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Adaptive Variable Structure Controller Application to Induction Motor Drive

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ABSTRACT
Variable structure control is an adaptive control that gives robust performance of a drive with parameter variation and load torque disturbance. Variable control structure is a robust control scheme based on the concept of changing the structure of the controller in response to the changing state of the system in order to obtain a desired response. The control is nonlinear and can be applied to the linear or nonlinear plant. A high speed switching control action is used to switch between different structures of the controller and the trajectory of the system is forced to move along a chosen switching manifold in the state space. The controller detects the deviation of the actual trajectory from the reference trajectory and corresponding changes the switching strategy to restore the tracking. Prominent characteristics such as invariance, robustness, order reduction, and control chattering are discussed in detail. Methods for coping with chattering are presented. Both linear and nonlinear systems are considered. By using Variable structure controller to control the step change in reference speed and drive system under load torque variations.
KEYWORDS- scalar control, vector control

I. INTRODUCTION:

Induction motor (IM) can be considered as the 'workhorse' of the industry because of its special features such as low cost, high reliability, low inertia, simplicity and ruggedness. Induction motors are suitable for industrial drives, because of their simple and robust structure, high torque to weight ratio, higher reliability and ability to operate in hazardous environments. However there control is a challenging task because the rotor quantities are not accessible which are responsible for torque production. DC machines are decoupled in terms of flux and torque. Hence control is easy. If it is possible in case of induction motor to control the amplitude and space angle (between rotating stator and rotor fields), in other words to supply power from a controlled source so that the flux producing and torque producing components of stator current can be controlled independently, the motor dynamics can be compared to that of DC motor with fast transient response. Variable structure control system where the structure or topology of the control is intentionally varied to stabilize the control and make its response robust.

II. Principle of Scalar control

As the name indicates is due to the magnitude variation of the control variables only and disregards the coupling effects in the machine.

The control of an induction motor requires a variable voltage variable frequency power source. With advent of the voltage source inverter (VSI), constant voltage/hertz (V/f) control has become the simplest, cheapest and hence one of the popular methods for speed control of induction motor.. Since flux is kept constant the full load torque Capability are maintained constant under steady state condition except low speed (when an Additional voltage boost is needed to compensate for stator winding voltage drop) In this control scheme, the performance of machine improves in the steady state only, but the transient responses poor. Scalar control drive drives give somewhat inferior performances but they are easy to implement. It gives the sluggish response because of inherent coupling i.e. both torque and flux are the function of voltage or current and frequency. However the importance diminished recently because of the superior performance of vector controlled drive.

III. Principle of Vector control

The principle of control of Induction motor is that the transient free operation of the Induction motor is achieved only if the stator or rotor flux linkages phasor is maintained constant in its magnitude and its phase is stationary with respect to the current phasor. By splitting the stator current into two orthogonal components, one in the direction of flux linkage, representing magnetizing current or flux component of current, and other perpendicular to the flux linkage, representing the torque component of current, and then by varying both components independently, the induction motor can be treated as a separately excited DC motor.

High dynamic performance of the Induction motor refers to the control similar to that of a separately excited DC motor. Separately excited DC motor is simple to control because they independently control the flux which when maintained constant contributes to independent control of the torque. The separately excited DC motor has the best control characteristics because of the independent control of flux producing component I_f and torque producing component i.e. I_a.

