A study of sensorless speed estimation and model predictive control of an induction motor

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Abstract - **The study is focused on predictive control algorithm Model, induction motor (IM) modeling, sensorless speed techniques for speed estimation. In this report, torque and flux are controlled using a model predictive control algorithm for an induction motor with speed estimation by sensorless speed technique. Mathematical modeling of asynchronous motor is done using only two state variables, the stator current and rotor flux, ψr and the electromagnetic torque obtained as a function of these two state variables. The rate of direct synthesis is estimated from the equations of state. The dynamic state equations ds – qs of the machine are modified to estimate the velocity signal. Synthesis is highly sensitive to machine parameters. A fault observer is also implemented to obtain a better torque reference.**
Keyword: Model predictive control, induction motor, sensorless control.

I. INTRODUCTION

The induction motor is widely used in industry because of its reliability and low cost. However, because the dynamic model of the induction motor is strongly nonlinear, the control of the induction motor is a challenging problem and attracts much attention. Many schemes have been proposed for the control of induction motor drives, among them field-oriented control. Traditionally, a PI controller is used to achieve fast 4-quadrant operation, smooth starting and acceleration of an induction motor drive. The PI-controller has several advantages such as simple control structure, easy design and low cost. However, the PI-controller exhibits poor transient response against system parameter changes and load disturbances, especially during low-speed operation. Due to rapid improvements in power electronic devices and microelectronics, field-oriented control and feedback linearization techniques have enabled high-performance induction motor drive applications. However, the motor parameters must be precisely known and accurate flux information is required. In addition, performance will be reduced due to changes in engine parameters and unknown external disturbances.

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Model predictive control has been greatly developed in the past few years both within the research control community and in industry. Its composition integrates optimal control, stochastic control, and process control with dead time, multivariable control, and future references when available. The MPC controller can thus provide an optimal solution while respecting the given constraints. For an induction motor, the use of flux and speed sensors located inside the machine can degrade the robustness of the machine and increase the associated maintenance costs. For current and voltage measuring equipment, it is proposed that the speed of an induction motor can be determined without the need to install speed and flux sensors. Several rate estimation schemes have been proposed, among them the model reference adaptive system (MRAS) has relative simplicity and low computational complexity and provides good performance, several possible MRAS structures. In this paper, a full-order adaptive observer is used to observe the stator currents and rotor flux, and the error between the estimated stator current and the actual stator current is considered as the system error to estimate the rotor speed and stator resistance. A different adaptive PI relation is used to estimate the rotor speed and stator resistance, which is derived from the Lyapunov criterion and the stability of the estimation is also demonstrated by it. In this paper, the field speed control of an oriented IM drive is developed based on the MPC technique. The field orientation principle is used to decouple the motor speed from the rotor flux amplitude. The regulatory law was designed in such a way that the effect of changes in engine parameters was largely limited. Based on a simplified IM model, the MPC provides the necessary control signal while respecting the given torque and speed limits so that they are within the permissible values. This optimal solution is calculated based on the current system states, the actual velocity error, and the predicted future output of the model. In addition, to reduce the associated maintenance costs, the most common model reference adaptive structure of the MRAS system is used to estimate the rotor speed. A full-order adaptive observer based on the IM equation is used to estimate the stator currents and rotor flux. The Lyapunov stability criterion is used to estimate the rotor speed based on the error between the actual measured stator currents and the estimated currents. In addition, the same algorithm derived from the Lyapunov stability criterion is presented to estimate the stator resistance, which results in the speed estimation error, to improve the accuracy of the system. Another purpose of this paper is the synthesis of adaptive controllers of sensorless induction motor drive.

II. DYNAMIC MODEL OF AN INDUCTION MOTOR

The vectors of stator current is and rotor flux ψ_r are chosen as state variables. The stator current is chosen mainly because it is a variable that can be measured and also avoids unwanted stator dynamics such as effects on stator resistance, stator inductance and back emf. Thus, the equivalent dynamics equations of the stator and rotor of the cage induction machine are obtained as shown below.

