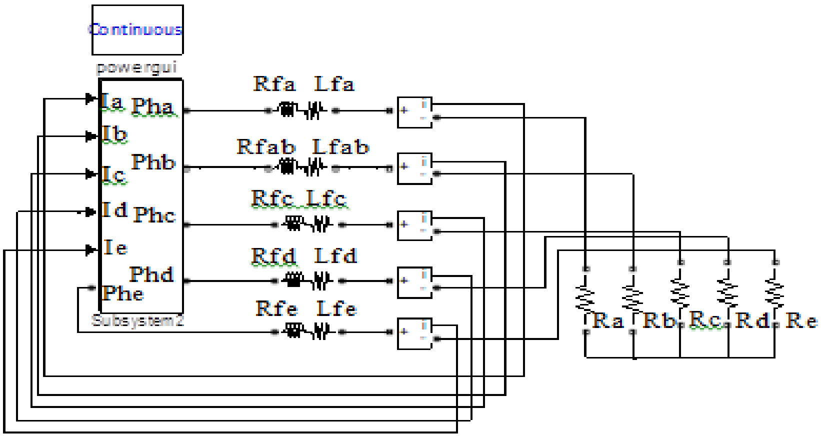


Figure 2. Actualized Matlab/Simulink model of proposed technique

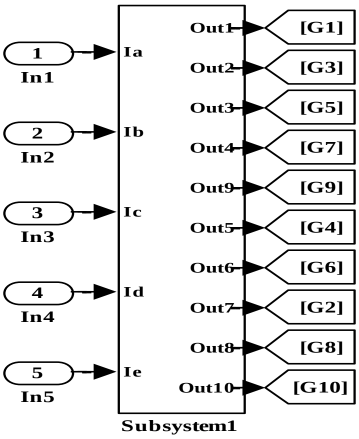


Figure 3 The inner subsystem included in the inverter block

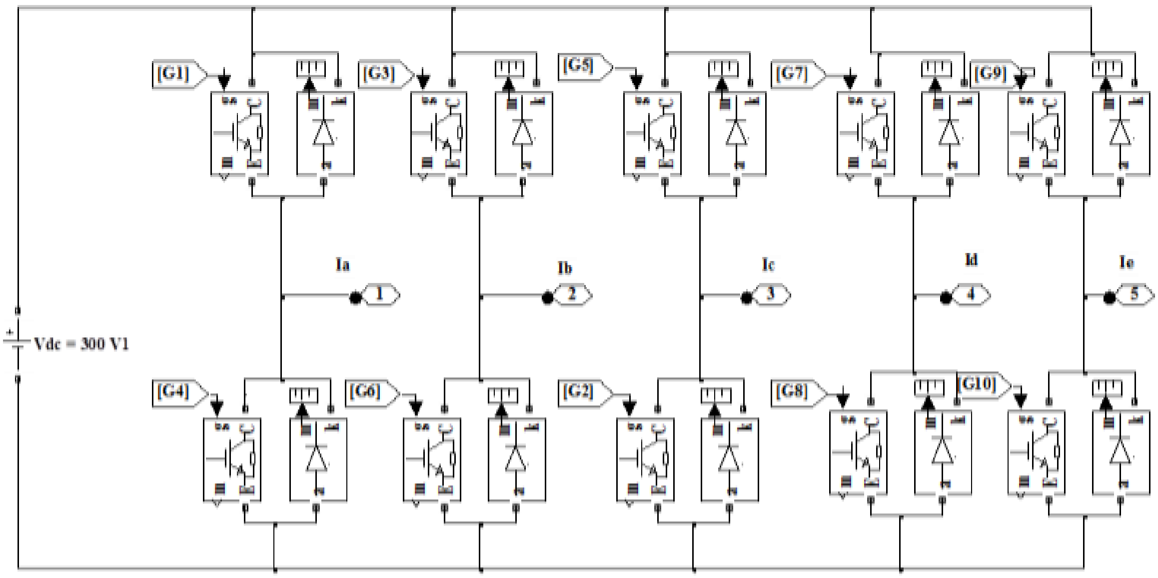


Figure 4. (Inverter1) subsystem

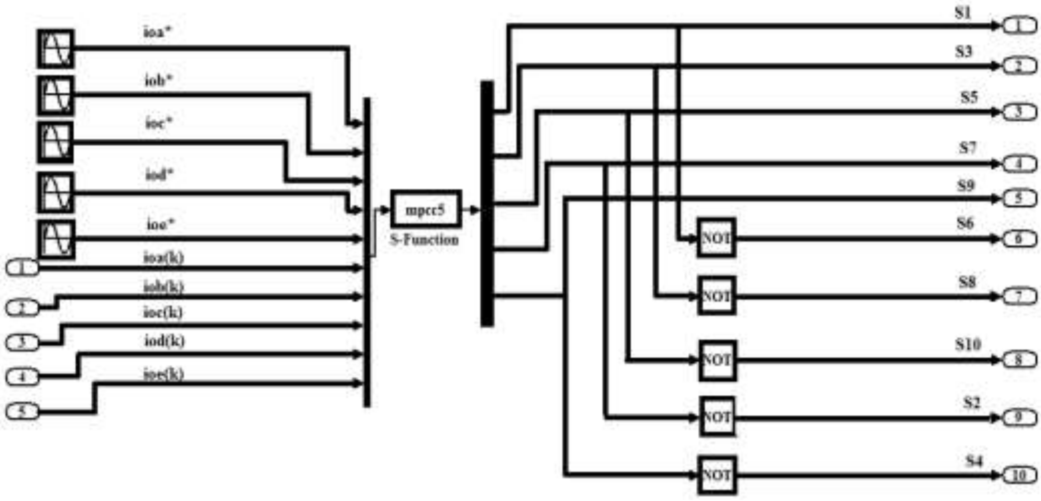


Figure 5. The MPC block

5. SIMULATION RESULTS

The simulation is achieved using Matlab/Simulink program, the goal is to optimize the cost function using extreme current limit and least error results from subtracting the estimated actual current and the required reference current value. The computation process is performed with two cases: 1- steady-state and step-change; the type of cost function used in this work is minimum absolute value. Figures 6-9 present the inverter 5-Ø terminals voltages, actual measured 5-Ø currents for both the traditional and the modified algorithm (maximum current and minimum currents error constraints). These results show the superiority of the proposed algorithm by reducing the overshoots. Figures 10-14 indicates an examination between the wanted 5-Ø currents versus the relating measured actual currents. These figures demonstrate the abridgement coordinating the two (anticipated and the reference values). As mentioned before, the algorithm selects the proper switching combination that yields the lowest cost function, which can be seen in Figure 15. Figure 16 illustrate the agreeable (THD) of the modified algorithm for the five-leg inverter output voltage.

To certify the authenticity and the quality of the FCS-MPC current control with maximum current and leas current error constraints technique, a mathematical analysis with different load in each phase with equal desired currents is implemented. The 5- Ø load voltages for this case study is illustrated in Figure 17. For this case-study, correlations include the real 5-leg currents, with the 5-leg comparable desired values is clarified in Figure 18. This outcome demonstrates that, in spite of the fact that the presences of unequal loads in each phase, the 5- Ø load currents pursue and nearly coordinate the ideal adjusted desired current values.

