

Finite control set model predictive direct current control strategy with constraints applying to drive three-phase induction motor

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ABSTRACT

In this, work the finite control set (FCS) model predictive direct current control strategy with constraints, is applied to drive three-phase induction motor (IM) using the well-known field-oriented control. As a modern algorithm approach of control, this kind of algorithm decides the suitable switching combination that brings the error between the desired command currents and the predicated currents, as low as possible, according to the process of optimization. The suggested algorithm simulates the constraints of maximum allowable current and the accepted deviation, between the desired command and actual currents. The new constraints produce an improvement in system performance, with the predefined error threshold. This can be applied by avoiding the switching combination that exceeds the limited values. The additional constraints are more suitable for loads that require minimum distortion in harmonic and offer protection from maximum allowable currents. This approach is valuable especially in electrical vehicle (EV) applications since its result offers more reliable system performance with low total harmonics distortion (THD), low motor torque ripple, and better speed tracking.

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1. INTRODUCTION

Most of the electric vehicles (EV) developed so far are considering dc machines, permanent magnet synchronous machines (PMSM), or induction machines. The suitability of dc machines motivates the EV designers to investigate different types of ac machines. The rated power limitation of the PMSM, along with the significant expense of permanent magnets, make these machines less applicable for EV applications. These motors require a larger size and higher weight when designed for high speed. The maintenance of minimal effort of IMs attracts many EV designers to consider them as an alternative to the machines above.

Recently, predictive control made huge attention to plan new power electronics drive systems. The rule of activity of this kind of control relies upon the load model, by predicting the following activity of the factors to be controlled, the controller then employs this prediction with predefined improvement procedure, to decide ideal control directions [1, 2]. The predictive control approach has many advantages that make it more usable in controlling converters, such advantages are the basic standard of activity, simple to carry out, furthermore, it can be achieved in different kinds of voltage source converters. On the other hand, it requires a notable number of computations; nevertheless, using fast PCs can take care of this issue [3-6].

Model predictive control (MPC) illustrates a progressively adaptable methodology when contrasted with different kinds of control approaches since it uses a reduced cost-function. In addition, it doesn't need a modulator to make the required voltage [7, 8]. Due to these benefits of MPC over traditional control strategies, it is broadly used in usual power converters, instead of multilevel converters. The fundamental reason that recognizes the MPC is the need to manage only one control path, where the deviation between the desired commands s and the estimated value of load currents is limited. Unlike traditional methods [9, 10], in this paper, finite control set MPC (FCS-MPC) methodology with current constraints, which added to the cost-function, is employed to control three-phase IM drives.

2. FCS-MPC WORKING STEPS AND SYSTEM MODEL

A power converter has discrete signal processing; a set number of switching combinations are employed to make the required output. Basically, the MPC estimates the following activity of the system, as indicated by every conceivable switching combination. These predictions are employed to evaluate and optimize the cost-function. In the long run, the switching combination, which produces minimum error is chosen as the switching order. The control issue of the battery source inverter can be limited to locate the best possible switching activity $S(t)$, this activity is the gateway that controls the switching process. These signals reform the output of the system $y(t)$, which follows the desired command signal $y^*(t)$. the mathematical expression $y(t_k)$ represents the estimation of $y(t)$ during the time period T_s , with the limited number of switching control activities of n , the prediction function (fp) is obtained from the discrete load model and its variable. The closest $S(t)$ to the desired command $y^*(t)$ is considered to the following stage. This is accomplished by using a cost-function fg , which relies upon the desired command, and the prediction variables, as [11, 12]:

$$gi = fg\{y^*(t_k + 1), y_{pi}(t_k + 1)\} \text{ for } i = 1, \dots, n. \quad (1)$$

When T_s is small enough with respect to the system dynamic, the desired command value can be considered consistent amid one sample instant $y^*(t_{k+1}) = y^*(t_k)$. The term fg in (1) describes the difference between the system prediction variable and the target desired command variable. This procedure prompts n number of (1) equal to the number of predictions n , since there are n predictions. Subsequently, the switching control activity that gives the least value of (1) is chosen as the order signal [13, 14].