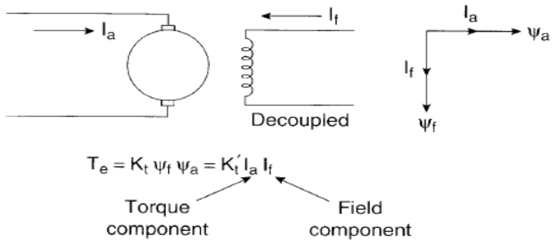


Fig . DC drive analogy

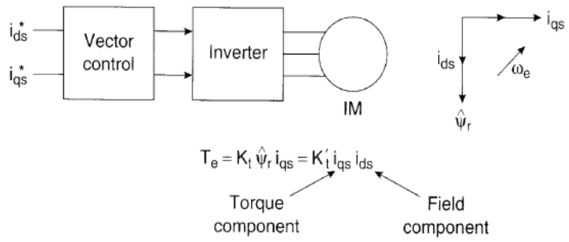


Fig. vector control of Induction motor

Depending upon the method of acquisition of flux information, the vector control or field oriented control method can be termed as: Direct or Indirect. In the direct method the position of the flux to which orientation is desired is strictly measured with the help of sensors, or estimated from the machine terminal variables such as speed and stator current/voltage signals. The measured or estimated flux is used in the feedback loop, thus the machine parameters have minimal effect on the overall drive performance. But the measurement of flux using flux sensors necessitates special manufacturing process or modifications in the existing machines. Also direct field orientation method have its inherent problem at low speed where the voltage drops due to resistances are dominant, and pure integration is difficult to achieve. The indirect vector control eliminates the direct measurement or computation of rotor flux from the machine terminal variables, but controls its instantaneous flux position by summing the rotor position signal with a commanded.

IV. Adaptive Variable structure controller

Adaptive Variable structure controller design provides a systematic approach to the problem of maintaining stability and satisfactory performance in presence of modelling imperfections. The adaptive variable structure controller is especially appropriate for the tracking control of motors, robot manipulators whose mechanical load change over a wide range. Induction motors are used as actuators which have to follow complex trajectories specified for manipulator movements. Advantages of adaptive variable structure controllers are that it is computationally simple compared adaptive controllers with parameter estimation and also robust to parameter variations. The disadvantage of adaptive variable structure control is sudden and large change of control variables during the process which leads to high stress for the system to be controlled. It also leads to chattering of the system states.

In [18] sliding mode control methods are applied to an indirect vector controlled induction machine for position and speed control. It is also applied in [9] to position control loop of an indirect vector control induction motor drive, without rotor resistance identification scheme. A sliding mode based adaptive input output linearizing control is presented for induction motor drives. In this case the motor flux amplitude and speed are separately controlled by sliding mode controllers with variable switching gains. A sliding mode controller with rotor flux estimation is presented.

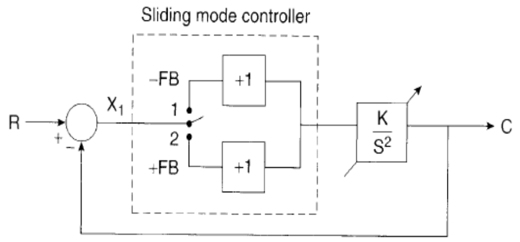


Figure 8.64 Variable structure control of second-order system

Although many speed estimation algorithms and sensorless control schemes are developed during the past few years, development of a simple, effective and low sensitivity speed estimation scheme for a low power IM drive is lacking in the literature. adaptive variable structure controller is a good choice for handling this type of problems.

V. Induction Motor Modelling

A proper model for the three phase induction motor is essential to simulate and study the complete drive system. The model of induction motor in arbitrary reference frame is derived.

Following are the assumptions made for the model:

1. Uniform airgap
2. The Stator and rotor MMF's are sinusoidal.

3. Mutual inductances are equal.
4. Saturation of the magnetic circuit is neglected.
5. The stator winding is a sinusoidal distributed winding.
6. Hysteresis and eddy current losses and skin effects are neglected.