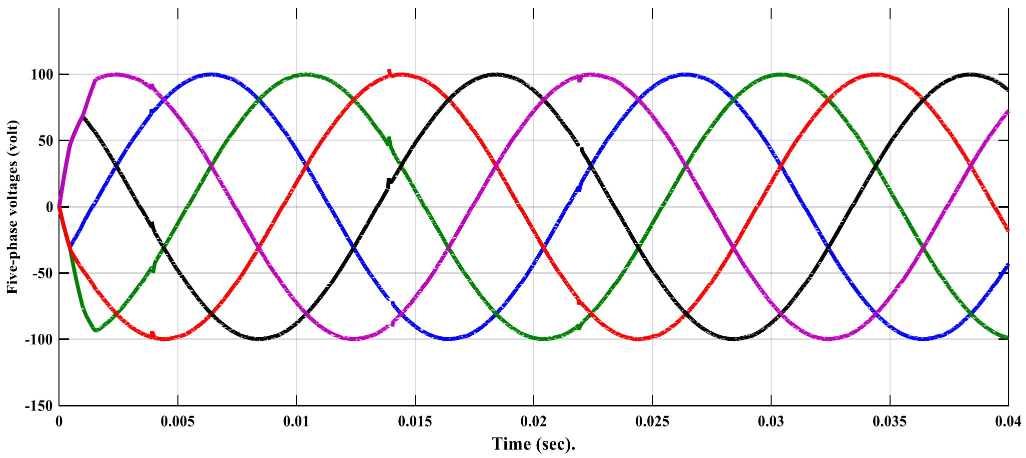


Figure 6. 5-Ø output voltages with modified voltages

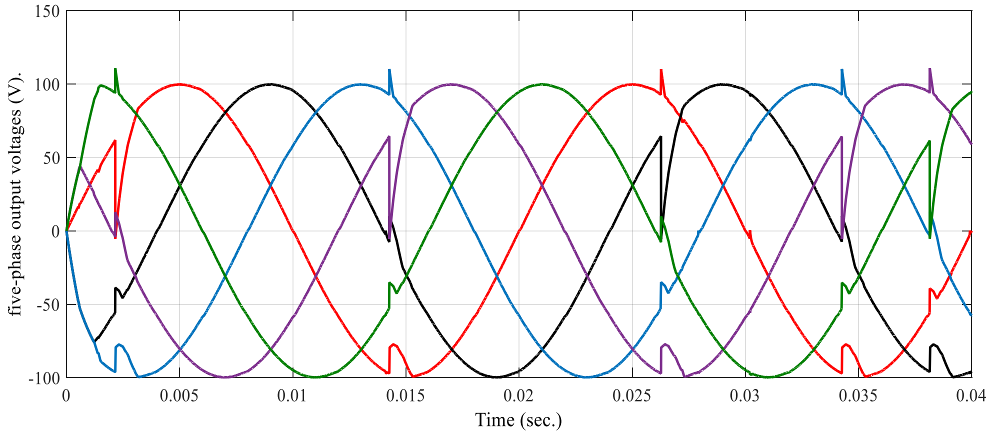


Figure 7. Traditional 5-Ø output load algorithm

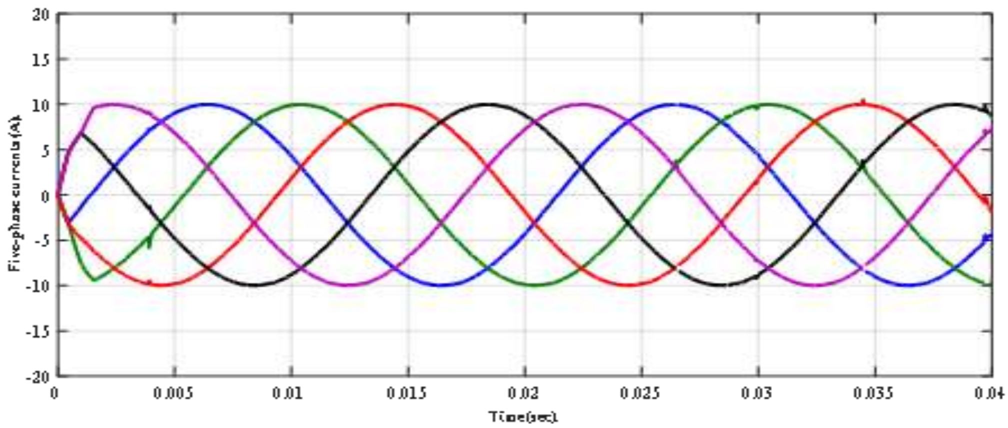


Figure 8. Traditional 5-Ø load currents algorithm

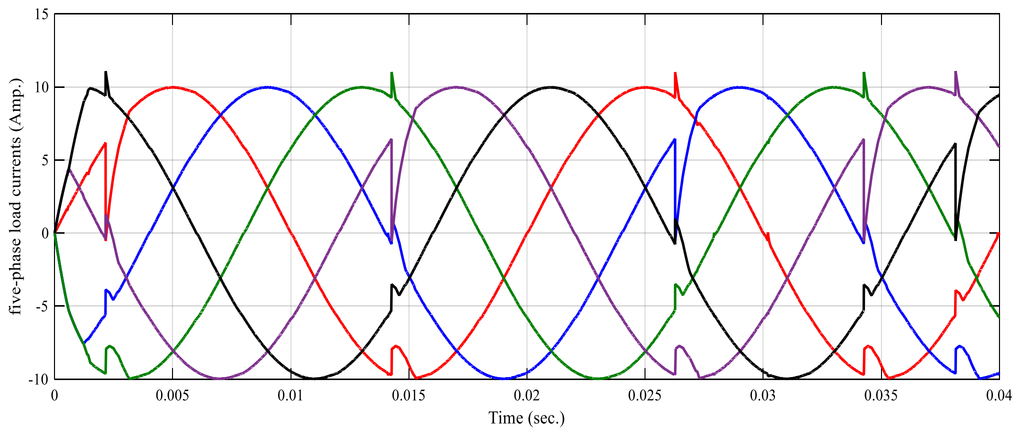


Figure 9. 5-Ø load currents with modified

