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Improvement of Induction Motor Torque Characteristics by Model Predictive Current Controller

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Abstract*: This paper describes the Model Predictive control (MPC) strategy to control the Torque of the Induction Motor (IM) according to the reference torque provided. IM fed with an Three Level Neutral Point Clamped (NPC) Inverter. MPC paves the way to replace complex Space Vector Modulation (SVM) into a simple understandable algorithm. It uses the discretized model of the IM. Stator current is used as a control variable hence called Model Predictive Current Control (MPCC). MPCC is derived from Field Oriented Control (FOC) Technique. MPCC achieves improved nominal torque compared to FOC, But current harmonics are high rather it's simplicity encourages it's usage and further development in MPC strategies for Embedded Drives. By the end of the paper, both FOC and MPCC controls of IM drive were discussed using MATLAB/SIMULINK.

***Keywords* : FOC, Induction Motor Drive, MPC, MPCC, NPC Inverter, Three level SVM, Torque Control.**

I. INTRODUCTION

Predictive control covers a very wide class of controllers that have found recent applications in power electronics converters and automated vehicles. The main advantage of predictive control [1] is the use of a mathematical model of the system for predicting the future behavior of the control variables. Model Predictive Current Control is derived from basic structure of FOC. But compared to FOC, MPCC [2] contains more distortion in current rather implies simple algorithm structure over SVM and improved reference torque tracking with nearer average value. Induction motor modelling done in continuous time domain referred to stationary reference frame. Because in stationary reference frame we can eliminate the rotor position dependency Wfr. This motor model fed with an NPC inverter by space vector modulation later on FOC designed. For MPC control algorithm discretized model of model equations considered. Reference of step torque considered and controllers designed to track the reference.

II. DYNAMIC MODEL OF IM

The per-phase equivalent circuit model of the motor gives good performance only under steady state operation. In adjustable speed drives, machine consists feedback elements, and therefore its transient behaviour has to be taken into consideration. Hence, require an dynamic model [11] of the induction motor to study the dynamic behavior of the machine under both transient and steady state conditions.

Consider, 3-ph squirrel cage induction motor in stationary reference frame. The modelling process of induction machines is typically performed in two stages. Starting from the three-phase abc quantities and using fundamental physical laws such as Faraday's law of induction and the Lorentz force, the machine's differential equations and its torque equation. In a second stage, to simplify the representation model is then transformed into an orthogonal reference frame.

$$\psi_s = L_s i_s + L_m i_{r.} \psi_r = L_r i_r + L_m i_r \tag{1}$$

$$Ls = Lls + Lm \,, Lr = Llr + Lm \tag{2}$$

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

K is transformation constant to stationary reference frame

$$vs = R_s i_s + \frac{d\lambda s}{dt} + jw_{fr}\lambda s \tag{4}$$

$$vr = R_r i_r + \frac{d\lambda r}{dt} + j(w_{fr} - wr)\lambda r \tag{5}$$

$$is = [i\alpha \; i\beta]^T \;; \; \lambda s = [\lambda\alpha \; \lambda\beta]^T \;;$$

$$vs = [v\alpha \; v\beta]^T \;; \quad \psi s = [\psi\alpha \; \psi\beta]^T \;;$$

$$vs = K[va \; vb \; vc]^T$$

$$Te = \frac{3}{2} pRe\{j\lambda s.\, conj\{is\}\} \tag{6}$$

$$M\frac{dw}{dt} = Te - Tl \tag{7}$$

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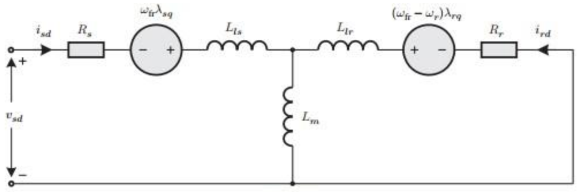
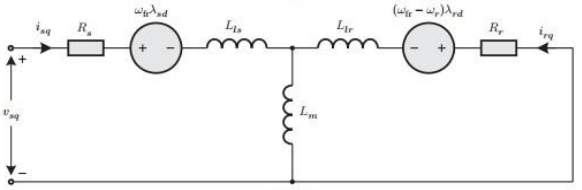


(a) d-axis



(b) q-axis

Fig. 1. Equivalent d-q model of 3-ph Induction Motor [2]

Faradays law (1),(2) and clarkes transformation (3) and equivalent circuit from Fig.1 by KVL (4) and Torque (6), (7)provides complete mathematical model. In the motor model Wfr can be treated as zero from (4) because, in stationary reference frame it is zero and Vr also (5), since in squirrel cage induction motor rotor end is short circuited.