Stator flux equation

$\psi_{qs} = L_s\, i_{qs} + L_m\, i_{qr}$ ………………….......…….. (2.1)
$\psi_{ds} = L_s\, i_{ds} + L_m\, i_{dr}2)$ ………………….......…….. (2.2)
In complex form it can be written as
$\psi_s = L_s\, i_s + L_m\, i_r$ ………………….......…….. (2.3)
Where as $\psi_s = \psi_{ds} + j\psi_{qs}$ ……...…. (2.4)
$i_s = i_{ds} + j i_{qs}$ ……………………………...……. (2.5)
$i_r = i_{dr} + j i_{qr}$ ……………….…………….……….. (2.6)
Rotor flux equation
$\psi_{qr} = L_r\, i_{qr} + L_m\, i_{qs}$ ………………........……. (2.7)
$\psi_{dr} = L_r\, i_{dr} + L_m\, i_{ds}$………………………………..……………… (2.8)
In complex form it can be written as
$\psi_r = L_r\, i_r + L_m\, i_s$ ……………………….….…….. (2.9)
Where as $\psi_r = \psi_{dr} + j\psi_{qr}$ ………………….………… (2.10)
$i_r = \frac{\psi_r}{L_r} - \frac{L_m}{L_r}\, i_s$ ……………………………………….. (2.11)
$\psi_s = L_s\, i_s + \frac{L_m}{L_r}\psi_r - \frac{L_m{}^2}{L_r}\, i_s$ ……..…………………..…. (2.12)
Stator voltage equations in stationary reference frame can be written as
$V_{ds} = R_s\, i_{ds} + \frac{d\psi_{ds}}{dt}$ ……………………………….. (2.13)
$V_{qs} = R_s\, i_{qs} + \frac{d\psi_{qs}}{dt}$ ……………………………..... (2.14)
In complex form it can be written as
$V_s = R_s\, i_s + \frac{d\psi_s}{dt}$ ……………………………….………. (2.15)
$V_s = R_s\, i_s + \frac{d}{dt}[L_s\, i_s + \frac{L_m}{L_r}\psi_r - \frac{L_m{}^2}{L_r}\, i_s\,]$....…………. (2.16)
$V_s = R_s\, i_s + L_s\frac{di_s}{dt} + \frac{L_m}{L_r}\frac{d\psi_r}{dt} - \frac{L_m{}^2}{L_r}\frac{di_s}{dt}]$ … ………….. (2.17)
$V_s = R_s\, i_s + [L_s - \frac{L_m{}^2}{L_r}]\frac{di_s}{dt} + \frac{L_m}{L_r}\frac{d\psi_r}{dt}$ ……..……… (2.18)
$L_s\left[1 - \frac{L_m{}^2}{L_s\, L_r}\right]\frac{di_s}{dt} + R_s\, i_s = V_s - \frac{L_m}{L_r}\frac{d\psi_r}{dt}$ …..……….. (2.19)
Rotor voltage equations can be written
$0 = R_r\, i_{qr} + \frac{d\psi_{qr}}{dt} - \omega_r\, \psi_{dr}$ …………………….…. (2.20)
$0 = R_r\, i_{dr} + \frac{d\psi_{dr}}{dt} + \omega_r\, \psi_{qr}$ ………………..… (2.21)
In complex form it can be written as
$R_r\, i_r + \frac{d\psi_r}{dt} - j\,\omega_r\,\psi_r = 0$ ………………..…… (2.22)

$R_r\,[\frac{\psi_r}{L_r} - \frac{L_m}{L_r}\, i_s] + \frac{d\psi_r}{dt} - j\,\omega_r\,\psi_r = 0$ ……………... (2.23)
$\frac{d\psi_r}{dt} = -\frac{R_r}{L_r}\psi_r + \frac{R_r L_m}{L_r}\, i_s + j\,\omega_r\,\psi_r$ ……………….. (2.24)
$\frac{d\psi r}{dt} = \frac{R_r L_m}{L_r}\, i_s - [\frac{R_r}{L_r} - j\,\omega_r\,]\psi_r$ ………………...…. (21.25)
$\frac{d\psi r}{dt} = \frac{1}{t_r}L_m\, i_s - \frac{1}{t_r}\psi_r + j\,\omega_r\,\psi_r$ ………………… (2.26)
$t_r\frac{d\psi r}{dt} = L_m\, i_s - \psi_r + j\,T_r\,\omega_r\,\psi_r$……………..………..….. (2.27)
Where $t_r = \frac{L_r}{R_r}$ ………………….. (2.28)
Substitute equation (2.27) in (2.20)
$L_s\left[1 - \frac{L_m{}^2}{L_s\, L_r}\right]\frac{di_s}{dt} + R_s\, i_s = V_s - \frac{L_m}{L_r}\left[\frac{R_r\, L_m}{L_r}i_s - (\frac{R_r}{L_r} - j\,\omega_r\,)\psi_r\,\right]$ ………………………. (2.29)
$L_s\,\sigma\frac{dis}{dt} + R_s\, i_s = V_s - \frac{R_r\, L_m{}^2}{L_r{}^2}\, i_s + \frac{L_m}{L_r}(\frac{1}{t_r} - j\,\omega_r\,)\psi_r$ ……..…………………………. (2.30)
Where $\sigma = \left[1 - \frac{L_m{}^2}{L_s\, L_r}\right]$ ……………………………….. (2.31)
$\sigma\, L_s\,\frac{di_s}{dt} + R_s\, i_s = V_s - R_r k_r{}^2\, i_s + k_r{}^2(\frac{1}{t_r} - j\,\omega_r\,)\psi_r$ ……..……………………….. (2.32)
Where $k_r = \frac{L_m}{L_r}$ ……………………………….. (2.33)
$\sigma\, L_s\,\frac{di_s}{dt} + (R_s + R_r k_r{}^2)i_s = V_s + k_r(\frac{1}{t_r} - j\,\omega_r\,)\psi_r$…………………………………. (2.34)
$\sigma\, L_s\,\frac{di_s}{dt} + R_\sigma i_s = V_s + k_r(\frac{1}{t_r} - j\,\omega_r\,)\psi_r$ …………… (2.35)
Where R_σ = (R_s + R_r 〖k_r〗 ^2)……………………………………………… (2.36)
$\frac{\sigma\, L_s}{R_\sigma}\,\frac{di_s}{dt} + \, i_s = \frac{V_s}{R_\sigma} + \frac{k_r}{R_\sigma}\,(\frac{1}{t_r} - j\,\omega_r\,)\psi_r$ ……………… (2.37)