The dynamic equations of the induction motor in any reference frame can be represented by using flux linkages as variables.
The voltage equations of the three phase induction motor in synchronous reference frame are given below

$$v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_e \psi_{qs} \quad (1)$$

$$v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_e \psi_{ds} \quad (2)$$

$$v_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega_e - p\omega_r)\psi_{qr} \quad (3)$$

$$v_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_e - p\omega_r)\psi_{dr} \quad (4)$$

The developed Torque T_e is;

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \quad (5)$$

The torque balance equation is:

$$J\frac{d\omega_r}{dt} = T_e - T_l - \beta\omega_r \quad (6)$$

Squirrel cage induction motor is mostly used and its rotor windings are short circuited,

$$\begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (7)$$

the flux linkage equations in matrix form are

$$\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix} = \begin{bmatrix} L_s & 0 \\ 0 & L_s \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} L_m & 0 \\ 0 & L_m \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} L_m & 0 \\ 0 & L_m \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} \quad (9)$$

Where Ls and Lrself-inductances of stator and rotor respectively and Lm is the mutual
Inductance between stator and rotor.

$$\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} = \begin{bmatrix} \frac{1}{L_r} & 0 \\ 0 & \frac{1}{L_r} \end{bmatrix}\begin{bmatrix} \psi_{dr} \\ \psi qr \end{bmatrix} + \begin{bmatrix} \frac{L_m}{L_r} & 0 \\ 0 & \frac{L_m}{L_r} \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix} = \begin{bmatrix} (L_s - \frac{L_m{}^2}{L_r}) & 0 \\ 0 & (L_s - \frac{L_m{}^2}{L_r}) \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} - \begin{bmatrix} \frac{L_m}{L_r} & 0 \\ 0 & \frac{L_m}{L_r} \end{bmatrix}\begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix}$$

$$= \begin{bmatrix} \sigma L_s & 0 \\ 0 & \sigma L_s \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} - \begin{bmatrix} \frac{L_m}{L_r} & 0 \\ 0 & \frac{L_m}{L_r} \end{bmatrix}\begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} \quad (11)$$

Where $\sigma = 1 - \frac{L^2{}_m}{L_s L_r}$ =Leakage coefficient.

$$\frac{d}{dt}\begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} \frac{R_r L_m}{L_r} & 0 \\ 0 & \frac{R_r L_m}{L_r} \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} \frac{-R_r}{Lr} & 0 \\ 0 & \frac{-R_r}{Lr} \end{bmatrix}\begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} +$$

$$\begin{bmatrix} 0 & -(\omega_e - p\omega_r) \\ (\omega_e - p\omega_r) & 0 \end{bmatrix}\begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} \quad (12)$$

$$\frac{d}{dt}\begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} a_5 & 0 \\ 0 & a_5 \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} -a_4 & \omega_{sl} \\ \omega_{sl} & -a4 \end{bmatrix}\begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} \quad (13)$$

Where

$a_5 = \frac{R_r L_m}{L_r}$, $a_4 = \frac{R_r}{L_r}$, and $\omega_{sl} = \omega_e - P\omega_r$

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} -a_1 & \omega_e \\ -\omega_e & -a_1 \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} +$$

$$\begin{bmatrix} a_2 & Pa_3\omega_r \\ -Pa_3\omega_r & a_2 \end{bmatrix}\begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} + \begin{bmatrix} c & 0 \\ 0 & c \end{bmatrix}\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix}$$

Where

$a_1 = \frac{1}{\sigma L_s}(R_s + R_r \frac{L_m{}^2}{L_r{}^2})$, $a_2 = \frac{1}{\sigma L_s} R_r \frac{L_m{}^2}{L_r{}^2}$,

$a_3 = \frac{1}{\sigma L_s}\frac{L_m}{L_r}$

$a_4 = \frac{1}{\sigma L_s}$

write above all equations in matrix form
The state space model of the induction motor in terms of stator current and rotor flux linkages is given as follows:

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} -a_1 & \omega_e & a_2 & pa_3\omega_r \\ -\omega_e & -a_1 & -a_3\omega_r & a_2 \\ -a_3 & 0 & -a_4 & \omega_{sl} \\ 0 & a_5 & -\omega_{sl} & -a_4 \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} + \begin{bmatrix} C & 0 \\ 0 & C \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix}$$

