Dynamic Models for Induction Motor Drives for Heavy Duty Regimes

Dragan Vidanovski[1]and Slobodan Mirčevski[2]

Abstract – **In this paper the different strategies for induction motor regulation are presented. At the beginning of the paper we will show the methods for speed control for Induction Motor (IM). The methods have advantages and drawbacks in use for certain Duty cycle, for example calculation speed, speed need for response, cost depending from the purpose of motor drive. Electric motor drives according international standard IEC 60034-1are divided in ten Duty types, from S1 to S10. This paper has purpose to make analysis for the S8, S9 and S10 duty types, which are with change of speed. The goal of this paper is to make proposition which method for speed control was adequate for certain Duty type cycle.**

Keywords – **scalar, vector control, Direct Torque control, Duty cycles S8, S9 and S10**

I. INTRODUCTION

In this paper we have made analysis of various methods for speed control and we want to show which of them is best for use for certain duty type. From the literature we know basically these methods for speed control: scalar (U/f=const.), vector, direct torque (DTC) and adaptive. We'll make an analysis for speed of feedback, the correct (exact) feedback signal and techno economical reasons for applying certain type of regulation for S8, S9 and S10 duty type drives with IM.

II. CONTROL STRATEGIES FOR SPEED REGULATIONS OF IM

For control of IM drives are used several main control strategies, i.e. scalar, vector, DTC and adaptive control. Every one of them has its own characteristics, advantages and drawbacks.

A. *Scalar control*

For scalar control the main condition is to have U/f=const. i.e. stator flux to remain constant in region of speed changes. It is shown in figure 1.

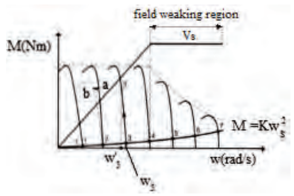


Fig.1. Torque-speed curves showing effect of frequency variations, load torque, and supply voltage change

From figure 1 for given speed w_3 at speed characteristic number 3, when load torque has a value of TL' <TL the speed is $w_3^{'}$<w_3 lower than nominal speed at given frequency. When we have voltage drop from the network than we have change in the torque-speed characteristic from a to b and change in the speed of the IM. In speed dynamics with acceleration/deceleration it is possible the IM to become unstable.

This method has advantages and drawbacks. Main advantage is the fact that there is no need of feedback, it works in wide range of frequencies and amplitudes till nominal speed, and there is a possibility for work in multi motor mode drive. This method depends from the following parameters i.e. voltage drop of the stator resistance, change of stator and rotor resistance, change of the input voltage of the inverter, works in two quadrants, producing draft in the speed while changing the value of the torque, flux, input voltage. This method has bad stability characteristic and slow response when we have dynamic mode of work.

B. *Vector control*

There are multiple sub strategies for vector or field-oriented control, i.e. direct, indirect, vector control (VC) of line-side PWM rectifier, stator flux-oriented VC, current feed VC, VC of cycloconverter drive, sensorless VC. Calculations of many parameters and their estimation are needed for accurate work of the IM drive. Voltage and current models of motors are used to calculate the flux vector and other parameters.
The stator equations in the q d reference system tied to stator reference system for the IM are the following [3]:

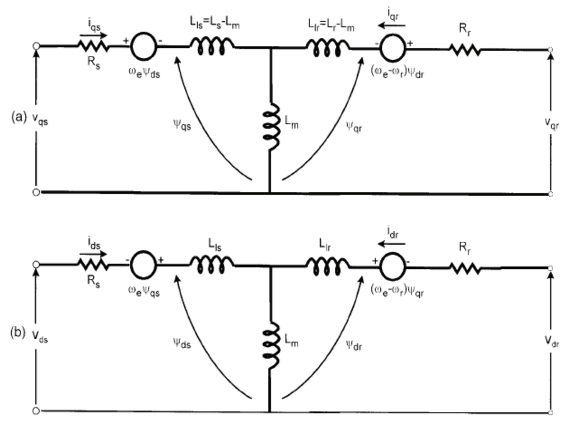


Fig.2. T equivalent scheme of IM in q d reference system tied to synchronous speed of the engine for dynamic mode

$$v_{qs} = r_s i_{qs} + \frac{d\Psi_{qs}}{dt} \quad (1)$$

[1] ELEM subsidiary REK Bitola, Bitola, Republic of Macedonia, e-mail: vidan.d@gmail.com
[2] Faculty of Electrical Engineering and Information Technologies, Skopje, Republic of Macedonia, e-mail: mirceslo@feit.ukim.edu.mk

$$v_{ds} = r_s i_{ds} + \frac{d\Psi_{ds}}{dt} \tag{2}$$

If the equations are tied to the synchronous speed of IM, then we obtain the following equations:

