

Sensorless Vector Control of Induction Motor with Slip Gain Tuning

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Abstract : In this project, the speed of an induction motor is controlled by indirect vector control using PI as well as fuzzy logic controller. Sensorless vector control is achieved by model reference adaptive control where voltage model is used as reference model and current model as the adaptive model. Sensorless drive system increase reliability and compactness of drive. In sensorless vector control speed is estimated from machine terminal voltage and current measurements. Fuzzy logic controller based sensorless induction motor drive is used in providing the smooth dynamic performance of induction motor. The performance of PI and fuzzy logic controller based sensorless induction motor drive is compared at dynamic load condition to verify the robustness of fuzzy logic controller based sensorless induction motor. For precise description of fuzzy variable higher order of fuzzy rule (9×9 fuzzy rule) is used. In indirect vector control slip gain tuning is required to avoid the misalignment of direct axis and quadrature axis component of vector control, caused by the parameter variation specially rotor resistance variation. Rotor resistance of induction motor depends on mainly the temperature, as temperature varies rotor resistance varies and misaligning d-q component of vector control results in overfluxing or underfluxing thereby deteriorating the torque control characteristics of induction motor. In this work, rotor resistance variation is compensated by using current control system. The current control loop is constructed in (γ - δ) coordinate, converting the d-q voltage and current components into γ - δ coordinate. The γ -axis is coincident of stator current or voltage component of stator resistance and δ -axis is perpendicular to γ -axis where the stator voltage or error due to rotor resistance variation will appear. The effect of stator resistance will not appear on δ -axis voltage. The rotor resistance is compensated in such a way that the voltages variation on δ -axis becomes zero. There is no special detection circuit required for compensation, thus compensation circuit become simple. The effectiveness of this scheme is tested through simulation.

I. INTRODUCTION

Major improvements in modern industrial processes over the past 60 years is largely assigned to advances in variable speed motor drives. Nowadays more than

60% of the electrical energy generated in the world is used by squirrel cage induction motors[4]. Induction motors are

relatively rugged and inexpensive machines. Therefore much attention is given to their control for various applications with different control requirements. Voltage per hertz (V/f) control, vector control and direct torque control are popular for induction motor drive. In V/f control, flux is maintained constant by keeping voltage to frequency ratio constant. This control method can control the speed in wide range with full load torque capability even at lower speed. This cause high energy savings but it is disadvantageous when the transient response is considered[1]. During the speed transition or change in loading there is change in the flux which is responsible for poor transient response. The change in flux is recovered in sluggish manner. This lead to over current , over heating during transient period which necessitates a drive to be oversize and no longer cost effective. The causes of deviation of the flux from the reference value is inherent coupling between flux and torque. They can be decoupled and controlled independently to obtain high transient response. This method of decoupling and controlling the flux and torque component is known as the vector control method. The basic working principle of vector control method is to split stator current into flux and torque producing component by transforming it into synchronously rotating frame of reference. The change in frame of reference cause the current to appear stationary which simplifies the control circuitry.

There are two types of vector control methods, direct and indirect field oriented control. In direct vector control method the rotor flux is estimated either by using flux sensor in the air gap or estimating it by sensing stator voltages. In indirect vector control the rotor flux is estimated using field oriented control equations which need instantaneous speed information[2]. The direct vector control is very difficult to implement practically for low speed application. The indirect field oriented control is preferred because of more accuracy over a whole speed range. Generally, the fixed gain PI controllers are used for generating torque and flux component from speed and flux errors.

It is simple and gives stable operation in wide speed range. However, unexpected change in load conditions or environmental factor would produce overshoot, oscillation of motor speed, oscillation of the torque, long settling time and thus causes deterioration of the drive performance. Also the accurate tuning of PI controllers demands the accurate mathematical model of system. The fuzzy logic controller can replace the PI controller. In involves some advantages like improvement in transient response, more stability and simplicity in design[12].

The advancement of power electronics, digital electronics and high speed processor like DSP has allowed to develop very effective drive control. The vector control strategy ideally needs to be implemented in real time. In reality, with high speed DSPs it is possible to perform all close loop calculations of vector control in few tens of microseconds. All the control advantages of DC machine can be achieved with this method. The speed sensor and its mounting arrangements can be avoided by implementing sensorless vector control. The speed of the motor can be estimated in high speed processors using the terminal voltage s and currents in high speed processors. The speed sensing using sensor requires shaft extension of motor and mounting arrangement. Sensorless control will become the system more economic and reliable.

