An Efficient Bidirectional Sensorless Induction Motor Drive Using Slip Estimation

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Abstract

This paper presents a new control strategy for three-phase induction motor which includes a simple sensorless scalar speed control thereby overcoming the difficulties in complex vector control method. For close-loop sensorless control, the speed is not measured directly but is estimated by means of a mathematical calculation. The required datas are the RMS values of stator current and voltage measured directly from the motor terminals. The proposed drive thus requires a low cost voltage/current sensor in the stator side and the name plate details is enough to implement the close-loop speed control. Stator resistance compensation for supplying torque at low speeds is also incorporated in the proposed scheme. The simulation results on a 4 kW induction motor drive in MATLAB software show fast dynamic response and good agreement between the actual speed and the estimated speed in both forward and reverse directions. The proposed method reduces the steady state error and it is possible to control speeds down to 100 RPM accurately with rated load torque.

Index terms: *Scalar speed control, sensorless closed loop control, stator resistance compensation*.

1. Introduction

Three phase squirrel-cage induction motors are widely used in industrial drives because they are rugged, reliable and economical. Single-phase induction motors are used extensively for smaller loads, such as household appliances like fans. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives (VFDs) in variable-speed service. VFDs offer especially important energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications. Squirrel cage induction motors are very widely used in both fixed-speed and VFD applications. The control of induction machine often requires control of machine currents, which is normally achieved by using a voltage source inverter. The volts per hertz (*v/f*) IM drives with inverters are widely used in a number of industrial applications. The low cost applications such as Variable-speed pumps, fans usually adopt v/f scalar control. For those applications which require higher dynamic performance, field oriented control (FOC) is preferred [5]. Nowadays an interest have been noted in applying sensorless control to high performance applications which is based on estimation of rotor speed by using the machine parameters such as instantaneous stator currents and voltages [4].

The advantages of sensorless control are the increased reliability of overall system with the removal of mechanical sensors, thereby reducing sensor noise and drift effects as well as cost and size [8]. At low speeds the control is still challenging due to the influence of stator resistance and slip. In addition, the nonlinear behavior of the PWM inverter in low voltage range makes it difficult to use constant v/f drives at frequencies below 3 Hz [1]. A simple method of stator resistance compensation consists of boosting the stator voltage by the magnitude of current resistance drop [3]. The proposed method predicts exact slip for any load at any speed. The proposed control scheme requires just the nameplate data, the equivalent circuit parameters obtained from conducting the no load and blocked rotor test on the machine. The simulated results of the control scheme illustrate better speed control and capable of supplying even torque at low speeds.

2. Basics of *v/f* Control

In the *v/f* control, the speed of induction motor is controlled by adjusting the magnitude of stator voltage and frequency in such a way that the air gap flux is always maintained at the constant value. Sometimes this scheme is called the scalar control because it focuses only on the steady-state dynamic. According to figure-1, the stator resistance (R_s) is assumed to be zero and the stator leakage inductance (L_s) is embedded into the rotor leakage inductance (L_r) and the magnetizing inductance, which is representing the amount of air gap flux, is moved in front of the total leakage inductance ($L = L_s + L_r$). As a result, the magnetizing current that generates the air gap flux can be approximately the stator voltage to frequency ratio. Its phasor equation for steady-state analysis can be given as

$$I_m = \frac{V_s}{j\omega L_m} \quad (1)$$

If the induction motor is operating in the linear magnetic region then L_m is constant and equation (1) can be simply expressed in terms of magnitude as

$$I_m = \frac{\Phi_m}{L_m} \quad (2)$$

$$I_m = \frac{V_s}{(2\pi f L_m)} \quad (3)$$

$$\Phi_m = \frac{V_s}{f} \quad (4)$$

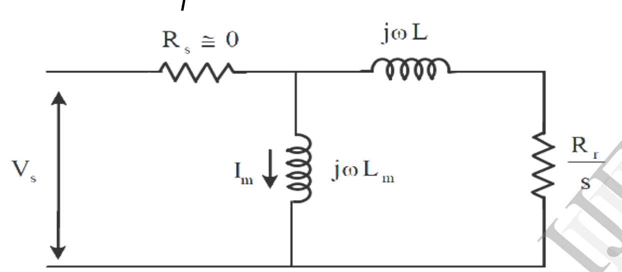

Figure.1. Simplified steady-state equivalent circuit of induction motor

In practice, the stator voltage to frequency ratio is usually based on the rated values. The typical *v/f* profile is shown in Figure.2. Basically, there are three speed ranges in the *v/f* profile as follows:

i. From 0 - f_c Hz, a voltage is required, so the voltage drop across the stator resistance cannot be neglected and must be compensated by increasing the Vs. So, the v/f profile is not linear. The cutoff frequency (f_c) and the suitable stator voltages may be analytically computed from the steady-state equivalent circuit with $R_s \neq 0$.