(14)

Using (2.9) and (2.10) and simplifying, we get

$$T_e = \frac{3}{2} p \frac{L_m}{L_r}\begin{bmatrix} \psi_{dr} & \psi_{qr} \end{bmatrix}\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix}$$

Or

$$T_e = \frac{3}{2} P \frac{L_m}{L_r} [\psi_{dr} i_{qs} - \psi_{qr} i_{ds}] \tag{15}$$

VI. The Field Oriented control

To achieve field orientation along the rotor flux, the flux component (d-axis component) of stator current, ids is aligned in the direction of rotor flux, ψ_r, and the torque component of stator current, i_{qs} is aligned in direction perpendicular to it. At this condition:

$$\psi_{qr} = 0 \text{ and } \frac{d}{dt}\psi_{qr} = 0 \tag{16}$$

$$\psi_{dr} = \psi_r = \text{rotor flux}$$

Hence the developed electromagnetic torque is given by

$$Te = \frac{3}{2} p \frac{L_m}{L_r} \psi_{dr} i_{qs} = K_t \psi_{dr} i_{qs} \tag{17}$$

With field orientation, the dynamic behaviour of the induction machine is given by:

$$\frac{di_{ds}}{dt} = a_1 i_{ds} + a_2 \psi_{dr} + \omega_e i_{qs} + c v_{ds} \tag{18}$$

$$\frac{di_{qs}}{dt} = -\omega_e i_{ds} - a_1 i_{qs} - p a_3 \omega_r \psi_{ds} + c v_{qs} \tag{19}$$

$$\frac{d\psi_{dr}}{dt} = -a_4 \psi_{dr} + a_4 i_{ds} \tag{20}$$

(2.15)

Slip frequency for obtaining indirect field orientation is given by

$$\omega_{sl} = \omega_e - p\omega_r = a_5 \frac{i_{qs}}{\psi_{ds}} \tag{21}$$

Where $a_5 = \frac{R_r L_m}{L_r}$

The DC machine like performance is only possible if i_{ds} is oriented in the direction of flux With ψ_r and i_{qs} is established perpendicular to it.

VII. Speed Estimation

A speed signal is also required in indirect vector control in the whole speed range and in the direct vector control for the low speed range.

The rotor speed of an induction motor is

$$\omega_r = \frac{\omega_e - \omega_{sl}}{p}$$

Here we can estimate the speed using direct synthesis from state equations

The ψ_{qr} expression can be written as

$$\frac{d}{dt}(\psi_{qr}) = \frac{L_r}{L_m} v_{qs} - \frac{L_r}{L_m}(R_s + \sigma L_s s) i_{qs} \tag{22}$$

The ψ_{dr} expression can be written as

$$\frac{d}{dt}(\psi_{dr}) = \frac{L_r}{L_m} v_{ds} - \frac{L_r}{L_m}(R_s + \sigma L_s s) i_{ds} \tag{23}$$

$\widehat{\omega_r}$ = Estimated rotor frequency in rad/sec

$\widehat{\omega_e}$ =Estimated synchronous frequency in rad/sec.

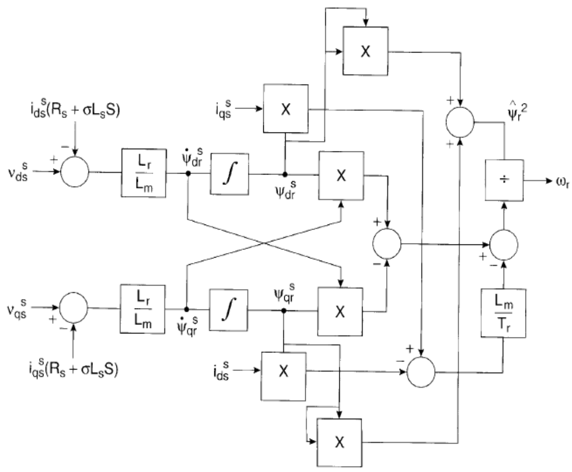
ω_{sl}^* =Command value of slip frequency in rad/sec