In indirect vector control, the direct axis component of stator current should be aligned with rotor flux at all operating condition, but it is deviated due to parameter variation under different operating conditions. It will give sluggish response. So slip gain (K_s) tuning is required in indirect vector control of induction motor for obtaining good dynamic response. The slip gain (K_s) is a function of machine parameters and it is desirable that these parameters match the actual parameters of machine at all operating condition to achieve decoupled control of the machine. $K_s = \frac{L_m R_r}{L_r \phi_r}$ where L_m is magnetizing inductance, L_r is rotor leakage inductance, R_r is rotor resistance and ϕ_r is d-axis rotor flux. With closed loop flux control, the estimated value of rotor flux (input to slip gain) is known therefore the variation of three machine parameter L_m, L_r, R_r is of concern. The saturation effect of magnetization inductance L_m almost cancels the variation of L_r , thus leaving the dominant effect of rotor resistance variation on K_s . Therefore K_s becomes a function of rotor time constant $T_r = \frac{L_r}{R_r}$ [2]. It is necessary to compensate the variational parameter of induction motor by slip gain tuning and improve torque control characteristic of induction motor. Vector control of induction motor using slip frequency control method is used in this work to incorporate the slip gain tuning. In indirect vector control, the rotor resistance of induction motor is used in computation of slip frequency. Torque control characteristics of induction motor will deteriorate due to temperature change and the rotor resistance variation. In this work, the slip gain tuning is done by detecting variations of rotor flux and stator voltages.

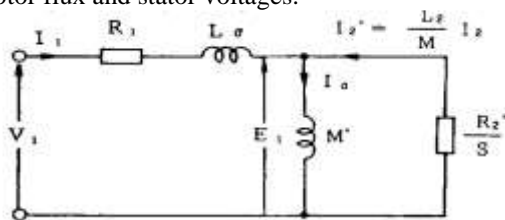


Fig.1: Equivalent circuit of induction motor[11]

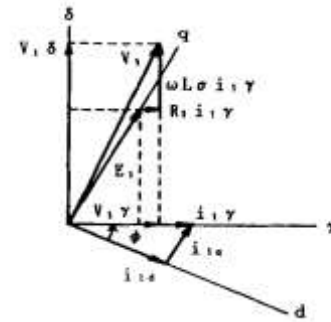


Fig.2: Vector diagram of circuit[11]

Fig.1 shows equivalent circuit of induction motor with stator current as a reference parameter and Fig.2 shows the corresponding vector diagram. Variational parameter of induction motor in compensated in indirect vector control [6] by compensating variational rotor resistance. For that a current control system is designed in ($Y-\delta$) coordinate. The vector quantity of d-q stator voltage and current is converted into $Y-\delta$ coordinate with stator current as a reference axis (Y axis). Voltage component of stator resistance is taken on Y axis.

Voltage variational component is taken on δ axis. Voltage variation on δ axis is caused by rotor resistance variation. Y axis component and δ axis components are perpendicular to each other. Effect of rotor resistance variation will appear on δ axis only and the effect of sator resistance will not appear on δ axis. Rotor resistance is compensated in such a way that voltage variation on δ axis is made zero by the current control system. Rotor resistance variation compensating circuit become simple because no special detection circuit is required[13].

II. INDIRECT VECTOR CONTROL OF INDUCTION MOTOR

Direct vector control and indirect vector control are two types of vector control methods based on the way in which angle θ is calculated. In direct vector control method the angle is calculated by estimating the rotor flux, direct axis and quadrature axis flux using voltage or current model. This method does not give accurate estimation at low speed hence generally indirect vector control method is preferred. In indirect field oriented control the three phase current is represented by the single stator current phasor. This current is split along two orthogonal components out of which one is aligned with the rotor flux and other component is used to control torque. These orthogonal components are called as quadrature and direct axis components. As these two components are perpendicular to each other change in one component keeps the other component unaffected. This way complete decoupling can be achieved. In indirect vector control slip speed ω_{sl} is calculated from Equation(1) which is derived from general induction motor model equations by