$t_\sigma \frac{di_s}{dt} + i_s = \frac{V_s}{R_\sigma} + \frac{k_r}{R_\sigma} (\frac{1}{t_r} - j\ \omega_r)\psi_r$ ………………….... (2.38)
Where,$t\_\sigma = (\sigma\ L\_s)/R\_\sigma$ ……………………………………………… (2.39)
General formula for torque developed is given as below for induction motor
$T_e = \frac{3}{2}\frac{P}{2}(\psi_{ds}\ i_{qs} - \psi_{qs}\ i_{ds})$ ………………………. (2.40)

$\psi_{qs} = L_s\ i_{qs} + L_m\ (\frac{\psi_{qr}}{L_r} - \frac{L_m}{L_r}\ i_{qs})$ ……………… (2.41)
$\psi_{ds} = L_s\ i_{ds}\ + L_m\ (\frac{\psi_{dr}}{L_r} - \frac{L_m}{L_r}\ i_{ds}\ )$ ………………….. (2.42)
$\psi_{qs} = \frac{L_m}{L_r}\psi_{qr} + (L_s - \frac{Lm^2}{L_r})i_{qs}$ ……………….…. (2.43)
$\psi_{ds} = \frac{L_m}{L_r}\psi_{dr} + (L_s - \frac{Lm^2}{L_r})i_{ds}$ ………….…………. (2.44)

$T_e = \frac{3}{2}\frac{P}{2}\left[\left(\frac{L_m}{L_r}\psi_{dr} + \left(L_s - \frac{Lm^2}{L_r}\right)i_{ds}\right)\ i_{qs} - \left(\frac{L_m}{Lr}\psi_{qr} + \left(L_s - \frac{Lm^2}{L_r}\right)i_{qs}\right)i_{ds}\right]$…………. (2.45)
$T_e = \frac{3}{2}\frac{P}{2}[\frac{L_m}{L_r}\psi_{dr}\ i_{qs} + (L_s - \frac{Lm^2}{L_r})i_{ds}i_{qs} - \frac{L_m}{Lr}\psi_{qr}\ i_{ds} - \left(L_s - \frac{Lm^2}{L_r}\right)i_{qs}\ i_{ds}]$ ……….. (2.46)
$T_e = \frac{3}{2}\frac{P}{2}[\frac{L_m}{L_r}\psi_{dr}\ i_{qs} - \frac{L_m}{Lr}\psi_{qr}\ i_{ds}]$ ……………………………………………….. (2.47)
$T_e = \frac{3}{2}\frac{P}{2}\ \frac{L_m}{L_r}(\psi_{dr}i_{qs} - \psi_{qr}\ i_{ds})$ ……………………………………………………. (2.48)
It can be writing the developed Torque equation in complex form as dot product of $\overline{\psi_r}$ and i_s
$i_s = i_{ds} + ji_{qs}$ …………………………………... (2.49)
$\psi_r = \psi_{dr} + j\psi_{qr}$ …………………………….……... (2.50)
Complex conjugate of ψ_r is $\overline{\psi_r} = \psi_{dr} - j\psi_{qr}$ ……………………………………… (2.51)
Take dot product of
$\overline{\psi_r}\ .\ i_s = (\psi_{dr} - j\psi_{qr})\ .\ (i_{ds} + ji_{qs})$……………………………………………… (2.52)
$\overline{\psi_r}\ .\ i_s = \psi_{dr}\ i_{ds} - j\psi_{qr}\ i_{ds}\ + j\ \psi_{dr}\ i_{qs} - j\ .\ j\ \psi_{qr}\ i_{qs}$ ……………………………… (2.53)
$\overline{\psi_r}\ .\ i_s = \psi_{dr}\ i_{ds} - j\psi_{qr}\ i_{ds}\ + j\ \psi_{dr}\ i_{qs}\ +\ \psi_{qr}\ i_{qs}$ ………………………………..…. (2.54)
$\overline{\psi r}\ .\ is = (\psi_{dr}\ i_{ds}\ +\ \psi_{qr}\ i_{qs}\ ) + j\ (\psi_{dr}\ i_{qs}\ - \psi_{qr}\ i_{ds})$ …………………………….. (2.55)
$(\overline{\psi_r}\ .\ i_s) = \psi_{dr}i_{qs} - \psi_{qr}\ i_{ds}$ ……………………… (2.56)
$T_e = \frac{3}{2}\frac{P}{2}\ \frac{L_m}{L_r}\mathrm{Imag}\ (\overline{\psi_r}\ .\ i_s)$ ……………………….……. (2.57)
Equations (2.26), (2.39) and (2.58) are used for modeling of induction motor. These equations will be used for estimating the stator and rotor flux, and for calculating predictions for the stator currents, stator flux, and electrical torque using the appropriate discrete-time version of the equations.
For an induction machine, it can be established that both the stator flux $\psi_s$and the electromagnetic torque $T_e$can be modified by choosing the correct voltage vector sequence that modifies the magnitude of the stator flux while simultaneously increasing or decreasing the angle between the rotor and stator flux. In this scheme, predictions for future values of stator flux and torque are calculated. Thus, the reference condition that is implemented by the cost function takes into account the future behavior of these variables. Predictions are calculated for each control option and the cost function selects a voltage vector that optimizes reference tracking.