The FCS-MPC is dependent on enhancing g_i in (1). This methodology establishes enormous industrial applications over the ongoing years, because of its simplicity, speed, and ability to deal with the nonlinearity and system constraints. The essential advances are achieved by estimating the load current value at the k^{th} instant, creating the desired currents command based on the necessary conditions and load requirements [15, 16]. The model discretization is accomplished by using the first-order approximation for all the variables, which produces satisfactory precision [17, 18].

$$\frac{di_o}{dt} = \frac{i_o(k+1) - i_o(k)}{T_s} \quad (2)$$

$$i_o(k+1) = \left(1 - \frac{T_s}{\tau_\sigma}\right) i_s(k) + \frac{T_s}{\tau_\sigma + T_s} \left\{ \frac{1}{R_\sigma} \left[\left(\frac{k_r}{\tau_r} - k_r j\omega \right) \hat{\psi}_r(k) + V_s(k) \right] \right\} \quad (3)$$

Where $i_o(k+1)$ is the predictive load current at the $(k+1)$ instant and can be computed using the load current estimation, and the output voltage at the k^{th} instant. The output voltage $v_o(k)$ relies on the (2^{nd}) desired command vectors, and the DC source voltage E . By achieving $v_o(k)$, 8 recognized estimations of $i_o(k+1)$ can be obtained. The FCS-MPC control strategy is programmed to distinguishes the proper switching combination in the k^{th} instant, which creates the difference between the processed predicted load current $i_o(k+1)$, and the desired command load current $i_o^*(k+1)$. The chosen switching combination is utilized to operate the inverter six switches, this combination is used till the end of $(k+1)$ instant. This procedure can be accomplished by utilizing (g) in (1), which related to the minimum difference as in (4) [19, 20]:

$$g(k+1) = \|i_o^*(k+1) - i_o(k+1)\| \\ = \|i_{o\alpha}^*(k+1) - i_{o\alpha}(k+1)\| + \|i_{o\beta}^*(k+1) - i_{o\beta}(k+1)\| \quad (4)$$

Where $i_{o\alpha}$ and $i_{o\beta}$ are the two-axis currents. In (4) (g) can be equal to zero, only when the predicted load current equivalent to its desired command value. The goal of the algorithm is to decrease (4) by decreasing the difference to zero. Likewise, any requirements, like maximum current points, error decrease, can be

included in (4) to improve the load running requirements and system protection. In one system, when the desired commands are obtained at the k^{th} instant, an extrapolation of these desired commands to the following $(k+1)$ instant is applied. This is practiced before considering them in (4). Furthermore, if the examining time T_s is not exactly or equal to $2\mu s$, then $i_o^*(k)=i_o^*(k+1)$ [21-23]. One of the upsides of predictive control is the chance of achieving direct control of the output variables without the need for internal control loops; they can arrive at values that are outside their permitted run. The second advantage of MPC is the plausibility to deal with system nonlinearities within the numerical model [24-29].

The proposed enhancement in this paper is achieved by adding two constraints to the cost-function. The first one is to prevent the predicted load current, from reaching its predefined maximum value. The second is designated to limit the difference (error) between the desired command and the measured currents. This can be achieved by representing the two constraints by sub-functions f_1 and f_2 , the proposed cost-function becomes:

$$g = g(k + 1) + f_1 \lim(i_s^p) + f_2 \lim(err) \tag{5}$$

where, i_s^p represents the maximum allowable predicted stator current, and $f_1 \lim(i_s^p)$ is a constraint function defined as:

$$f_1 \lim(i_s^p) = \begin{cases} \infty, & |i_s^p| > i_{max} \\ 0, & |i_s^p| \leq i_{max} \end{cases} \tag{6}$$

while $f_2 \lim(err)$ represents another constraint, function defined as:

$$f_2 \lim(err) = \begin{cases} \infty, & |error| > c_1 \\ 0, & |error| \leq c_1 \end{cases} \tag{7}$$

where c_1 is a predefined error value between the desired command and the predicted stator current. When the two predefined constraints are violated, the two sub-functions bring the cost-function (g) to a very large value and will be eliminated from the calculations. This will result in choosing the next minimum (g). The proposed approach is implemented on the traditional field-oriented control (FOC) strategy to drive a 3-phase IM, where the torque and flux are treated independently. The overall proposed system (implemented in MATLAB) is demonstrated in Figure 1.