$$\angle\theta_e = \tan^{-1}\left(\frac{\psi_{qr}}{\psi_{dr}}\right) \tag{24}$$

And

$$\omega_r = \frac{1}{\psi_r^2}\left[(\psi_{dr}\dot{\psi}_{qr} - \psi_{qr}\dot{\psi}_{dr}) - \frac{Lm}{Lr}(\psi_{dr} i_{qs} - \psi_{qr} i_{ds})\right] \tag{25}$$

The block diagram for speed estimation using direct synthesis from state equations as shown below



VIII. DESIGEN OF ADAPTIVE VARIABLE STRUCTURE CONTROLLER

Assuming the load torque, T_l to be a disturbance to a system, the speed dynamic equation is simplified as

$$\dot{\omega}_r = f_1 + nosie \tag{26}$$

$$f_1 = -\frac{1}{J}\beta\omega_r + bi_{qs} \tag{27}$$

And

$$b = \frac{K_T}{J}\psi_{dr}{}^{*} \tag{28}$$

To track the speed accurately in the second order speed control system, the conditions to be satisfied are

$$\dot{\omega}_r \,\big|_{\omega_r = \omega^*{}_r} = 0$$ and

$$\ddot{\omega}_r \,\big|_{\omega_r = \omega^*{}_r} = 0$$

$$\ddot{\omega}_r = \frac{-\beta}{J}\dot{\omega}_r + b\,\dot{i}_{qs} + noise \tag{29}$$

$$\omega_s = p\omega_r + a_5\frac{i_{qs}}{\psi_{dr}} \tag{30}$$

from the above following equation is obtained

$$\dot{i}_{qs} = (p\omega_r + a_4\frac{i_{qs}}{i_{ds}})i_{ds} - a_1 i_{qs} - pa_3\omega_r L_m i_{ds} + cv_{qs} \tag{31}$$

$$\omega_{sl} = a_5\frac{i_{qs}}{\dot{\psi}_{dr}} = \frac{R_r L_m}{L_r}\frac{i_{qs}}{L_m\,\dot{i}_{ds}} = a_4\frac{i_{qs}}{i_{ds}} \tag{32}$$

$$\dot{i}_{qs} = -(a_1 + a_4)i_{qs} - P\omega_r(1 + a_3 L_m)i_{ds} + cv_{qs}$$

or

$$\dot{i}_{qs} = f_2 + cv_{qs} \tag{33}$$

Where

$$f_2 = -(a_1 + a_4)i_{qs} - P\omega_r(1 + a_3 L_m)i_{ds}$$

Substituting (3.2) and (3.6a) in (3.5a), we get

$$\ddot{\omega}_r = -\frac{\beta}{J}f_1 + bf_2 + bcv_{qs} + d \tag{34}$$

$$\ddot{\omega}_r = G + u + d \tag{35}$$

Where d=total disturbance

And $u = bcv_{qs}$ =control input

And $$G = -\frac{\beta}{J}f_1 + bf_2 \tag{36}$$

G is a function, which can be estimated from measured values of current and speed. U is directly proportional to v_{qs} and decides the modulating signals and hence output voltage of the PWM voltage source interver

Let

$$G = \hat{G} + \Delta G \tag{37}$$

Where $\hat{G}$ is an approximate of G, and ΔG is the estimation error due to modelling imperfection.

The control problem is to obtain the system states,

$$X = [\omega_r \;\dot{\omega}_r]^T \tag{38}$$

To teack a specific time varying state, in the modeling imperfection and disturbance.

Let $$e = \omega_r - \omega^*{}_r \tag{39}$$

And

$$\dot{e} = \dot{\omega}_r - \dot{\omega}^*{}_r \tag{40}$$

$\rightarrow$

be the tracing error in the speed and its rate of change respectively

Let $E = [e\;\dot{e}]^T$ be the tracking error vector.