putting $\varphi_{qr}^e = 0$ and $\frac{d\varphi_{dr}^e}{dt} = 0$ These equation represented the vector control conditions

$$\omega_{sl} = \frac{L_m R_r}{L_r \varphi_r} i_{qs}^* \quad (1)$$

$$\theta = \theta_r + \theta_{sl} = \int (\omega_r + \omega_{sl}) dt \quad (2)$$

The integration of synchronous speed is angle θ which is used for transformation. The cosine and sine of angle θ is called as unit vector. The equation of the electromagnetic torque and rotor flux is given as follows

$$T_e = \frac{3}{4P} * \frac{L_m}{L_r} * \varphi_r * i_{qs} \quad (3)$$

$$\varphi_r = L_m i_{ds} \quad (4)$$

The block diagram of vector control using fuzzy logic controller is shown below in Fig.3 The fuzzy controller observes the pattern of the speed error and the flux error and correspondingly updates the output Δi_{qs}^* and Δi_{ds}^* . This regulates the flux and speed at the reference value. The advantage of using fuzzy controller is the improvement in the performance of the motor.

No overshoot and oscillations occurs in the torque and flux value. The response of speed is faster and smoother. The design and implementation of this controller does not demand the mathematical modeling of the system. It gives robust performance even in the presence of unexpected load changes and motor parameter variation.

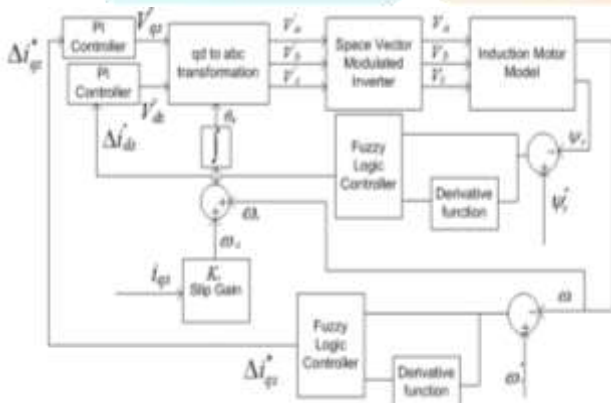


Fig.3: Block diagram of vector control using fuzzy logic controller

Simulation of indirect vector control of induction motor using PI and Fuzzy logic controllers has been performed. The three phase AC supply is passed through rectifier and rectified voltage is used as an input DC voltage for the three phase inverter. In flux and torque control block of simulation, the speed controller generates the torque producing current component and flux controller produces the flux producing component with the help of either PI or Fuzzy based controller. These component are passed through the PI controller to produce the reference voltage command. These voltage are transform into three phase by using park and clark transformation and applied to PWM inverter.

III. MRAS BASED SENSORLESS VECTOR CONTROL

Usually a speed sensor is required in the closed loop operation for both scalar control and vector control. The speed sensor or tachometer is mounted on the motor shaft. the shaft encoder may present problems. Delicate critical encoders with internal signal electronics are used, which lower the reliability of the motor system. In addition, the sensor increases cost factor as the provision of special motor shaft and encoder mounting surfaces leads to more expensive machine control systems. The elimination of the speed sensor has been one of the important features in the modern motor control systems. Speed of induction motors estimate without the speed sensor. The information of the rotor speed can be obtained by processing the stator voltages and currents measured at the motor terminals. The rotor speed is estimated by employing a closed-loop observer named model reference adaptive systems (MRAS). In MRAS, a comparison is made between the outputs of two observers. One observer does not involve the rotor speed to be estimated, and one does.