The last relevant examination is applying a step-change in the desired current values. Figures 19-20 illustrate the 5- Ø load current values and voltages under a step-change at 0.01 sec. This demonstrate the sufficiency of the proposed algorithm, it is robust against the transient change in the desired current values.

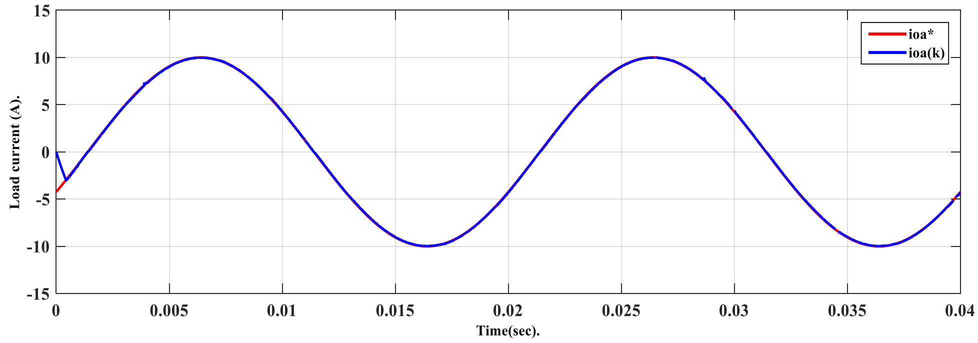


Figure 10. Ø-a current, actual (blue-line), and (red-line)

