Analysis of the Model Predictive Current Control of the Two Level Three Phase Inverter

Çiğdem GÜNDOĞAN TÜRKER

Department of Mechatronic Engineering, Istanbul Gedik University
Istanbul, Turkey
cigdem.gundogan@gedik.edu.tr

Abstract: Model Predictive Control (MPC) Algorithms have been very popular and used widely in industrial applications of power converters and drives. Major advantage of MPC is the flexibility to control different variables, with constraints and additional system requirements. Also, it has been an alternative to the classical control techniques without need of additional modulation techniques, MPC needs the proper system model in order to calculate optimum values of the controlled variables. This paper gives an introduction about the Model Predictive Current Algorithm. Model Predictive Current Control Algorithm is implemented for a two phase three level drive system. After the system is modelled, the control algorithm is verified for different load condition of an induction machine.

Key Words: Two Level Three Phase Inverter, Induction Machine, Model Predictive Control.

1. INTRODUCTION

Predictive Control techniques have been applied in electrical machines and drive systems such as energy, communications, medicine, mining, transportation, etc. Most industrial applications such as automative, space and aeronautics, railway, ship transport, nuclear process have own particular requirements and need electrical drives with fault-tolerant and high reliability. With these requirements and growing voltage levels, the control of the multiphase converters has been improved in last ten years [1-2].

Field-oriented control (FOC) and direct torque control (DTC) methods are most established methods in three-phase electrical drives control. FOC is a modulation-based approach with a coordinate transformation from stator fixed to a rotor flux-oriented coordinate system. In DTC approach, the state of the switches is selected from a lookup table depending on the stator flux angle and the outputs of hysteresis controllers for flux and torque. As it is implied from the absence of a modulator, DTC shows a faster transient response than FOC but it has higher current, flux, and torque ripples [4-8].

Model Predictive Control (MPC) techniques with several advantages have been an alternative to conventional controllers. The common property of the Model Predictive Control Techniques is the precalculation of the future actions of the system in a prediction horizon time by using the system model directly. The optimal control action is defined according to a cost function. The system variables are been evaluated by comparing the reference values in a sampling time. The direct application of the control action to the converter without requiring a modulator is the main advantage of MPC. Also, the cost function is an important stage in the design of an MPC, since required constraints and nonlinearities of the multidimensional systems are easily implemented and evaluated to select the optimal switching states. However, the high switching frequency, current ripples and computational efforts are some major drawbacks [9-12].

This paper is organized as follows: Firstly, the whole system which includes induction machine driven by two level three phase inverter is described and modelled mathematically. In section 3, Model Predictive Control Algorithm is introduced detaily. Finally, the simulation of the control algorithm for the drive system is presented.

2. SYSTEM MODEL

In this study, the system is modelled for the induction machine driven by a two level three phase inverter. Two level three phase inverter topology and voltage vector are shown in Figure 1. Two semiconductor switches in each phase leg work in a complementary manner. When the upper switch is on with switching state '1', the lower switch is off with switching state '0'. There are eight possible switching combinations for the two level three phase inverter as the variables $u_{abc} = [u_a \quad u_b \quad u_c]^T \in \{0,1\}$ are introduced. In this way, each phase of the two level inverter can produce two discrete voltage levels $-\frac{V_{dc}}{2}$ and $\frac{V_{dc}}{2}$ [13-14].

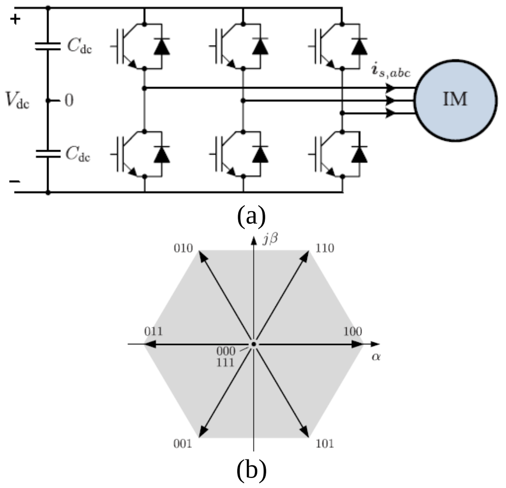

Figure 1. a) Topology of two level three phase inverter, b) Voltage vector diagram.

By employing the Clarke Transformation which the switching states are transformed from the abc plane to the $\alpha\beta$ plane, final control set contains only seven unique voltage vectors $v_{\alpha\beta} = [v_\alpha \quad v_\beta]^T$.