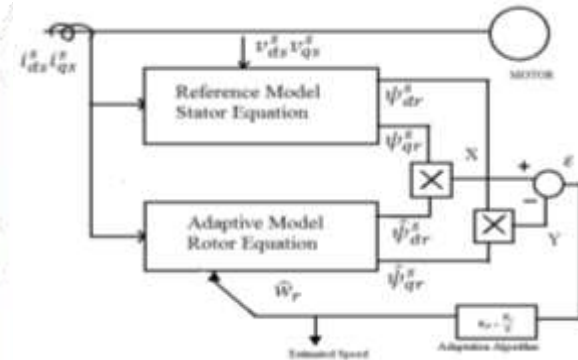


Fig.4: Block Diagram of Model Reference Adaptive System[1]

Model Reference Adaptive System MRAS is based on the comparison between the outputs of two observers. Fig.4 illustrates the structure of MRAS for speed estimation. MRAS is a technique to estimate induction motor speed from measured terminal voltages and currents for sensorless control. In MRAS, two models namely Reference model and adaptive model are present.

Reference Model Equations

$$\dot{\psi}_{dr} = \frac{L_r}{L_m} v_{ds} - \frac{L_r}{L_m} \left(R_s + \sigma L_s \frac{d}{dt} \right) i_{ds}$$

$$\dot{\psi}_{qr} = \frac{L_r}{L_m} v_{qs} - \frac{L_r}{L_m} \left(R_s + \sigma L_s \frac{d}{dt} \right) i_{qs}$$

where φ_{dr} and φ_{qr} is flux linkage, L_r , L_m are inductances, R_s is resistance and σ is motor leakage coefficient.

Adaptive model equations

$$\hat{\psi}_{dr}^s = \int \left(\frac{L_m}{T_r} i_{ds} - \omega_r \hat{\psi}_{qr}^s - \frac{1}{T_r} \hat{\psi}_{dr}^s \right)$$

$$\hat{\psi}_{qr}^s = \int \left(\frac{L_m}{T_r} i_{qs} + \omega_r \hat{\psi}_{dr}^s - \frac{1}{T_r} \hat{\psi}_{qr}^s \right)$$

where ω_r is rotor electrical speed and $T_r = L_r/R_r$ is the rotor time constant.

The current model flux equations are defined as an adaptive model. This model can calculate fluxes from the input stator currents only if the speed signal ω_r is known. With the correct speed signal, ideally, the fluxes calculated from the reference model and those calculated from the adaptive model will match, that is, $\psi_{dr}^s = \hat{\psi}_{dr}^s$ and $\psi_{qr}^s = \hat{\psi}_{qr}^s$, where

$\hat{\psi}_{dr}^s$ and $\hat{\psi}_{qr}^s$ are the adaptive model outputs. An adaptation algorithm with PI control, as indicated, can be used to tune the

speed ω_r so that the error $\zeta = 0$. Reference model is the voltage model where stator voltages and currents are the inputs whereas in adaptive model inputs are the estimated speed and the stator currents. Both models calculate ϕ_{dr} and ϕ_{qr} . A comparison is made between the outputs of two observers and the error between them is made zero using adaptive mechanism and hence the rotor speed is estimated.

$$\omega_r = \xi \left(k_p + \frac{k_i}{s} \right) \tag{7}$$

where $\xi = X - Y = \hat{\psi}_{dr}^s \psi_{qr}^s - \hat{\psi}_{qr}^s \psi_{dr}^s$
 In steady state $\zeta = 0$, Balancing the fluxes; in other words $\psi_{dr}^s = \hat{\psi}_{dr}^s$ and $\psi_{qr}^s = \hat{\psi}_{qr}^s$. To implement MRAS technique in MATLAB the motor parameters are required.

IV. SLIP GAIN TUNING OF INDUCTION MOTOR

Current control system based rotor resistance compensating model is simulated as shown in Fig.5 Rotor resistance variation compensation circuit is tested through simulation, as load torque of induction motor change rotor resistance will also change and it will change voltage on d axis and this variational voltage on d axis detected by current control loop as shown in Fig.6