III. SENSOR-LESS SPEED ESTIMATION

The rate of direct synthesis can be estimated from the equations of state. The $d^s - q^s$frame machine dynamic state equations are modified to estimate the velocity signal. Synthesis is highly sensitive to machine parameters. The rotor circuit equation of the $d^s - q^s$equivalent circuit can be given as
$\frac{d}{dt}\ (\psi_{dr}) + R_r i_{dr} +\ \omega_r\ \psi_{qr} = 0$ ………………………………………..... (3.1)
$\frac{d}{dt}\ (\psi_{qr}) + R_r i_{qr} -\ \omega_r\ \psi_{dr} = 0$ ……………………………………..…... (3.2)
Adding terms $\left(\frac{R_r\ L_m}{L_r}\right)\ i_{ds}$ and $\left(\frac{R_r\ L_m}{L_r}\right)\ i_{qs}$ respectively on both sides of above equation, it gives
$\frac{d}{dt}\ (\psi_{dr}) + \frac{R_r}{L_r}\ (L_m i_{ds} + L_r i_{dr}) + \omega_r\ \psi_{qr} = \frac{L_m\ R_r}{L_r}\ \ i_{ds}$ ……………………... (3.3)
$\frac{d}{dt}\ (\psi_{qr}) + \frac{R_r}{L_r}\ (L_m i_{qs} + L_r i_{qr}) - \omega_r\ \psi_{dr} = \frac{L_m\ R_r}{L_r}\ \ i_{qs}$ …………………….... (3.4)
$\psi_{qr}\frac{d}{dt}\ (\psi_{dr}) + \psi_{qr}\frac{R_r}{L_r}\ (L_m i_{ds} + L_r i_{dr}) + \omega_r\psi_{qr}\ \psi_{qr} - \frac{L_m\ R_r}{L_r}\ \ i_{ds}\ \psi_{qr} = 0$ ..... (3.5)

$\psi_{dr}\frac{d}{dt}\ (\psi_{qr}) + \psi_{dr}\frac{R_r}{L_r}\ (L_m i_{qs} + L_r i_{qr}) - \omega_r\ \psi_{dr}\psi_{dr} - \frac{L_m\ R_r}{L_r}\ \ i_{qs}\ \psi_{dr} = 0$…….. (3.6)

It can be simply as

$$\psi_{qr}\dot{\psi_{dr}} + \psi_{qr}\frac{R_r}{L_r}\left(L_m i_{ds} + L_r i_{dr}\right) + \omega_r \psi_{qr}^2 - \frac{L_m R_r}{L_r}\ i_{ds}\,\psi_{qr} = 0$$

.... (3.7)

$$\psi_{dr}\dot{\psi_{qr}} + \psi_{dr}\frac{R_r}{L_r}\left(L_m i_{qs} + L_r i_{qr}\right) - \omega_r\,\psi_{dr}^2 - \frac{L_m R_r}{L_r}\ i_{qs}\,\psi_{dr} = 0$$