$$v_{qs} = r_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_e \Psi_{ds} \tag{3}$$

$$v_{ds} = r_s i_{ds} + \frac{d\Psi_{ds}}{dt} - \omega_e \Psi_{qr} \tag{4}$$

The equations (3) and (4) show that fluxes on q and d axis induce electromotive force (EMF) which is shifted for $\pi/2$ of Ψ_{ds} and Ψ_{qs} respectively. If the rotor is not moving (spins), i.e. $\omega_r = 0$, then the equations for the rotor are:

$$v_{qr} = r_r^{'} i_{qr} + \frac{d\Psi_{qr}}{dt} + \omega_e \Psi_{dr} \tag{5}$$

$$v_{dr} = r_r^{'} i_{dr} + \frac{d\Psi_{dr}}{dt} - \omega_e \Psi_{qr} \tag{6}$$

If the machine rotates, then:

$$v_{qr} = r_r^{'} i_{qr} + \frac{d\Psi_{qr}}{dt} + (\omega_e - \omega_r)\Psi_{dr} \tag{7}$$

$$v_{dr} = r_r^{'} i_{dr} + \frac{d\Psi_{dr}}{dt} + (\omega_e - \omega_r)\Psi_{qr} \tag{8}$$

The main advantage of q d dynamic model is that sinusoidal variables in stationary reference system appear as DC magnitudes in the reference system tied to the synchronous speed of IM. Fluxes developed in the IM are the following:

$$\Psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) \tag{9}$$

$$\Psi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) \tag{10}$$

$$\Psi_{qm} = L_m (i_{qs} + i_{qr}) \tag{11}$$

$$\Psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \tag{12}$$

$$\Psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \tag{13}$$

$$\Psi_{dm} = L_m (i_{ds} + i_{dr}) \tag{14}$$

where leakage inductivity of the stator and rotor coil is $L_{ls} = L_s - L_m$, $L_{lr} = L_r - L_m$. By adjusting the equations we obtain the following:

$$\Psi_{qr} = \frac{L_r}{L_m}(\Psi_{qs} - \sigma L_s i_{qs}) \tag{15}$$

$$\Psi_{dr} = \frac{L_r}{L_m}(\Psi_{ds} - \sigma L_s i_{ds}) \tag{16}$$

where $\sigma = 1 - \frac{L^2{}_m}{L_s L_r}$ is called the leakage factor.

For the control of IM it is necessary to present rotor flux through stator flux and current, i.e. equations (15) and (16). By using Fig. 2, the presented voltage equations and derivation of equations (15) and (16) derived for Ψ_{qr} and Ψ_{dr} we'll obtain the system of equations presented in matrix form:

$$\begin{bmatrix} \frac{d\Psi_{qr}}{dt} \\ \frac{d\Psi_{dr}}{dt} \end{bmatrix} = \frac{L_r}{L_m}\left\{ \begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} - r_s \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} - \sigma \begin{bmatrix} \frac{di_{qs}}{dt} \\ \frac{di_{ds}}{dt} \end{bmatrix} \right\} \tag{17}$$

This system of equations is called *Voltage Model of IM*.

With appropriate changes of (17) we'll obtain the following equations in the matrix form:

$$\begin{bmatrix} \frac{d\Psi_{qr}}{dt} \\ \frac{d\Psi_{dr}}{dt} \end{bmatrix} = \begin{bmatrix} \omega_r & -\frac{1}{\tau_r} \\ -\frac{1}{\tau_r} & -\omega_r \end{bmatrix} \begin{bmatrix} \Psi_{qr} \\ \Psi_{dr} \end{bmatrix} + \frac{L_m}{\tau_r}\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} \tag{18}$$

where $\tau_r^{'} = L_r / r_r^{'}$ is rotor time constant. It is called *Current Model of IM.*

From the equations for voltage and current model of IM (17) and (18) respectively, it is clear that the change of rotor flux rotor is expressed by stator variables: voltage, power and speed that are measurable by appropriate methods and devices.

From the voltage equations (17) we see the dependence of the IM parameters, as stator resistance r_s and leakage inductances of the stator, rotor and mutual inductance L_{ls}, L_{lr}, L_m. The temperature increases have significant impact on the estimated values of the parameters. The change in the value of stator resistance is dominant. For low frequencies, or low speeds of IM, the voltage signals v_{qs}, v_{ds} are very small. When we make a model, errors may occur in the integration mode, because it can happen to integrate the offset (noise) that occurs in system motor - inverter.