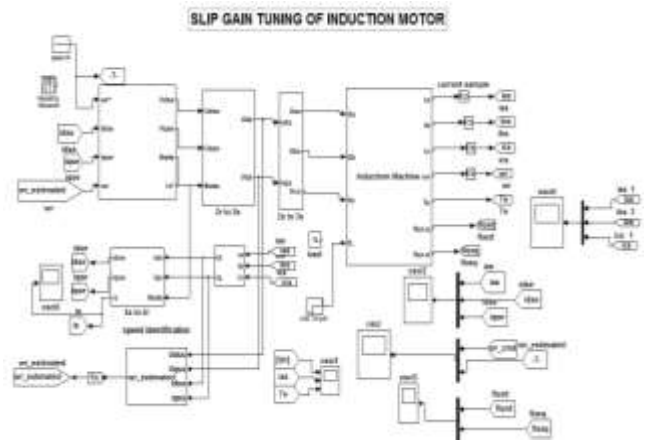


Fig.5: Slip gain tuning of induction motor

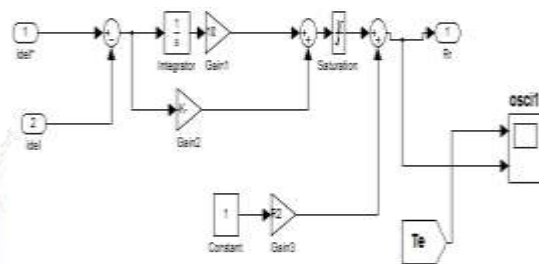


Fig.6:

rotor resistance compensating circuit

Rotor resistance variation is compensated by using current control system. The current control loop is constructed in $(\gamma-\delta)$ coordinate, converting the $d-q$ voltage and current components into $\gamma-\delta$ coordinate. The γ -axis is coincident of stator current or voltage component of stator resistance and δ -axis is perpendicular to γ -axis where the stator voltage error due to rotor resistance variation will appear. The effect of stator resistance will not appear on δ -axis voltage. The rotor resistance is compensated in such a way that the voltages variation on δ -axis becomes zero.

V. SIMULATION RESULTS AND DISCUSSION

The induction motor details are as follows; $V=400V$, $f=50Hz$, $P=4$, $R_s=0.9327ohms$, $L_{ls}=0.08533H$, $R_r=0.765ohms$, $L_{lr}=0.08533H$, $L_m=0.081866H$. By keeping reference speed constant at different time interval 1400rpm, 1100rpm, 1000rpm, at time 0,3.5 and 7 second respectively. load torque is changed to 0 N-m, 5 N-m, and 10 N-m at time 0, 4 and 12 seconds respectively. It can be seen from Fig.3.3, a smooth torque control is obtained within its operating range. It can also be seen from these results that, throughout the range of operation, the flux producing component of the stator current (i_d) remains constant while the torque producing component (i_q) only varies to produce the desired torque. These results show that torque can be independently controlled without affecting flux in the motor. Thus decoupled control is obtained.

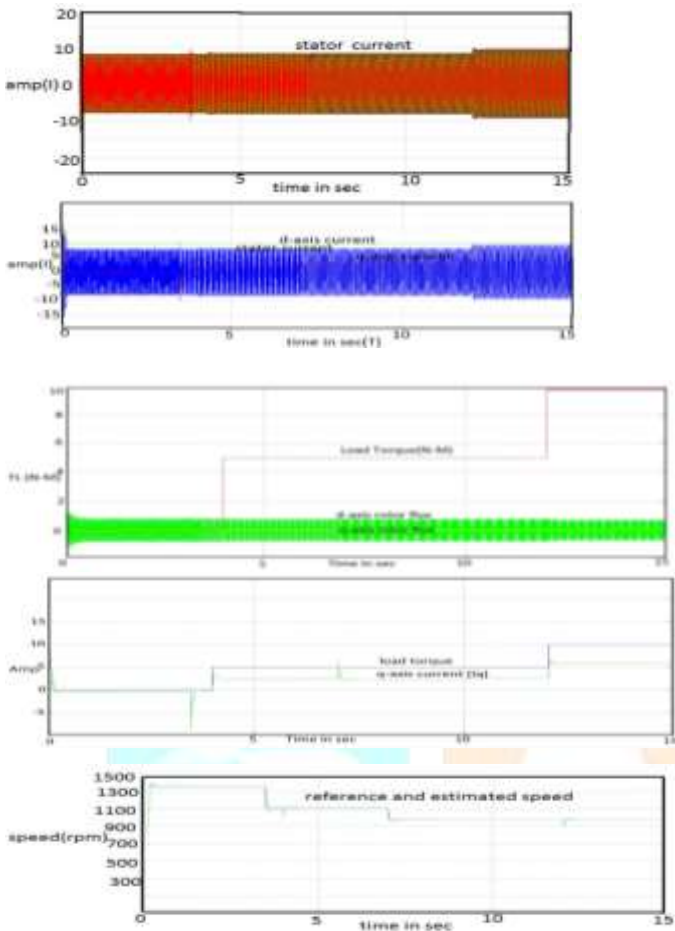


Fig.7: simulation results of indirect vector control using fuzzy logic controller