Thus, the actual voltages applied to the windings of the induction machine are calculated as;

$$v_{\alpha\beta} = \frac{V_{dc}}{2} u_{\alpha\beta} = \frac{V_{dc}}{2} K u_{abc} \tag{1}$$

The matrix K is given by;

$$K = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{2}$$

$[0 \quad 0 \quad 0]^T$ and $[1 \quad 1 \quad 1]^T$ produces zero voltage vectors called zero switching states, whereas the others produce active voltage vectors as active switching states.

Regarding the dynamics of the induction machine, the differential equations are given in $\alpha\beta$ coordinate system which is stator fixed for $\omega_k = 0$.

$$i_s+\tau_\sigma \frac{di_s}{dt}=\frac{1}{r_\sigma}\upsilon_s-j\omega_k\tau_\sigma i_s+\frac{k_r}{r_\sigma}\left(\frac{1}{\tau_r}-j\omega_{el}\right)\psi_r \tag{3}$$

$$\psi_r+\tau_r\frac{d\psi_r}{dt}=L_m i_s-j(\omega_k-\omega_{el})\tau_r\psi_r \tag{4}$$

Where the coefficients are given by $\tau_\sigma = \frac{\alpha L_s}{r_\sigma}$ and $r_\sigma = R_s + k_r^2 R_r$ with $k_r = \frac{L_m}{L_r}$, $\tau_r = \frac{L_r}{R_r}$ and $\sigma = 1 - \frac{L_m^2}{L_s L_r}$.

ψ_s, ψ_r ; the fluxes, i_s, i_r; the currents, R_s, R_r; the resistances, L_s, L_r; inductances, l_m; mutual inductance between stator and rotor, v_s; the stator voltage and v_r; the rotor voltage. $w_{el} = p * w_m$ is the electrical angular machine speed. $(*)_s$ denotes stator variables, $(*)_r$ denotes the rotor variables.

The stator flux ψ_s can be estimated as;

$$\frac{d\psi_s}{dt} = v_s - R_s i_s \tag{5}$$

The electromagnetic torque equation is given by;

$$T_e = \frac{3}{2} p(\psi_s \times i_s) = \frac{3}{2} p(\psi_r \times i_r) \tag{6}$$

The mechanical differential equation is can be described by

$$\frac{dw_m}{dt} = \frac{1}{j}(T_e - T_j) \tag{7}$$

3. MODEL PREDICTIVE CURRENT CONTROL

MPC needs the proper system model in order to calculate optimum values of the controlled variables. The system behaviour in next sampling interval is calculated for every switching state of the inverter in a certain prediction horizon. MPC determines the optimum switching states by minimizing a cost function. A cost function is defined according to the desired behavior of the system including controlled variables reference tracking by comparing the controlled variable with its reference value. Figure 2 shows the basic control scheme of the system [15].

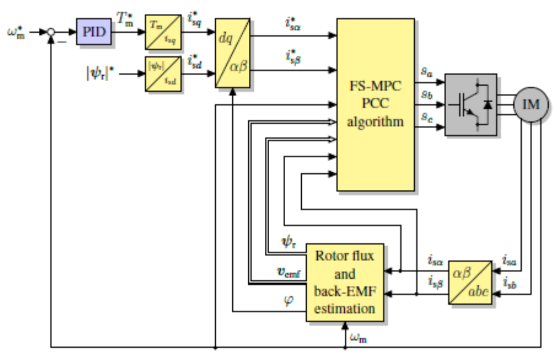

Figure 2. Basic control schema for the whole system

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The predictive current controller relies on the model of the physical drive system to predict future stator current trajectories. The current references $i_{sd}^*$and i_{sq}^* are transformed to $\alpha\beta$ current references, $i_{s\alpha}^*$ and $i_{s\beta}^*$, and the controller operates in $\alpha\beta$ coordinates which makes the control more efficiently in stationary coordinates.
Conventional speed PID controller generates the torque reference. The constant reference value of the rotor flux magnitude is set. Based on the reference values of the field and torque, the currents i_{sd} and i_{sq} are produced by the equations below;

$$i_{sd}^* = \frac{|\psi_r|^*}{L_m} \tag{8}$$

$$i_{sq}^* = \frac{T^*}{\frac{3L_m}{2L_r}|\psi_r|^*} \tag{9}$$

The State-Space models of the induction machine can be designed as;

$$x=\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix}, \quad u=[\upsilon_\alpha,\upsilon_\beta], \quad y = i_s \tag{10}$$

y is taken as the system output vector, whereas $u_{\alpha\beta}$ constitutes the switching voltage vector provided by the controller.

- ❖ Based on the discrete model of system, the current values of the controlled variables (x(k)) at step k are used to predict their next values x(k+1) for all N possible switching states.
- ❖ In the proposed predictive algorithm, future current I(k+1) is evaluated for each of the possible seven voltage vectors which produce seven different current predictions.
- ❖ The voltage vector whose current prediction is closest to the expected current reference $x_{ref}(k+1)$ is applied to the load at the next sampling instant.