III. THREE LEVEL NPC INVERTER

The NPC inverter topology was originally proposed by Nabae et al. in 1981. This diode clamped inverter provides three voltage levels per phase. Today, it constitutes the most widely used voltage source inverter [12] in MV drive applications [3]. Neutral point clamping involves voltage waveform fixed to neutral reference. Three level helps to minimize the distortions in waveform.

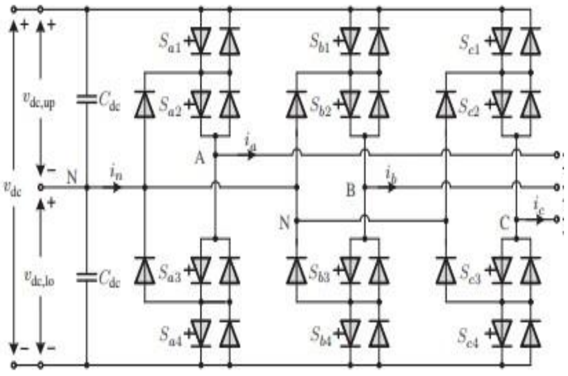


Fig. 2. Neutral Point Clamped Three Level Inverter [4]

Let the variable $U_x \in \{-1,0,1\}$ represents the switch position in one phase leg, with $x \in \{a, b, c\}$. In each phase leg, the inverter can produce three voltage levels as shown in Fig.2. The phase voltages as summarized in Table 1.

$$vs = \frac{Vdc}{2} K[ua\ ub\ uc]^T \qquad (8)$$

Input voltage in motor model can be written in terms of switching states as in (8)

Table 1. Switching states for NPC inverter

Switch position	Phase voltage	S_{x1}	S_{x2}	S_{x3}	S_{x4}
1	$V_{dc,up}$	1	1	0	0
0	0	0	1	1	0
-1	$V_{dc,low}$	0	0	1	1

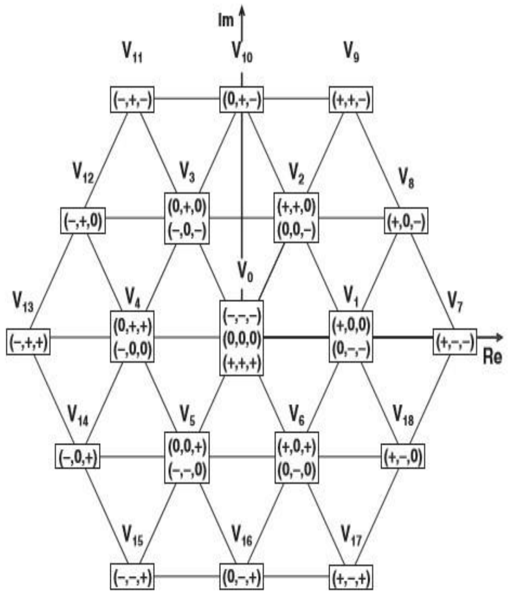


Fig. 3. Available 27 possible Switching states for 3 levels

For switching 3 level inverter there are 27 possible states with {1,0,-1} selection. In total 27 states only 19 are enough to drive the motor, remaining 8 are called redundant .i.e other switch combinations also results same output from Fig.3 . SVM switching can be performed by selecting reference voltage and by knowing the sector and sub sector which it belongs then modifying the switch sequence according to simulation time. Which is the difficult part in SVM [7] switching. Hence alternative options like MPC are coming forward for easier understanding of operation.

IV. FOC

The thought behind this FOC is to have independent torque and flux control by considering two current components. D,Q are two components of currents. Where D represents rotor flux magnitude control and Q represents Torque control. Proper relation between the electro magnetic torque T_e and the rotor flux magnitude ψ_r and stator current required. This can be obtained from equation which shows the relation between the stationary αβ and rotating reference frame d-q, from there inter related with the rotor flux vector.

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Since the variables are represented in stationary coordinate system, the electromagnetic torque will be controlled by quadrature component of stator current i_{sq} and the rotor flux magnitude can be controlled by its real part i_{sd}..