……….…. (3.8)

$$\psi_{dr}\dot{\psi_{qr}} - \psi_{qr}\dot{\psi_{dr}} + \psi_{dr}\frac{R_r}{L_r}\left(L_m i_{qs} + L_r i_{qr}\right) - \psi_{qr}\frac{R_r}{L_r}\left(L_m i_{ds} + L_r i_{dr}\right) - \omega_r\,\psi_{dr}^2 + \omega_r\,\psi_{dr}^2 - \frac{L_m R_r}{L_r}\ i_{qs}\,\psi_{dr} + \frac{L_m R_r}{L_r}\ i_{ds}\,\psi_{qr} = 0$$

.... (3.9)

$$\left(\psi_{dr}\dot{\psi_{qr}} - \psi_{qr}\dot{\psi_{dr}}\right) + \psi_{dr}\frac{1}{t_r}\left(L_m i_{qs} + L_r i_{qr}\right) - \psi_{qr}\frac{1}{t_r}\left(L_m i_{ds} + L_r i_{dr}\right) - \omega_r\left(\psi_{dr}^2 + \psi_{dr}^2\right) - \frac{L_m}{t_r}\left(i_{qs}\,\psi_{dr} - i_{ds}\,\psi_{qr}\right) = 0$$

.... (3.10)

$$\left(\psi_{dr}\dot{\psi_{qr}} - \psi_{qr}\dot{\psi_{dr}}\right) + \psi_{dr}\frac{1}{t_r}\left(\psi_{qr}\right) - \psi_{qr}\frac{1}{t_r}\left(\psi_{dr}\right) - \omega_r\left(\psi_{dr}^2 + \psi_{dr}^2\right) - \frac{L_m}{t_r}\left(i_{qs}\,\psi_{dr} - i_{ds}\,\psi_{qr}\right) = 0$$

.... (3.11)

Whereas Rotor flux linkages $L_m i_{qs} + L_r i_{qr} = \psi_{qr}$ and $L_m i_{ds} + L_r i_{dr} = \psi_{dr}$

$$\left(\psi_{dr}\dot{\psi_{qr}} - \psi_{qr}\dot{\psi_{dr}}\right) - \omega_r\left(\hat{\psi}_r^2\right) - \frac{L_m}{t_r}\left(i_{qs}\,\psi_{dr} - i_{ds}\,\psi_{qr}\right) = 0$$

…………….. (3.12)

Whereas

$$\hat{\psi}_r^2 = \psi_{dr}^2 + \psi_{dr}^2)$$

$$\omega_r = \left[\left(\psi_{dr}\dot{\psi_{qr}} - \psi_{qr}\dot{\psi_{dr}}\right) - \frac{L_m}{t_r}\left(i_{qs}\,\psi_{dr} - i_{ds}\,\psi_{qr}\right)\right] / \,\hat{\psi}_r^2$$

……………….. (3.13)

IV. MODEL PREDECTIVE CONTROLLER

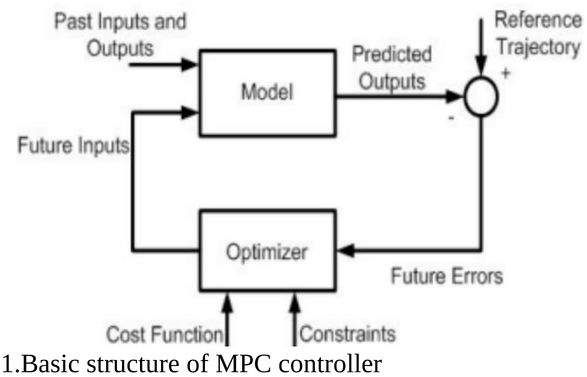

Fig.1.Basic structure of MPC controller

The Predictive Control model is widely accepted in industry as an effective means of solving large multivariable constrained control problems. The MPC algorithm mainly depends on

a) Internal dynamic process model.
b) History of past control movements a
c) Optimization cost function in the prediction horizon.

The main idea of MPC is to choose a control action by iteratively solving an optimal control problem online. This aims to minimize a performance criterion in the future horizon, possibly subject to the constraints of manipulated inputs and outputs, where the future behaviour is calculated according to the plant model. Problems arise with guaranteeing closed-loop stability, handling model uncertainty, and reducing on-line calculations. The interest of this control technique is obvious when the trajectory that the system is to follow is known in advance, such as in a robot, chemical process, or machine tools where prediction occurs. A simple block diagram characterizing the basic structure of the MPC controller is shown in Fig. 1. In this figure, the model is used to predict the future performance of the power plant based on past and present values and on the basis of proposed optimal future control actions. These actions are calculated by the optimizer taking into account a cost function (where future tracking error is considered) as well as constraints. It should be noted that the predicted output from the system model and the actual error are used to obtain the control signal. The general object is to tighten the future output error to zero, with minimum input effort. The cost function to be minimized is generally a weighted sum of square predicted errors and square future control values, e.g. in Generalized Predictive Control (GPC) [5]:

$$J(N_1, N_2, N_u) = \sum_{j=N_1}^{N_2} \beta(j)\left[\hat{y}(k+j\,|\,k) - w(k+j)\right]^2 +$$

$$+\sum_{j=1}^{N_u} \lambda(j)\left[u(k+j-1)\right]^2$$

Where J is the cost function and it is concerned by how to minimize the error signal; 1 2 N N, are the lower and upper prediction horizons over the output; Nu is the control horizon.
β ( )j and λ( )j are weighting factors; yˆ is the predicted output; w represents the reference trajectory over the future horizon N (indicates how many iterations will be done) ; u is the control signal; j is predictive horizons (iteration counter or indicator); k is the sampling instant and j k| indicates at moment k, i will make iteration j.

V. PROPOSED MODEL PREDEVTIVE CONTROLLER

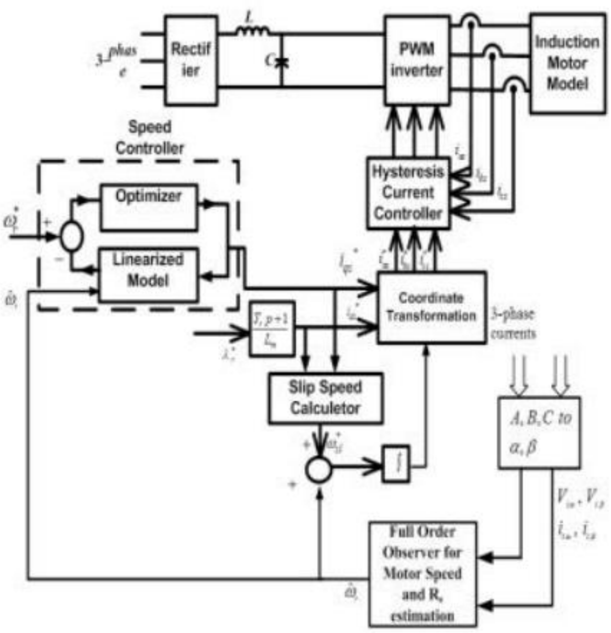

Fig.2. The proposed control scheme based on MPC

The block diagram of the sensorless IM drive system including the proposed MPC controller is shown in Fig. 2. The measured speed is used for closed loop control and compared with the reference speed. The measured and reference speeds are fed to the model predictive controller in order to obtain the torque current command i*qs .Using indirect field oriented technique, the transfer function of the motor can be deduced as:

$$\text{Transfer function} = \frac{\omega_r}{T_e - T_L} = \frac{1}{J_m\, s + f_d}$$

For easy implementation, the simplified linearized model of the IM described by equation is employed in the structure of the MPC controller .

VI. MATLAB SIMULATION AND RESULT

Squirrel Cage Induction Motor Parameters

$t_s = 2e^{-6};$
$t_{mpc} = 40e^{-6};\ \ \% 25kHz$
$t_{speed} = 100e^{-6};\ \ \% 10kHz$
$L_m = 172e^{-3};$
$L_s = 178e^{-3};$
$L_r = 178e^{-3};$
$R_s = 1.405;$
$R_r = 1.395;$
$P = 2;\ \%pole\ pairs$

$P_n = 4\ kW$;
$V_L = 400v$;
$f_s = 50Hz$
$N_r = 1430\ rpm$
$T_L = 25Nm$
$J = 0.0131\ Kg\ m^2$

Model predictive control block

For Voltage source inverter V_{dc} is selected depending on requirement of V_{rmsL} value that is 400 V. As it is two level inverter hence required V_{dc} should be selected 650 V.

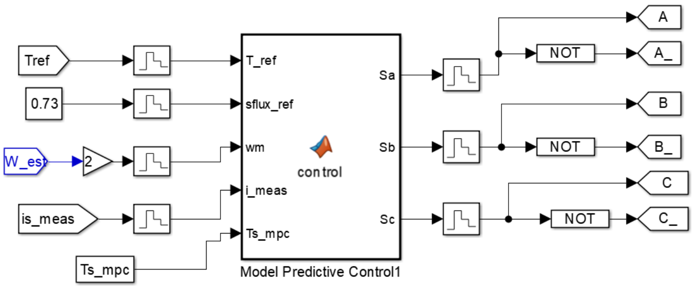

Fig.3. Model predictive control algorithm block

For this simulation the PI value is kept as K_p=0.6 and K_i=5. Weighting factors are selected as $\boldsymbol{\lambda_1 = 0.3\ and\ \lambda_2 = 35}$. Reference stator flux peak value is taken as 0.73Wb, as Stator flux is proportional to voltage and frequency we can calculate reference stator flux value as

$$\psi_s = \frac{Vs}{\omega_e}$$

……………………………………………………………… (1)