Fig.8 shows the simulation result of sensorless vector control of induction motor, showing reference speed and estimated speed for reference speed change to 1400rpm, 1100rpm and 1000rpm at 0, 3.5 and 7 second respectively. It can be seen that speed is estimated accurately using MRAS observer.

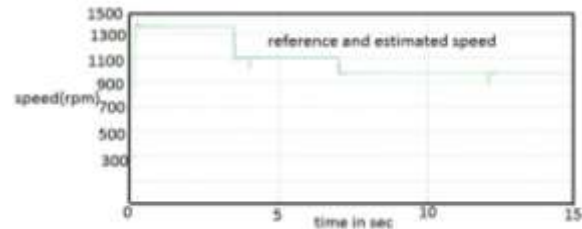


Fig.8: sensorless vector control results (estimated and actual speed)

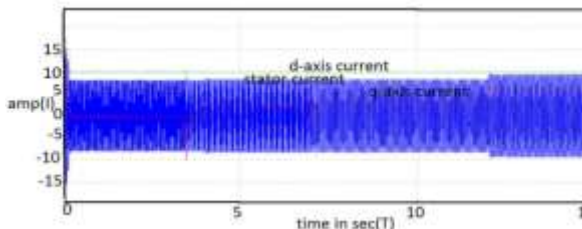
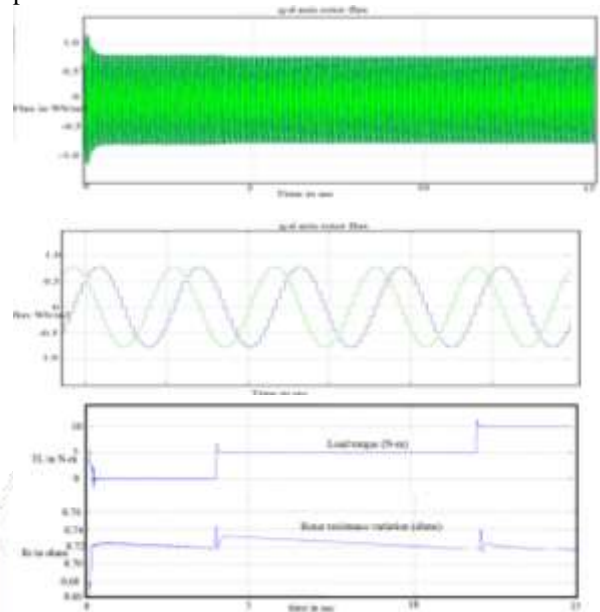


Fig.8: sensorless vector control results (estimated and actual speed)

Fig.9 shows the rotor flux response and rotor resistance compensation of induction motor (gain tuning) the flux is tightly around the reference values and there is no transient occur. Under all operating condition these q-d quantity are in aligned position. Its eliminates over fluxing and under fluxing problem.



VI. CONCLUSION

The focus of this project has been the implementation of indirect vector control and sensor less vector control with slip gain tuning. generalized dynamic mathematical model of the induction motor is simulated in synchronous reference frame. Using this motor model an indirect field orientation control is simulated. From the waveform of q axes flux and d axis current, it is concluded that proper field orientation is achieved because the value of q axis flux is zero and there is no change in d -axis current due to the application of load torque. Hence total flux is completely oriented along d-axis, and q-axis current will respond to the change in load torque but not d-axis current.

Model reference adaptive system (MRAS) is tested to observe rotor speed. This is a flux observer with voltage model and current model combination. The outputs of this observer were fed to speed estimator. Using this observer, sensorless vector control is simulated and found satisfactory simulations results. In sensorless vector control also proper field orientation is achieved because the value of q axis flux is zero and there is no change in d-axis current due to the application of load torque and slip gain tuning eliminates the motor over fluxing and under fluxing problem due to rotor resistance variation.

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