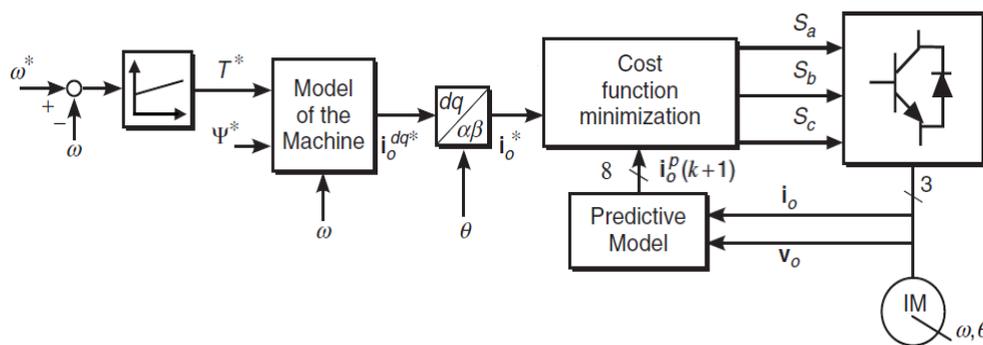


Figure 1. Overall control system

3. RESULTS AND DISCUSSION

The MATLAB/Simulink 2019 package is used in simulation. The proposed FCS-MPC constant current control over all model, with traditional FOC IM drive is described in Figure 2. The 3-phase IM parameters are: $J = 3.1 \text{ kg.m}^2$, $p = 2$, $L_m = 10.46 \text{ mH}$, $L_s = 0.3027 \text{ mH}$, $L_r = 0.3027 \text{ mH}$, $R_s = 14.85 \text{ m}\Omega$, $R_r = 9.295 \text{ m}\Omega$, $\text{nominal torque} = 792 \text{ Nm}$, $\text{nominal flux} = 0.73 \text{ wb}$, $\text{DC-link voltage} = 400 \text{ V}$, $T_s = 2 \mu s$. The simulation scheme has six principal components: desired command current generator, measured currents, error calculation, predictive current control algorithm, inverter model, coordinate conversion, and the 3-phase IM Model.

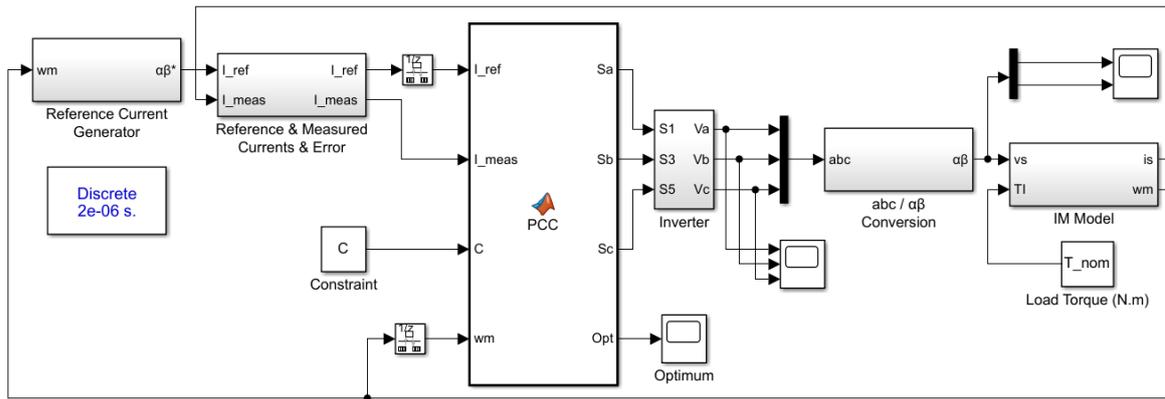


Figure 2. Block diagram of the proposed system

The First subsystem in the simulation layout is the desired command current generator, in this stage, the desired command speed can be changed in steps. The traditional proportional integral (PI) controller is used to generate the desired command torque, from the error between the desired command and the measured speed. Different approaches of PI controllers can be applied. The desired command of rotor flux magnitude is assumed to be constant. The relative desired command values of the rotor field and the torque create desired command currents in the d-q coordinate system. In the sub-system block of the predictive algorithm, the current in the $\alpha\beta$ system is obtained, therefore the inverse Park change transform is introduced to fulfill this above requirement.