In the current equations (18), the values of time constant τ_r and mutual inductance dominate. The influence of temperature on rotor resistance directly affects on the slip of IM and the q and d component of the rotor fluxes, which undermines the principle of decoupled, and therefore it is necessary to correct the control of IM. The change of temperature in the coils of the stator and rotor certainly depend on the type of the IM load.

It is obvious that both IM models have their advantages and weaknesses. For a good control system it is necessary to select and adapt such a model that will use the best features of (17) and (18). Including the fact that VC has internal feedback control, we can conclude that it has better stability than scalar control. Using the field weakening control, VC covers the small speed regions. With this type of control, power factor is increased, TDH becomes lower and IM drive works in all four quadrants.

Disadvantages of this control method are the complexity of the control (needed DSP), sensibility of motor parameters (especially for small speeds). Ideal decoupling control is not possible because of the change of parameters and the final response time of the switches in the PWM inverter.

C. Direct Torque Control

In this section we will present the Direct Torque Control strategy. It has many advantages. The most important are not having feedback current control, not additional PWM algorithm is applied, no vector transformation as in VC. In this control system tables with voltage vectors are used, and it can be seen in which quadrant the flux and the torque vector are placed. As a consequence of the previously stated the switches become active.

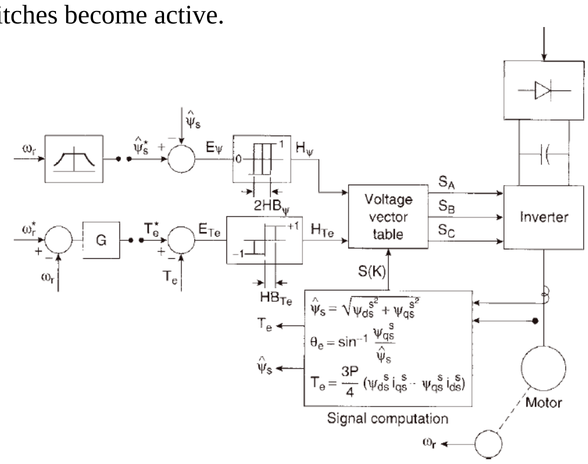


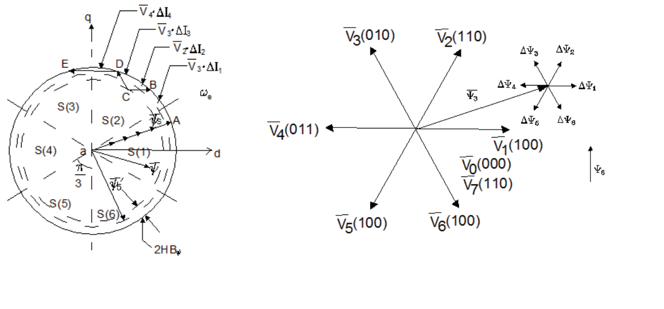
Fig.3. Direct torque control (DTC)

The speed control loop and the flux program as a function of speed are shown in figure 3. The command stator flux $\Psi*$, and torque $T*$, magnitudes are compared with the respective estimated values, and the errors are processed through hysteresis-band controllers, as shown. The flux loop controller has two levels of digital output according to the following relations:

$$H_\psi=1 \text{ for } E_\psi>+HB_\psi.$$

$$H_\psi =-1 \text{ for } E_\psi <-HB_\psi.$$

where $2HB_\psi$ is total hysteresis-band width of the flux controller. The circular trajectory of the command flux vector ψ_S* with the hysteresis band rotates in an anti-clockwise direction, as shown in figure 4:



a) б)

Fig.4. Trajectory of stator flux vector in DTC control (a), and voltage vectors (b) and corresponding stator flux variation in time

While working with this control type peaks are produced and distortion of the current, torque and flux, and it has limitations for small speeds (mainly of the change of the stator resistance). A modification has been made in the DTC with fuzzy logic and neuro-fuzzy control with internal loops with SVM (Scalar Voltage Modulation). Adding these methods we lose the simplicity and the time response of the DTC.

D. Adaptive control

Adaptive control techniques can be generally classified as Self-tuning control, MRAC (Model Referencing Adaptive Control), Sliding mode or variable structure control, Expert system control, Fuzzy control, Neural control.

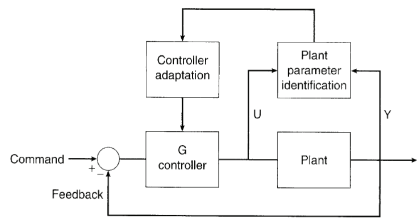


Fig.5. Block diagram of Self-tuning control

In this method, as the name indicates, the controller parameters are tuned on-line to adapt to the plant parameter variation. In the figure 5 is presented a self-tuning control.