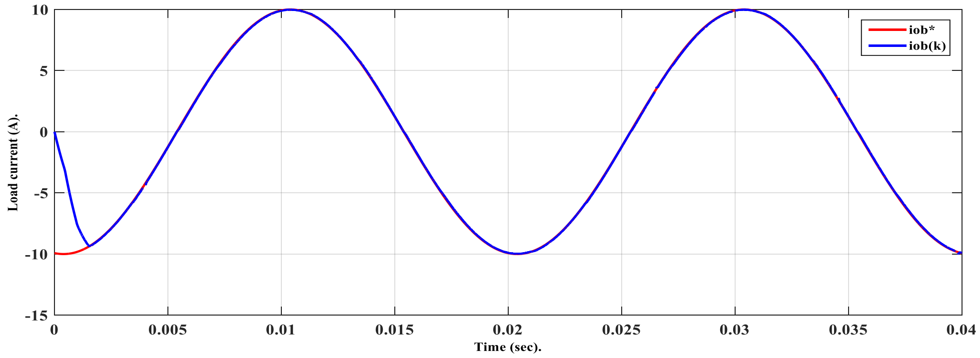


Figure 11. Ø-b current, actual (blue-line), and desired desired(red-line)

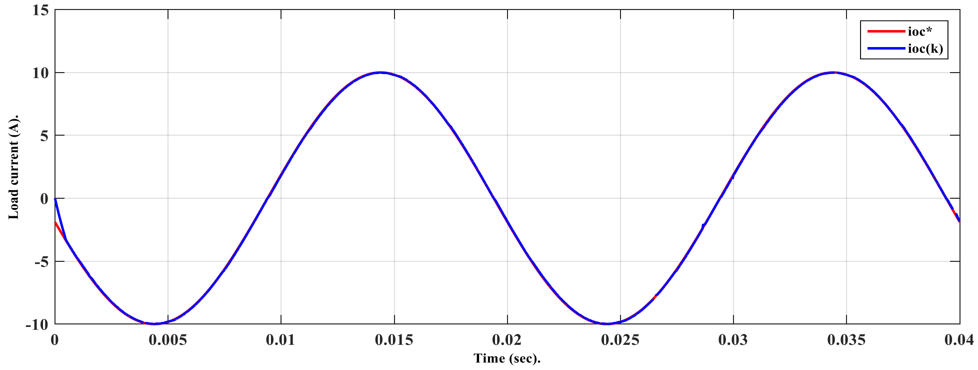


Figure 12 Ø-c current, actual (blue-line), and (red-line)

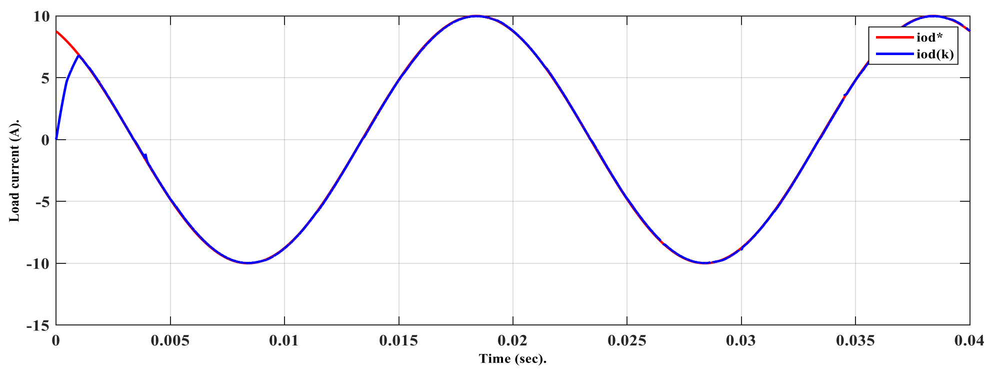


Figure13. Ø-d current, actual (blue-line), and desired desired (red-line)