The predictive algorithm is executed in an embedded MATLAB function. The cost-function of the optimization process is accomplished in this sub-system based on the system model. The inputs for this sub-system are desired command currents, estimated rotor speed, and stator actual currents, while its outputs are the gating signals of the inverter switches.

Figure 3 demonstrates the tracking of the actual speed, the desired command speed, and the error between them. The low error values for different speed conditions (increase, constant, and decrease), represent the main requirement for a good performance in the FOC system. The generated desired command torque from the PI controller is shown in Figure 4, this indicates the proper selection of the PI parameters, to produce the desired command torque. To ensure the motor operation within its current ratings, the system generates 3-phase desired command currents, this can be illustrated in Figure 5. Figure 6 shows the actual (measured) motor 3-phase stator currents, these currents are obtained without applying the proposed constraints. The effect of using the new constraints, which added to the cost-function on stator currents, is shown clearly in Figure 7. Comparing to the results in Figure 6, less distortion and better low harmonics content are obtained after applying these constraints.

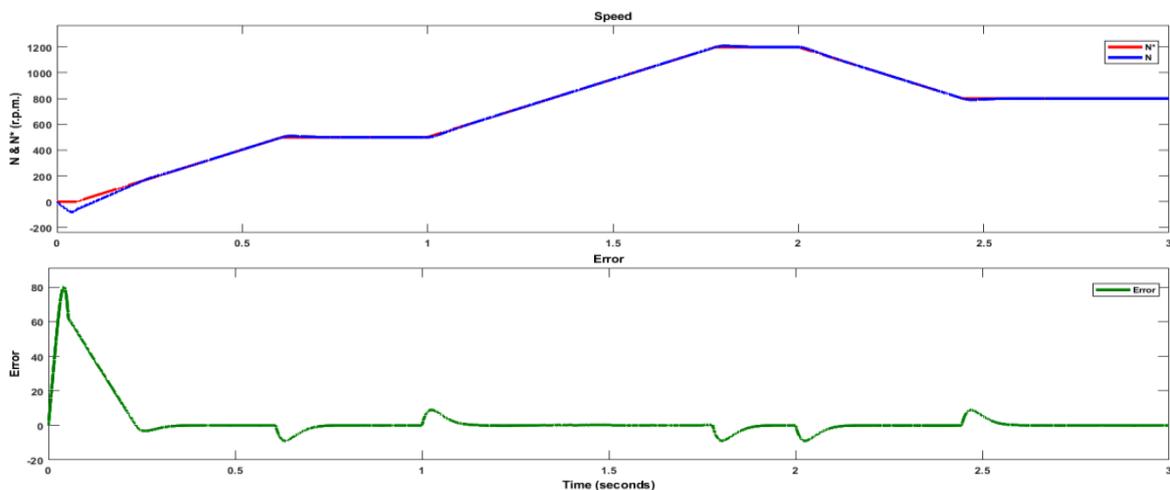


Figure 3. Desired command speed, measured speed, and error between them

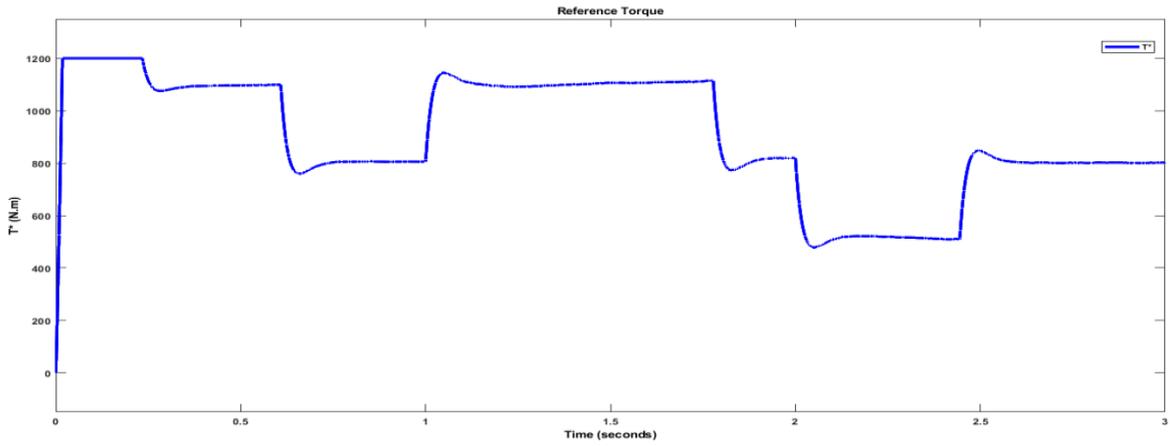