A time varying surface, s(t) is defined in the state space by the scalar equation,

$$S(x,t) = 0$$

Where

$$S(x,t) = (\frac{d}{dt} + \lambda)e = \dot{e} + \lambda e \tag{41}$$

λ is a positive constant which determines the band width of the system. Starting from the initial condition, E(0) = 0, the tracking task, X →X*, which means x has to follow X* with a predefined precision, is considered as solved, if the state vector, E remains in the sliding surface, S(t) for all t ≥ 0 and also implies that scalar quantity s is kept at zero. A sufficient condition for this behavior is to choose the control law, u of (3.8) and (3.8a) so that

$$\frac{1}{2}\frac{d(S^2)}{dt} \le -\eta|S|$$

IX. Design of Controller Gain

$$(G - \hat{G} + d - \dddot{\omega}_r^{*})\,\mathrm{sgn}(s) - K \le -\eta \tag{42}$$

$$K \geq (|\Delta G_{\max}| + |d_{\max}| + \eta + \upsilon \quad (43)$$

$|\Delta G_{\max}|$ = upper bound of the estimation error, (G-$\hat{G}$)

d_{max} = upper bound of the noise, d, and

v = upper bound of command acceleration $\dddot{\omega}_r^{*}$

The controller gain K is determined from the maximum amount of imperfection in the estimation process and maximum noise due to parameter variations and disturbance (load torque). If modeling imperfection and parameter variation is large, the value of K should be large. Then discontinuous or switched component (K.sgn(s))has a more dominant role than the continuous or compensation component, (-$\hat{G} - \lambda\dot{e}$)and lead to chattering. Conversely, better knowledge of the system model and parameter values reduces gain, K and results smooth control response. If large control bandwidth is available, poor knowledge of dynamic model may lead to respectable tracking performance, and hence large modelling efforts may produce only minor improvement in tracking accuracy

v = upper bound of command acceleration $\dddot{\omega}_r^{*}$

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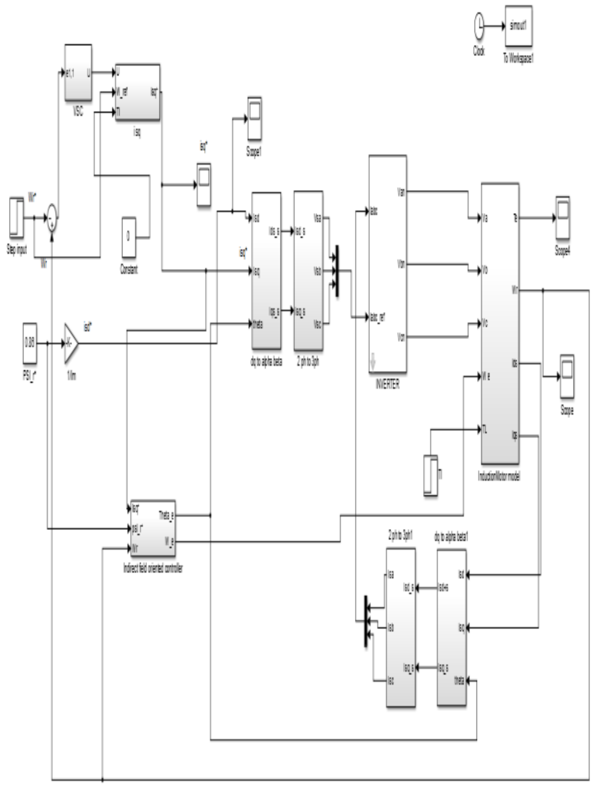