In other words, the selected vector will be the one that minimizes the cost function.

Adding system constraints is a remarkable feature of MPC. These constraints can be added simply to the cost function with their specific weighting factors. It can be implemented by an additional term to the cost function as the distance between the measure value of voltage at the current state and the future state (one step time forward) as given below;

$$j=(i_{s\alpha}^*-i_s(k+1))^2+(i_{s\beta}^*-i_{s\beta}(k+1))^2+\lambda(u(k+1)-u(k))^2 \tag{11}$$

4. SIMULATION OF THE CONTROL ALGORITHM

MPC algorithm for the two level inverter and induction machine is simulated on the Matlab/Simulink in Figure 3. The algorithm is executed with a sampling time $T_s = 100\mu s$. The DC link voltage is 550V. The parameters of the induction machine is given in Table 1.

Table 1. The parameters of the induction machine.

Parameters	Value
Nominal power P_{nom}	$2.2kW$
Synchronous frequency f_{syn}	$50Hz$
Nominal current $\lvert i_{s,nom}\rvert$	$10A$
Nominal speed ω_{nom}	$2800rpm$
Number of pole pairs p	1
Stator resistance R_s	2.68Ω
Rotor resistance R_r	2.12Ω
Stator inductance L_s	$283.4mH$
Rotor inductance L_r	$283.4mH$
Mutual inductance L_m	$275.1mH$
Inertial J	$0.062kgm^2$

In the simulation, the reference value of the rotor flux magnitude is set to $|\psi_r|^* = 0.7Wb$. The torque reference is produced by the speed PI controller. The current references i_s^* are calculated as described in the MPC algorithm.

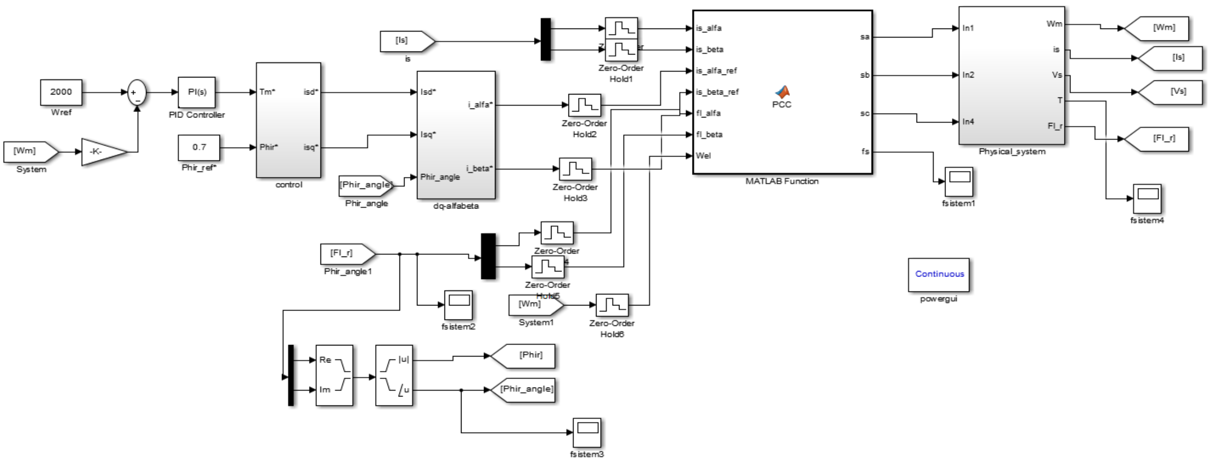

Figure 3. The simulation blocks of MPC of the two level inverter driving the induction machine.

The stator currents at 2800rpm without load torque are presented in Figure 4. Figure 5 shows the stator currents when a load torque of 4 Nm is implemented.

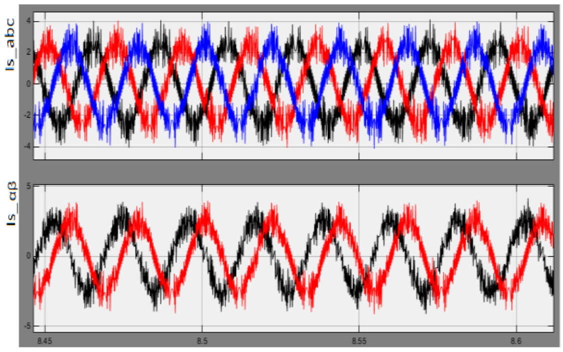

Figure 4. Steady state stator currents and αβ currents waveforms at no load and 2800rpm.