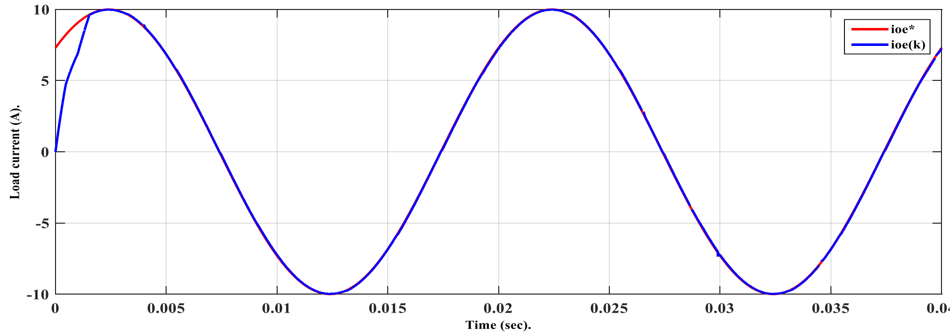


Figure 14. Ø-e current, actual (blue-line), and desired (red-line)

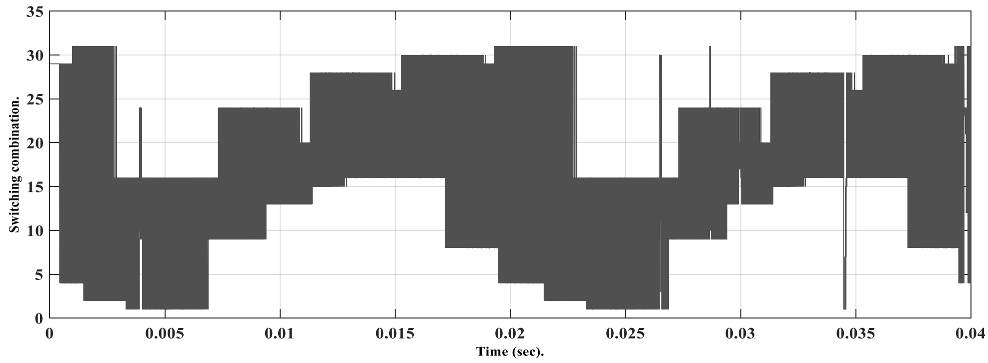


Figure 15. The chosen applied switching combination

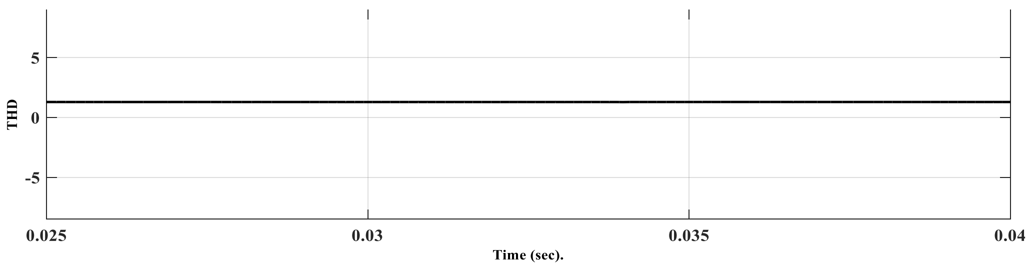


Figure 16. THD for the inverter voltage

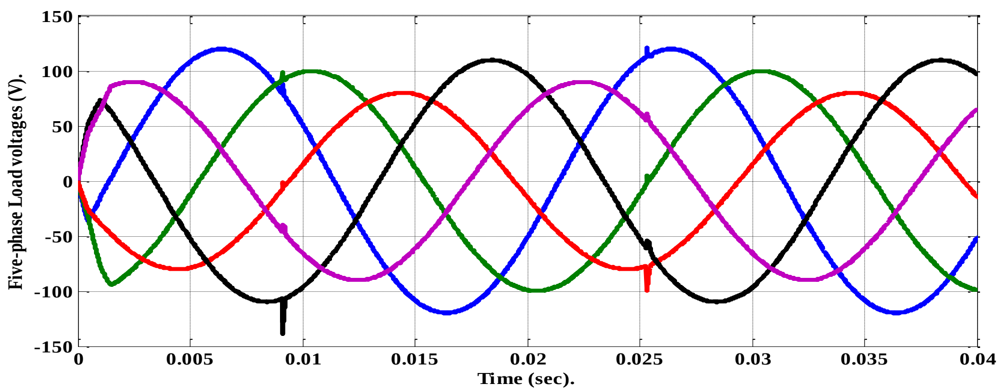
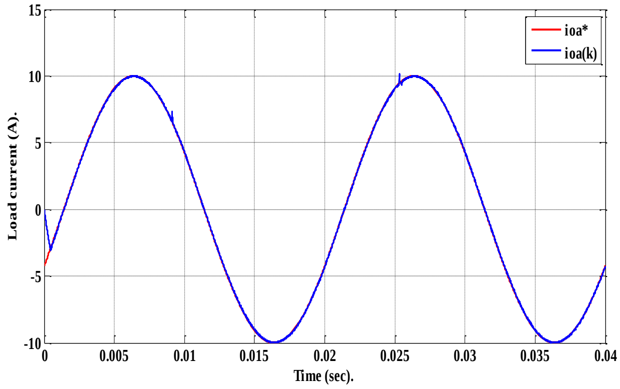
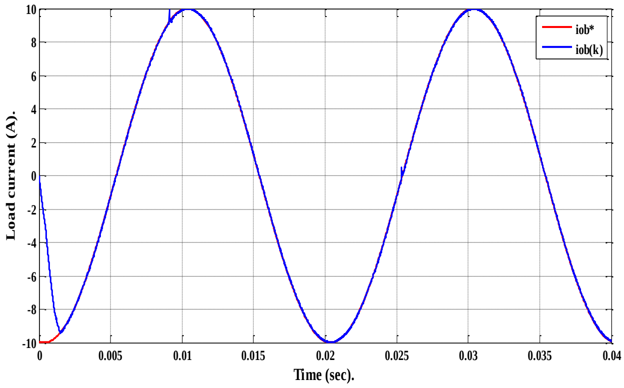