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} id \\ iq \end{bmatrix} \tag{9}$$

$$i_{sd}{}^{*} = \frac{\psi_r{}^{*}}{X_m} \tag{10}$$

$$i_{sq}{}^{*} = \frac{X_r T_e{}^{*}}{X_m \psi_r} \tag{11}$$

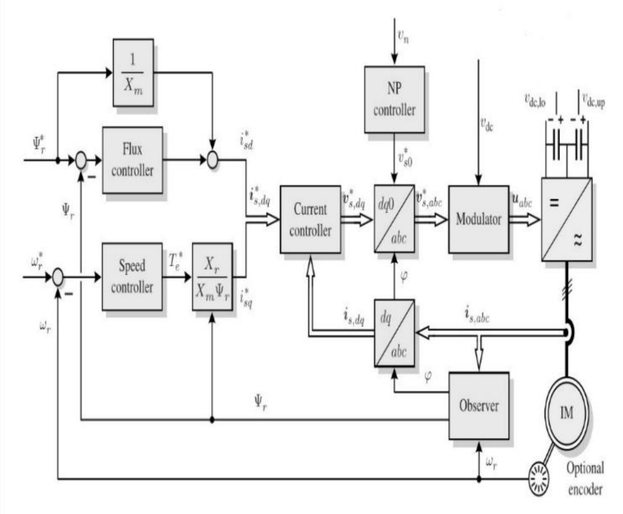

Fig. 4. Block diagram of FOC [3]

Block diagram for FOC [4] is shown in Fig.4 in that, the reference current i_{sq}* is collected from an outer speed control loop from (11) on the other hand i_{sd}* is obtained from the rotor flux control loop as in (10). d-q to stationary reference frame completed by (9). The stator current errors were controlled with PI controllers those generate the stator reference voltages v_{sd}* and v_{sq}*. Then, the obtained voltages are transformed based on angle and then fed to the inverter by space vector pulse width modulator.

V. MPC

MPC has rapidly emerged in power electronics. If any variable with mathematical model with k+1 instant can used as MPC variable.

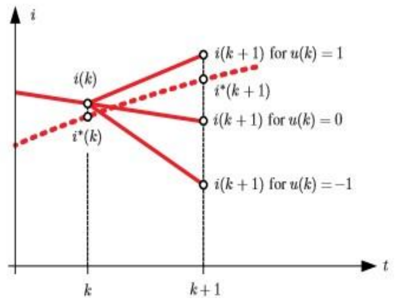

Fig. 5. Current tracking for various switching options

Similarly, let current expressed in discrete form then for different possible inputs there is a next possible state which can be identified or predicted at present state as shown in Fig.5

VI. MPCC

Before going the Model predictive control we need to have state space model [10] for discrete analysis Those can be obtained from continuous motor model equations [5] by taking derivatives of current and flux linkage term to left hand side.

$$\frac{di_s}{dt} = \left(wr - \frac{\phi}{D} I\right) i_s + \left(\frac{Rr}{D} I - wrQ\frac{Xr}{D}\right) \psi s + \frac{Xr}{D} Vs \tag{12}$$

$$\frac{d\psi s}{dt} = -R_s i_s + vs \tag{13}$$

$$Xs = Xls + Xm;\ Xr = Xlr + Xm;$$

$$\phi = R_s X_r + R_r X_s; D = X_r X_s - X_m{}^{2};$$

$$Q = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

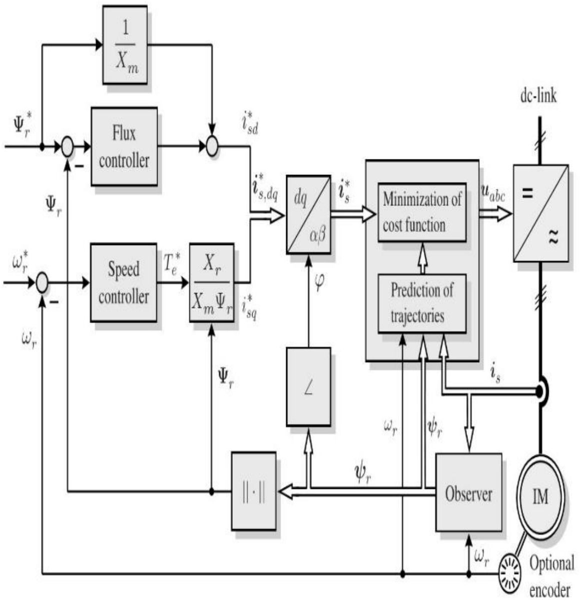

Fig. 6. Block diagram of MPCC [3]

MPCC control comprises three stages of operation reference current calculation, future current prediction for different switching options, optimized switching selection by cost function minimization as shown in Fig.6. We choose stationary orthogonal coordinates and set the angular speed of the reference frame to zero.