In an MRAC, as the name indicates, the plant's response is forced to track the response of a reference model, irrespective of the plant's parameter variation and load disturbance effect. Such a system is defined as a robust system. The reference model may be fixed or adaptive and is stored in the DSP's memory.

The advantage of using the Fuzzy Logic controller is that the knowledge of the exact parameters of the motor is not necessary. Depending on which input parameters are known voltage vs. current, temperature vs. stator current or flux error vs. change in flux error, the estimation of rotor resistance is made from rule table. This model uses PI controller, limiter and filters presented in figure 6:

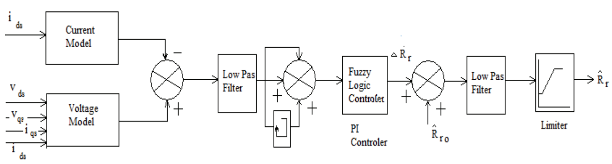


Fig.6. Fuzzy Logic controller

Indirect field oriented vector-controlled induction motor drives are widely used in industrial applications for high performance drive systems. Because indirect field orientation utilizes an inherent slip relation, it is essentially a feed forward scheme and hence naturally parameter sensitive, particularly to the rotor resistance. A mismatch between the actual rotor flux and the estimated rotor flux leads to error between the actual motor torque and the estimated torque and hence leads to poor dynamic performance.

The idea for using Artificial Neural Network ANN in estimation of rotor resistance is to use the learning algorithm for learning the dynamic behavior of induction motor. With using the voltage (17) and current (18) equations with NN model of IM we can calculate weights of NN and then calculate motor parameters.

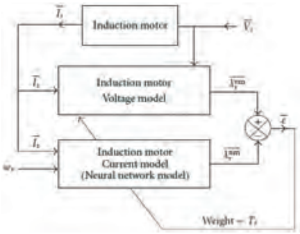


Fig.7. ANN approach for calculation of motor parameters

II. DUTY TYPES S8, S9 AND S10

The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international cooperation on all questions concerning standardization in the electrical and electronic fields.

A. Duty type S8 – Continuous-operation periodic duty with related load/speed changes

A sequence of identical duty cycles, each cycle consisting of a time of operation at constant load corresponding to a predetermined speed of rotation, followed by one or more times of operation at other constant loads corresponding to different speeds of rotation (carried out, for example, by means of a change in the number of poles in the case of induction motors). There is no time de-energized and at rest.

B. Duty type S9 – Duty with non-periodic load and speed variations

A duty in which generally load and speed vary non periodically within the permissible operating range. This duty includes frequently applied overloads that may greatly exceed the reference load.

C. Duty type S10 – Duty with discrete constant loads

A duty consisting of a specific number of discrete values of load (or equivalent loading) and if applicable, speed, each load/speed combination being maintained for sufficient time to allow the machine to reach thermal equilibrium. The minimum load within a duty cycle may have the value zero (no-load or de-energized and at rest).

III. PROPOSITION WHICH METHOD FOR SPEED CONTROL WAS ADEQUATE FOR CERTAIN DUTY TYPE CYCLE

For S8 duty type cycle our proposition is to use several types of speed controls:

- indirect VC,
- VC without feed forward from speed,
- no need for special dynamic request,
- no need for fast speed response,
- usage of resistor for stopping the IM drive is good solution,
- it’s possible to use thyristors and GTO.

For S9 duty type cycle our proposition is to use these types of speed controls:

- indirect VC,
- VC with feed forward from speed,
- need for fast dynamical request,
- need for fast speed response,
- usage of resistor for stopping the IM drive is good solution,
- using inverter for dynamic break and for energy feedback,
- usage of IGBT and FET is the good solution.

For S10 duty type cycle our proposition is to use these types of speed controls:

- Direct Torque Control DTC,
- VC with feed forward from speed,
- fast dynamical request is needed,
- fast speed response is needed,
- usage of IGBT and FET is the good solution.

IV. CONCLUSION

The main goal of this paper is to give a contribution in the process of decision making, which method in speed control is the most adequate for S8, S9 and S10 duty type cycles.

Conclusion from this paper is that scalar control is not adequate for these types of duty cycles, which are with changes of speed and torque. For S8 duty type cycles it is possible to have good speed regulation with small investment. The most expensive equipment is for S10 duty type drives, because of the needs of fast speed response and fast dynamical request. In present the price of energy converters is decreased and with the features they have like energy saving, avoiding damages in the work machine (IM, mechanical part) and so one, the investment is refunded for a short time.

In present market is existed many companies with wide range of different types of speed drive inverters. Appropriate choice is made by electrical engineers, who must have in mind the technical and economical aspect of projects they make.

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