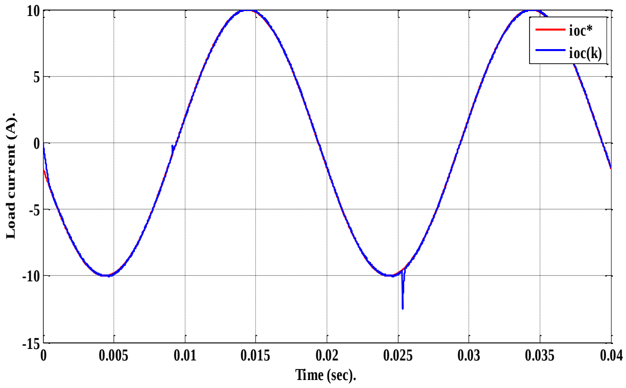
Figure 17. 5-Ø load voltages for the case of balanced desired currents with different load in each phase



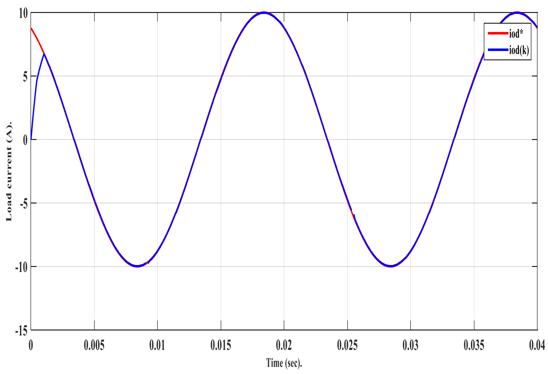
Ø-a



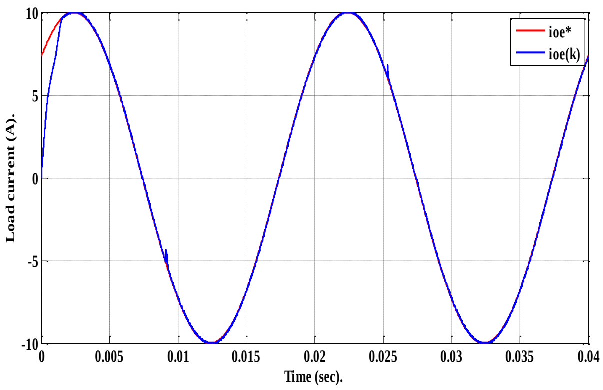
Ø-b



Ø-c



Ø-d



Ø-e

Figure 18. 5-Ø actual load currents (blue-line) with desired currents (red-line) for the case of balanced desired currents with different load in each phase