A. *Reference Current Calculation*

Reference current calculation is similar to FOC as shown in (10), (11) and variation of rotor flux considered as constant.

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B. *Current Prediction*

Discretized mathematical models obtained from continuous motor model equations(12),(13) from [9]. Discretization involves forward Euler model, as derivative it self represents future state, which is key point for MPC implementation.

$$i_s(k+1) = Ai_s(K) + B1\psi_r(k) + B2u(k) \tag{14}$$

$$A = I(1 - \frac{Ts}{\tau s}); \quad B1 = \left(\frac{1}{\tau r}I - w_r Q\right)\frac{X_m}{D}Ts\,;$$

$$B2 = \frac{X_r}{D}\frac{Vdc}{2}KTs$$

$$\tau s = \frac{X_r D}{R_s X_r{}^2 + R_r X_m{}^2}\,; \qquad \tau r = \frac{X_r}{R_r}$$

From (14) stator current of induction motor obtained for different possible switch position u(k).

C. *Optimized Switching for current error*

In the third stage optimization [7,8]. optimization function J provided. At minimum J, i.e at minimum error respective Uabc applied to inverter.

$$J = ||i_s{}^* - i_s(K+1)|| \tag{15}$$

1) *Logic for optimization*

```
U={all active 19 states eliminating redundent
states}€{-1,0,1}
For(i=1:19)
Calculate is(k+1);
Calculate J; from(15)
End
Choose U at minimum J occurs
```

VII. SIMULATION RESULTS

Considered 5.4HP squirrel cage induction motor with parameters provided in table. IGBT as switch considered with practical limitations and used for simulation. FOC and MPCC controllers designed using MATLAB/SIMULINK software [6]. The circuit design done with the help of reference mode shown in Fig. 4 Fig. 5 respectively.

Table 2. Drive details

Power	5.4HP
Voltage line-line	400V
Speed	1430rpm
Poles	4
Frequency	50Hz
Rotor leakage resistance	1.405ohm
Stator leakage resistance	1.395ohm
Stator leakage inductance	00.005839H
Rot leakage inductance	0.005839H
Mutual Inductance	0.1722H
Full load Torque	26.711N-m

A. *FOC Simulink*

For FOC reference torque considered of 10-20 N-M placed and Drive model taken from Table 2. We may consider speed or torque as reference. For 10-20 N-M torque approximately 8-10A current drawn by motor due change in load speed varied hence slight increase in current observed. If it is speed in series, We need PI control for torque conversion. The Average Torque deviates from Reference.

Reference voltage vector is calculated from model shown in Fig.4. Obtained reference voltage subjected to SVM vector space for proper switching area selection. Nearest switch option obtained and converted to required sampling instant and fed to IM.