Figure 4. Generated desired command torque

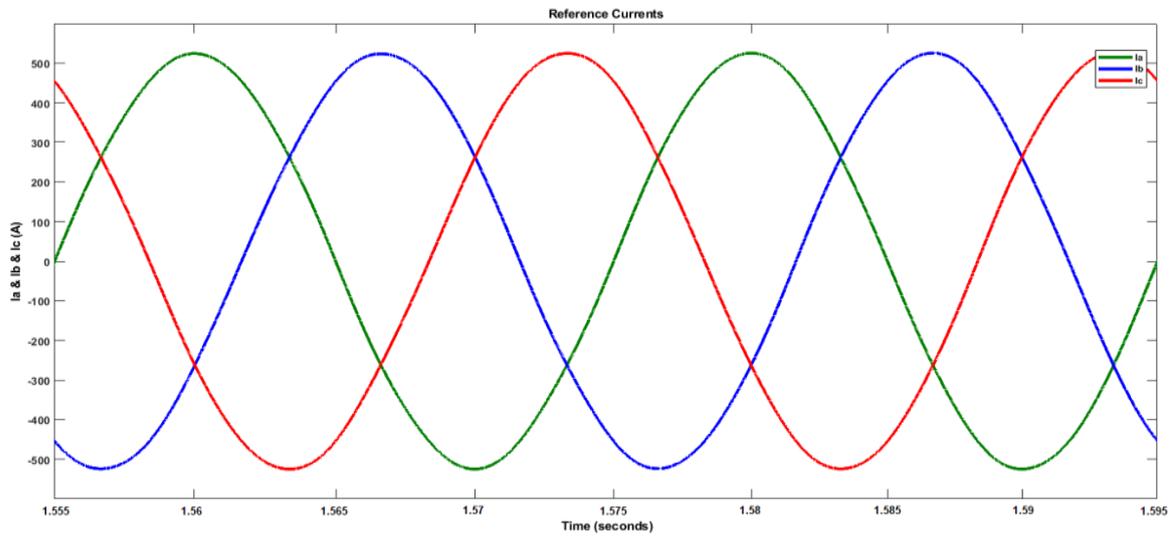


Figure 5. Generated desired command 3-phase currents

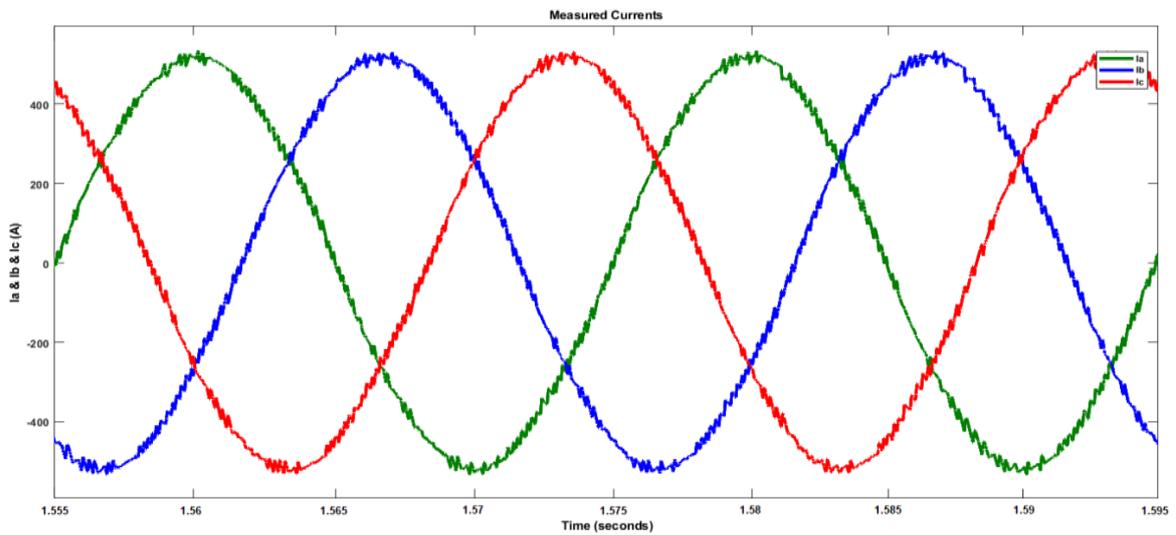


Figure 6. Measured 3-phase motor currents without constraints

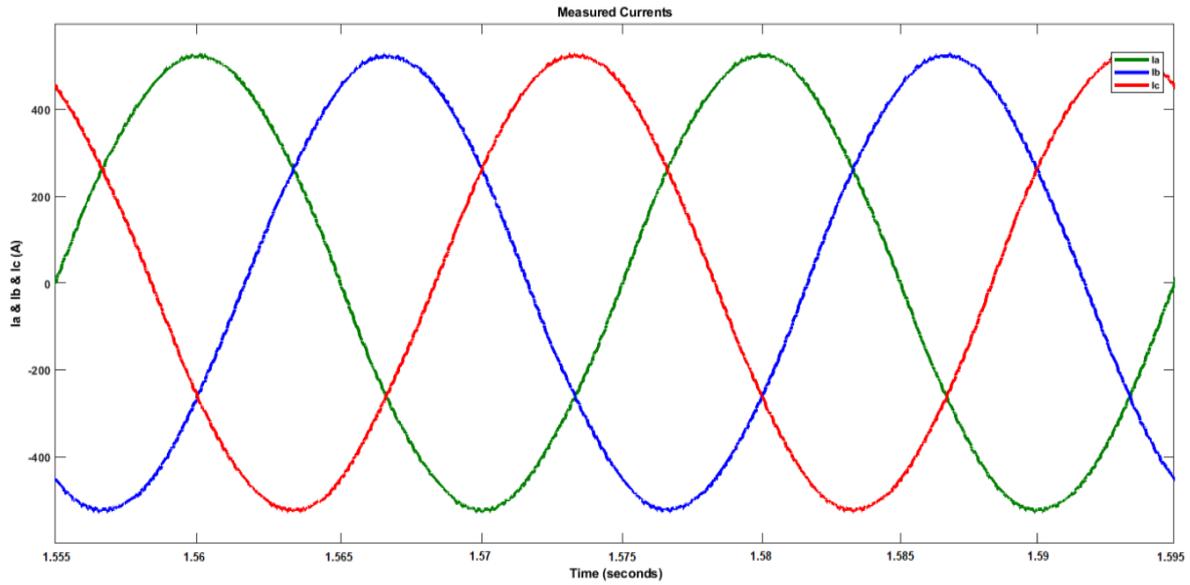


Figure 7. Measured 3-phase motor currents with constraints

To confirm the conclusion, Figures 8 and 9 show the current errors before and after applying the proposed constraints. By tuning c_1 in (7) the currents error can be reduced by (up to 80%) which reflects on improving the motor performance. Figures 10 and 11 illustrate the improvement in the load currents harmonic content, less THD is obtained (1.02%) reduction when applying the proposed constraints.