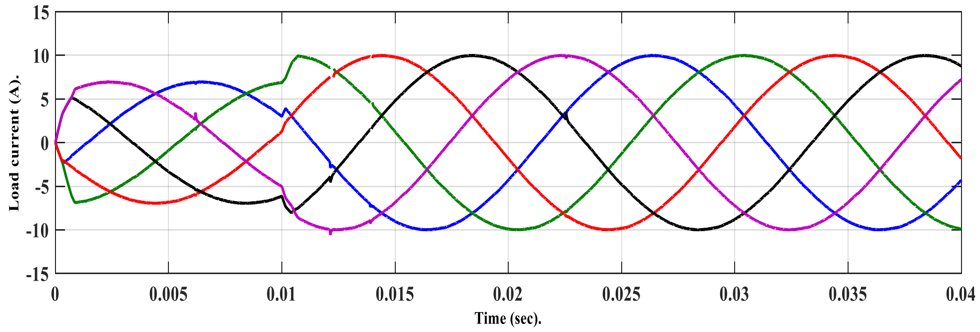


Figure 19. 5-Ø actual load currents when a step change in the desired currents

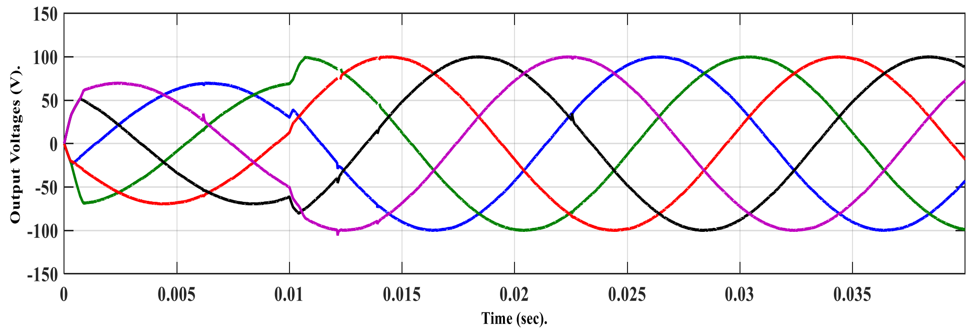


Figure 20. 5-Ø voltages when a step change in the desired currents

6. CONCLUSION

The paper presents a mathematical analysis for the 5-Ø (DC voltage input inverter), a Matlab/Simulink FCS-MPC model is built to control the 5-Ø currents. The analysis considers a cost function optimization, adding new two constraints 1- maximum allowable output current, and 2- minimum current error constraints is presented. The proposed algorithm chooses one from the finite (25=32) switching combinations produced by the 5-Ø inverter switches, in each period (K +1) the load current is predicted. This value results by matching the desired and the real current values at period (K), based on that the algorithm could choose the proper switching combination that yields least cost-function error value, and then stratify this chosen combination to the DC voltage input inverter. The obtained analysis results avow the genuineness of that technique. Additionally, the application of this technique and the new control path, affirms the superiority than traditional methods in the literature. Moreover, the new constraints provide a good THD since it discards any unwanted deflections. Various examples are used to confirm the adequacy, and sufficiency of the proposed technique, for instance: Not equal desired current values while each phase contain the same load, and Sudden change in the desired values. The results demonstrated that the 5-Ø actual currents pursue and nearly coordinate the desired values

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