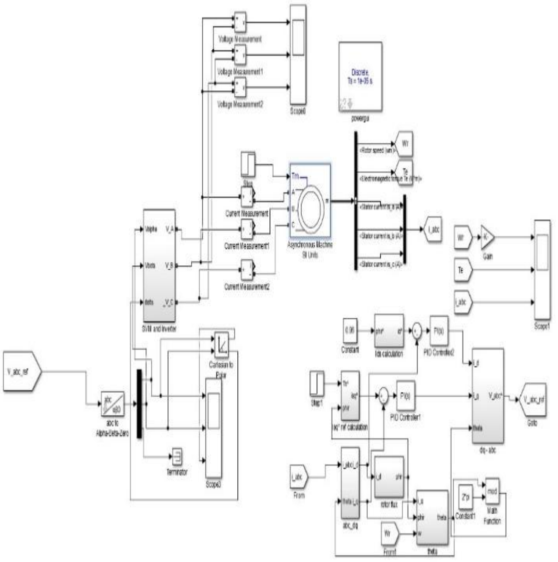

Fig. 7. FOC Simulink circuit

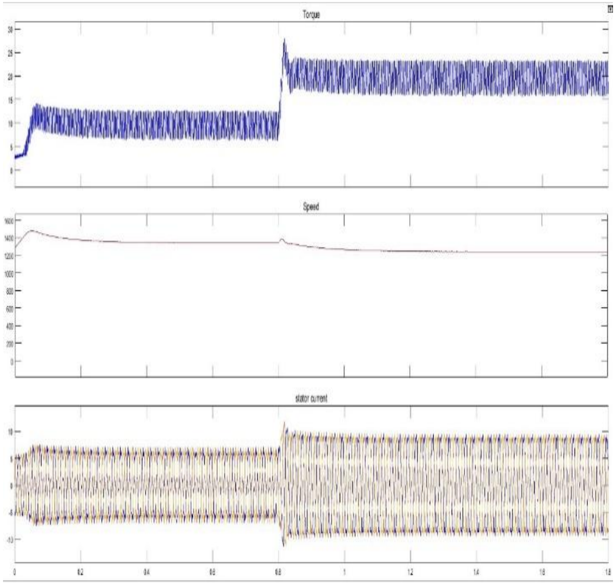

Fig. 8. FOC Simulink result

B. *MPCC Simulink*

To know the behavior of controller, reference torque step from 10 N-m to 20 N-m step is given in the circuit design. Followed by d-q model as shown in Fig.6, Asynchronous machine model considered with specified drive details. MPC code implemented according to algorithm given in MPCC. Delay considered, because the present state calculations selected as next switching states to inverter.

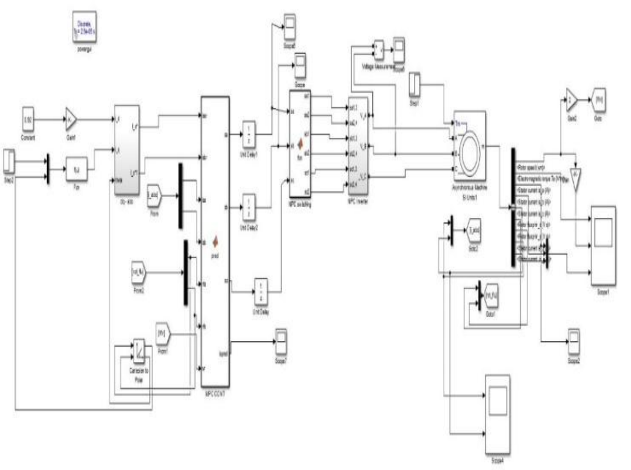

Fig. 9. MPCC Simulink circuit

As the torque increases, current drawn by motor also increases from 8-10A approximately that can be observed from the outputs. But in some areas distortions raise to 10-12 A. As Torque Increases Speed Decreases from free running 1430 rpm to 1400pm. Average Torque nearly equates reference and eliminates usage of SVM. Computation time for prediction is 25us.

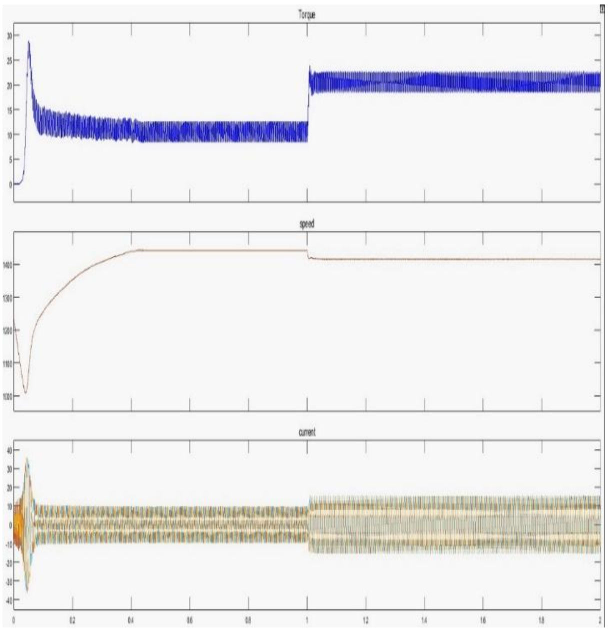

Fig. 10. MPCC Simulink Result

VIII. CONCLUSIONS

MPC is an emerging control structure pioneering in all fields especially in Drives and Automated Vehicles. Due to its versatility in structure it is easy to understand. As System on Chip technology available it is easy to implement with less cost than FOC. As in the case of MPCC, current prediction equation helps to minimize the SVM necessity for inverter switching and reduces complexity. Its flexibility and easy understanding implies the researchers to develop different Model Predictive control Algorithms like Torque and flux Controls.

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