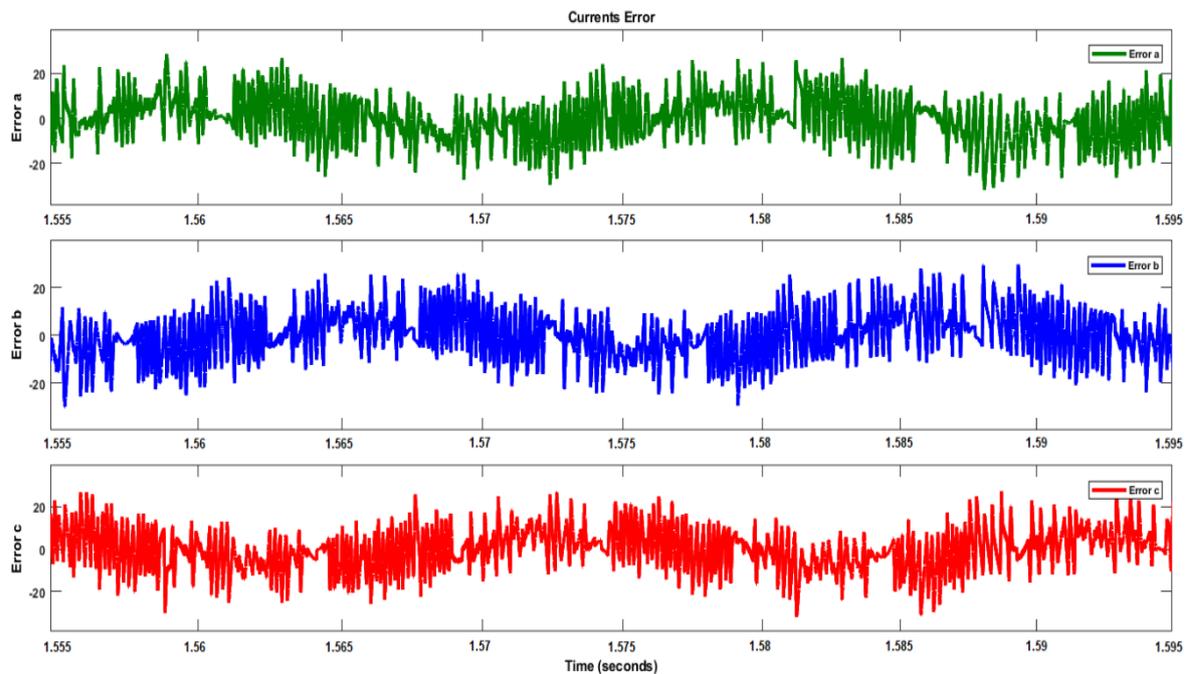


Figure 8. Error-values between the desired command and measured motor currents without constraints

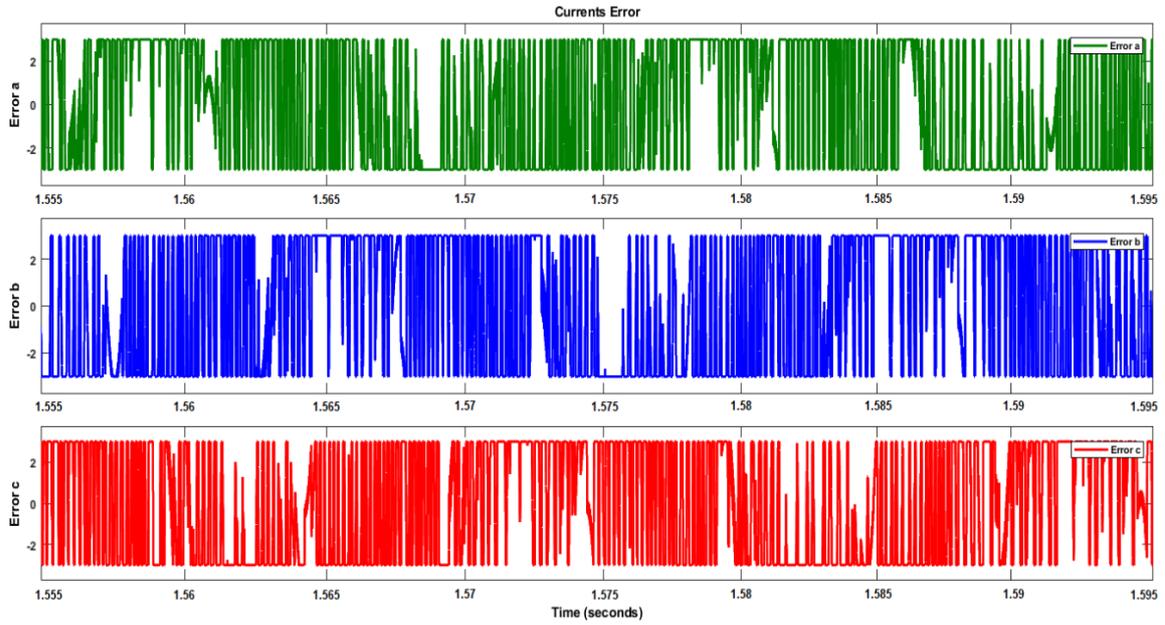


Figure 9. Error-values between the desired command and measured motor currents with constraints