$\psi_s = \frac{Vs}{2\pi fs}$ ………………………………………...……………..… (2)

$V_s = Phase\ peak\ volatge\ value = \sqrt{2}\,V_{\mathrm{rms_{ph}}} = \frac{\sqrt{2}}{\sqrt{3}}\,V_{\mathrm{rms_L}}$

$V_{\mathrm{rms_L}}\ value\ is\ known$

Suppose here in this case $V_{\mathrm{rms_L}} = 400\ V$ and f_s = 50 Hz ,for this values ψ_s can be calculated

$$\psi_s = \frac{\frac{\sqrt{2}}{\sqrt{3}}\ 400}{2\pi 50}$$

= 1.03Wb.……………………………………………………………….… (3)

Peak vlaue of $\psi_s = \sqrt{2}\,\psi_s$ =0.73 Wb. …………………………………………….…. (4)

Hence this stator flux value is taken as refernce vlaue for model predictive control algorithm.

Reference Speed is step changes from 157 rad/sec to 188 rad/sec, correspondingly the speed from induction motor model follow this reference speed.

$N = \frac{120f}{p}$ here p is number of poles as IM taken is 4 pole machines.

$$N = (120\ X\ 50)/4 = 1500\ \text{rpm}$$

………………………………………………... (5)

$\omega_r = \frac{2\pi N}{60} = \frac{2\pi\ 1500}{60} = 157\ \text{rad/sec}$ …………………………………..… (6)

$\omega_r = \frac{4\pi f}{p} = \frac{4\pi\ 50}{4} = 157\ \text{rad/sec}$ ……………………………………..… (7)

$$\omega\_e = p/2\ \ \omega\_r$$

……………………………………………………. (8)

In torque response some ripples are present hence in current too. Load $T_L = 10Nm$ is provided. Sampling time $t_s = 2e^{-6}\ sec$, Model predictive sampling time is $t_{mpc} = 40e^{-6}$ sec (25 kHz) (switching frequency) and outer loop

VII. SIMULATION RESULT

Case 1: Constant speed and constant torque

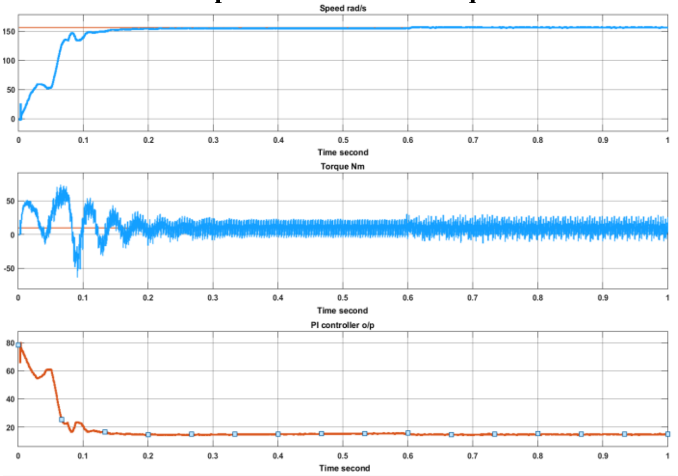

Fig (a) Constant speed and constant torque

The dynamic response of the induction motor is observed at a torque of 10 Nm which is kept constant and the reference speed at a frequency of 50 Hz means 157 rad/s. It is observed that the speed estimation is achieved quickly in 0.1 seconds and has reached the set speed reference value. Here the sample time is $t_s = 2e^{-6}\ sec$, the predictive sample time of the model is $t_{mpc} = 40e^{-6}$ sec (25 kHz) (switching frequency) and the outer loop is $t_{speed} = 100e^{-6}\ sec$.