Fig. Adaptive Variable structure controller with induction motor drive

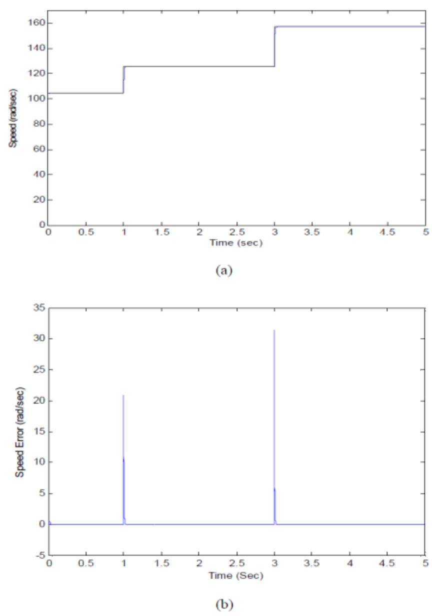

Fig. step change in reference speed with adaptive variable structure controller Speed

a)
b) Speed error

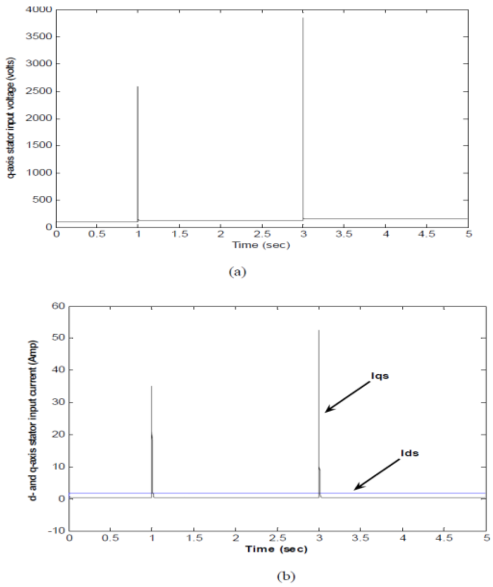

Fig . step change in reference speed with adaptive variable structure controller

a) q-axis stator input voltage
b) d-and q-axis stator current

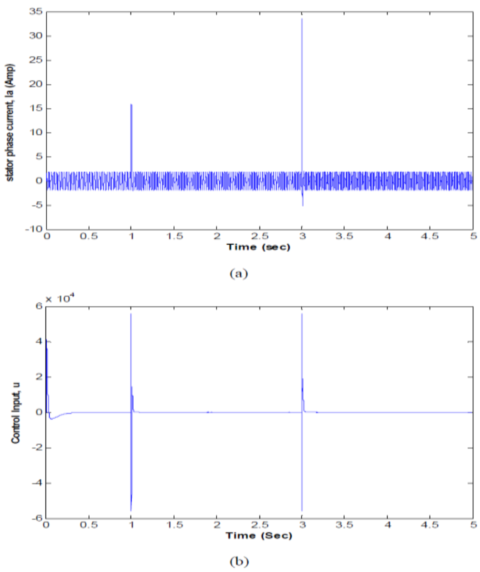

Fig. step change in reference speed with adaptive variable structure controller

a) Stator phase current in amp
b) Control input,u in rads/s^3

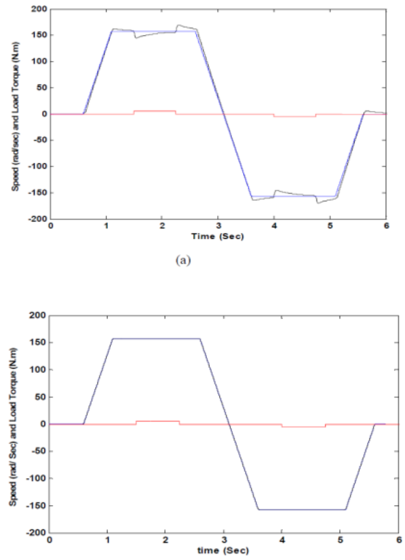

Fig. Performance of the drive system under load torque variations

a) with P-I controller
b) with adaptive voltage structure controller

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