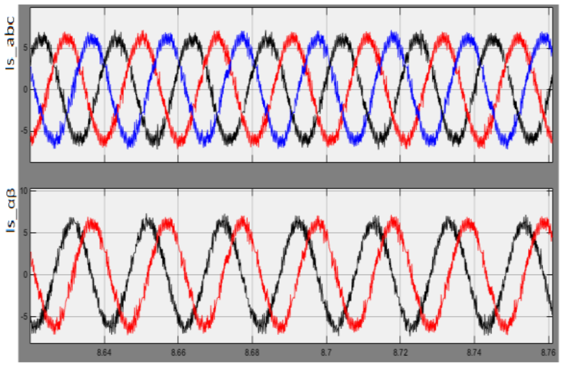

Figure 5. Steady state stator currents and αβ currents waveforms at 4Nm load torque and 2800rpm.

Figure 6 shows the load torque impact on the speed. At about time 7s, 4Nm was applied to the machine which was rotating at 2800rpm.

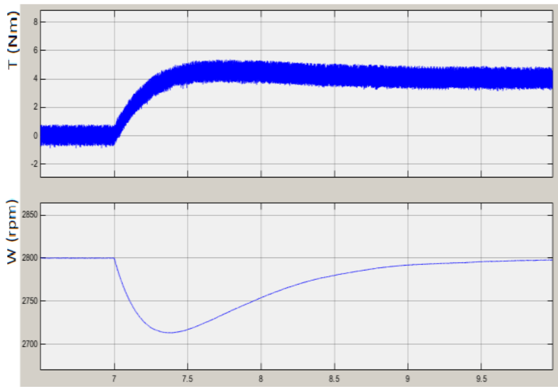

Figure 6. Load torque impact by changing from 0Nm to 4Nm at 2800rpm.

In Figure 7, speed reference impacts by changing from 1500 to 2800 rpm. Figure 8 shows the current control result by changing the speed reference.

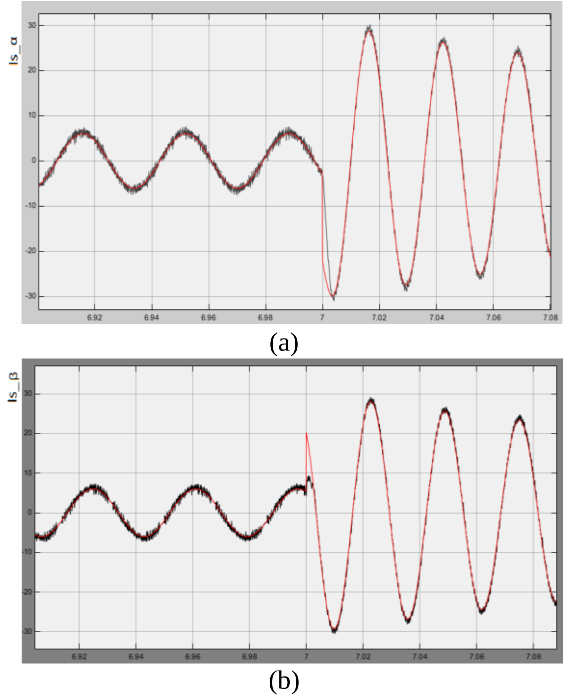

Figure 7. a) $I_{s\alpha}$ b) $I_{s\beta}$ stator current steps by changing the speed from 1500 to 2800 rpm.

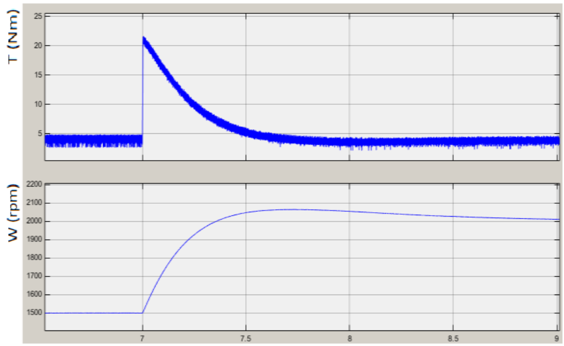

Figure 8. Speed reference impact, 4Nm at 2800 rpm.

5. CONCLUSION

Predictive control techniques have been a very powerful alternative in the electric drives applications. It is simple to apply and allows the control of different converters without the need of additional modulation techniques or internal cascade control loops. The important disadvantage of MPCs which is high calculation power is overcome by today's microcontrollers.

Major advantage of MPC is the flexibility to control different variables, with constraints and additional system requirements. This is great potential and flexibility to improve the performance, efficiency, and safety demanded by the industry applications.

Model Predictive Current Control is introduced and presented for the system consisting of a two level inverter and an induction machine. It is

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implemented in Matlab/Simulink and obtained simulation results of the system for different load and speed conditions. It is clearly seen that the algorithms can track the system references without any problems for steady state and speed steps.

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