Case 2: Step speed and constant torque

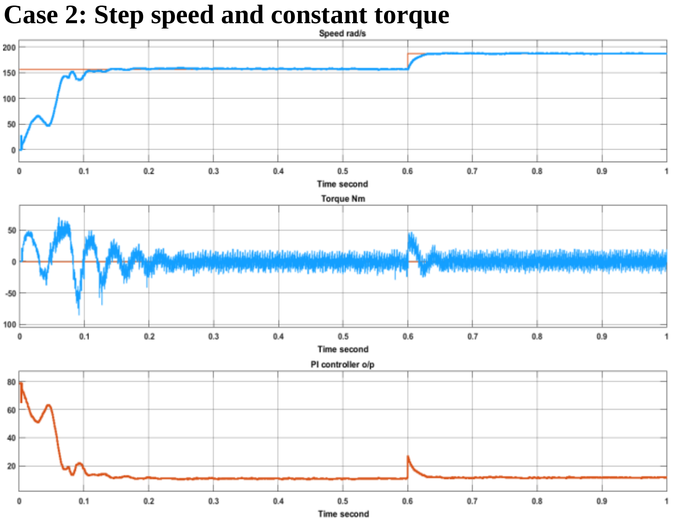

Fig (b) Step speed 157 rad/s to 188rad/sec and constant torque

In this case the Induction motor dynamic response is observed at torque 5 Nm keeping constant and step speed reference at 50 Hz frequency means 157 rad/sec to 60 Hz frequency means 188 rad/sec. It is Observed that speed estimation is good at low torque condition, and it achieved set reference value of speed at 0.1 second. Here the Sampling time $t_s = 2e^{-6}\ sec$, Model predictive sampling time is $t_{mpc} = 40e^{-6}$ sec (25 kHz) (switching frequency) and outer loop $t_{speed} = 100e^{-6}\ sec$.

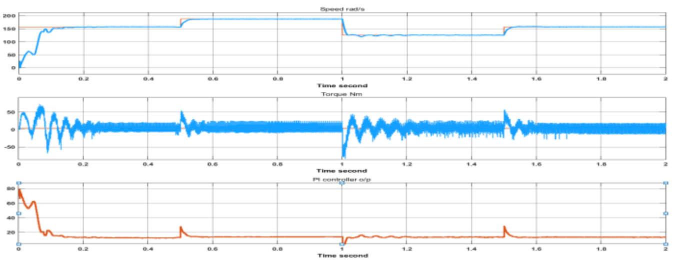

Fig (c) Step speed 157 rad/s to 188 rad/sec then 125.6 rad/s and again 157 rad/s and constant torque

In this case the Induction motor dynamic response is observed at torque 5 Nm keeping constant and step speed reference at 50 Hz frequency means 157 rad/sec to 60 Hz frequency means 188 rad/sec. It is Observed that speed estimation is good at low torque condition, and it achieved set reference value of speed at 0.1 second. Here the Sampling time $t_s = 2e^{-6}\ sec$, Model predictive sampling time is $t_{mpc} = 40e^{-6}$ sec (25 kHz) (switching frequency) and outer loop $t_{speed} = 100e^{-6}\ sec$.

Case 3: Constant speed and step torque

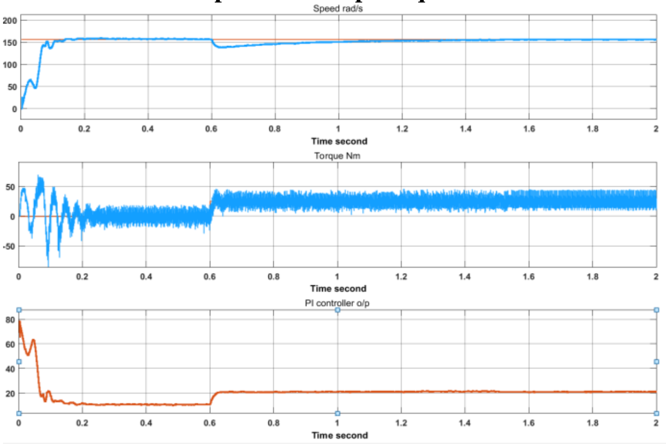

Fig (d) Constant speed and step torque

In this case the Induction motor dynamic response is observed at step change in torque from 0 Nm to 25 Nm and constant speed at 50 Hz frequency means 157 rad/sec It is Observed that speed estimation is at change point in down and it takes time to reach reference set value. and it requires 0.4 second more to reach set point of speed. Here the Sampling time

$t_s = 2e^{-6}\ sec,$

Model predictive sampling time is

$t_{mpc} = 40e^{-6}$ sec (25 kHz) (switching frequency) and outer loop

$t_{speed} = 100e^{-6}\ sec.$

VIII. SUMMARY

It has been shown that the model predictive control strategy is effective for achieving good dynamic response of the induction motor by implementing the MPC algorithm. The MPC method is simple and the control algorithm is simple. The MPC strategy avoids the use of linear and non-linear controllers. Additionally, it is not necessary to include any type of modulator. The drive signals for the IGBTs are generated directly by the control. MPC has been successfully implemented in MATLAB for sensorless speed control induction motor with direct synthesis speed estimation technique.

IX. FUTURE SCOPE

MPC can be implemented for de-excitation with DTC for induction motor, also induction motor vector control with MPC based de-excitation capability. A comparison study can be done to implement MPC for DTC, field weakening or with some new control technique. For EV/HEV induction motor applications, it is necessary to develop an improved version of the MPC algorithm for smooth and ripple-free speed control. Model predictive control of power converters and electric drives is fundamental work in modern practice that has the potential to advance the performance of future power processing and control systems.

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