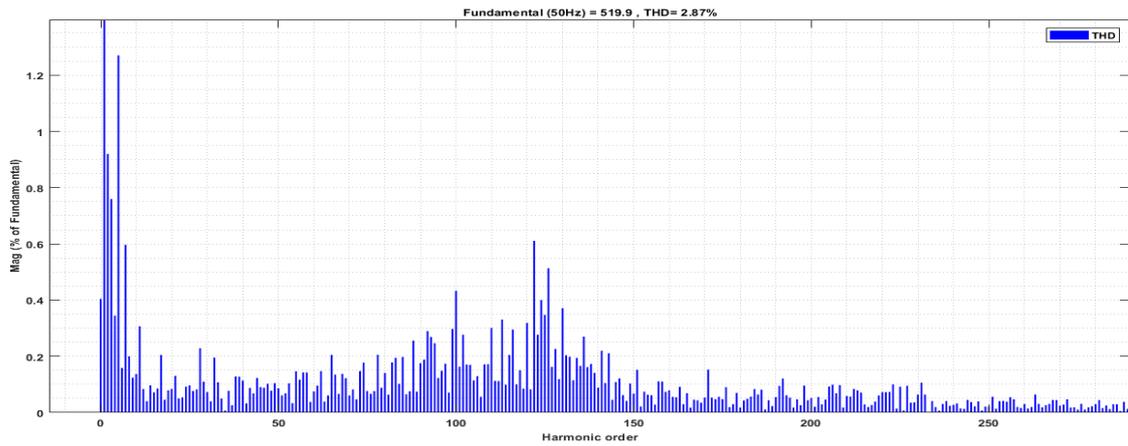


Figure 10. Motor currents harmonic content, and THD without constraints

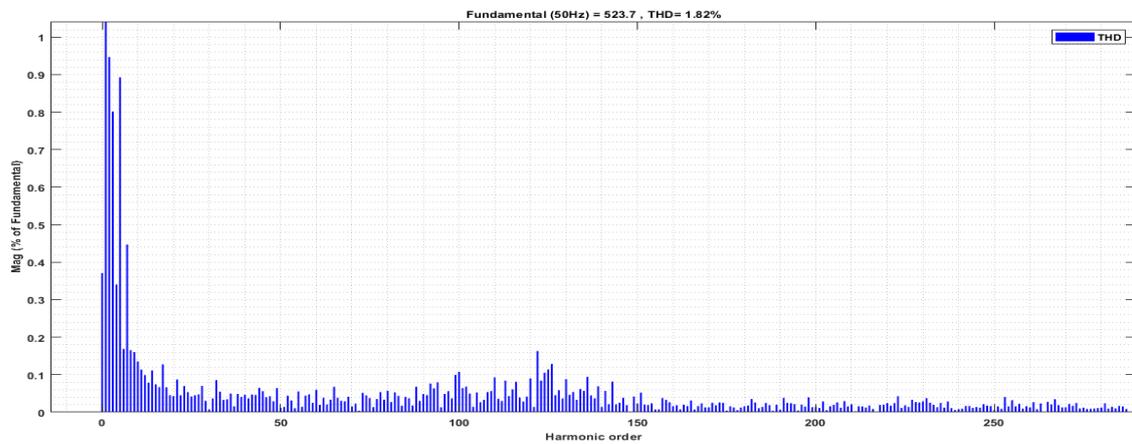


Figure 11. Motor currents harmonic content, and THD with constraints

4. CONCLUSION

In this paper, a new modification is presented to enhance the cost-function of the FCS-MPC when applied to control the IM with traditional FOC. The second suggested constraint produces a reduction in the currents error of (up to 80%), less difference between the measured and desired command speed, and keeps the motor currents within their desired command values, which means less torque ripples. In addition, an improvement in the THD of 1.02% is obtained, this can be implemented with applications that require low harmonics. The robustness of the control system is observed from the simulation results and proper cost-function objectives. The proposed approach fulfills the load requirements including less THD, and good protection from overload currents, regardless of the additional executing time. This proposed approach is valuable especially in EV applications, since its result offers more reliable system performance, with low THD, low motor torque ripple, and better speed tracking.

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