ii. In f_c - f_{rated} Hz, it follows the constant *v/f* relationship. The slope actually represents the air gap flux available as seen in equation (3).

iii. At higher f_{rated} Hz, the constant v/f ratio cannot be satisfied because the stator voltages would be limited at the rated value in order to avoid insulation breakdown at stator windings. Therefore, the resulting air gap flux would be reduced, and this will cause reduction in developed torque correspondingly. This region is usually so called "field weakening region". To avoid this, constant *v/f* principle is also violated at these frequencies.

Since the stator flux is maintained constant which is independent of the change in supply frequency, the torque developed depends only on the slip speed. So by regulating the slip speed, the torque and speed of an AC Induction motor can be controlled with the constant *v/f* principle.

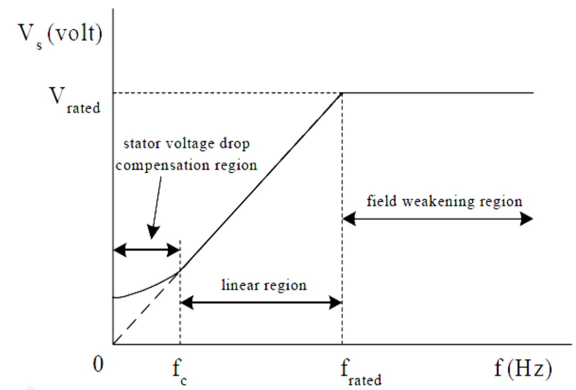

Figure.2. Stator voltage versus frequency profile under v/f control

3. Proposed Scheme

A new method of speed estimation is used in which the slip is calculated by evaluating the various power stages of an induction machine from input to the output..

The power transferred from the stator to rotor of an induction machine when operating on a certain load is expressed by equation (5).

$$P_2 = \frac{2\pi N_S T}{60} watts \quad (5)$$

Total mechanical power developed by rotor is given by

$$P_{Mech} = \frac{2\pi NT}{60} watts \quad (6)$$

Where,

Ns=Synchronous speed of RMF in RPM
N=Actual speed of the rotor in RPM
T=Torque developed in NM.

Rotor copper loss is expressed as

$$\text{Rotor Cu loss} = \frac{2\pi N_S T}{60} - \frac{2\pi NT}{60} \quad (7)$$

= S x Power input to rotor

Where,

S= Slip

Therefore,

$$Slip = \frac{Total.rotor.cu.loss}{Power.input.to.rotor} \qquad (8)$$

Once the slip is calculated the actual speed of the rotor can be calculated as

$$N = (1 - S)N_S \qquad (9)$$

Thus the actual speed of the rotor is estimated by calculating the rotor power input and the rotor copper loss. The values of input power to rotor and rotor losses are calculated from the name plate detail and the measured data which includes RMS values of stator voltage and current, stator resistance and reactance.

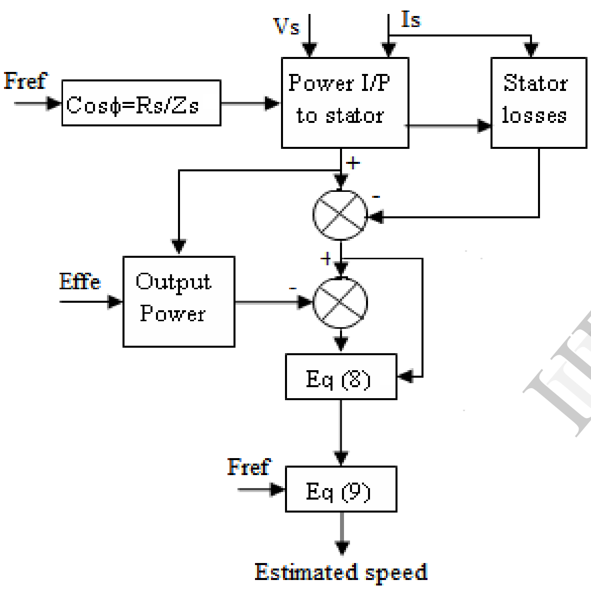

Figure.3. Slip and Speed Estimation

Figure.3 depicts the block diagram for calculating slip and speed.

Where,

V_s = Stator Phase voltage
I_s = Stator phase current
Fref = Reference frequency according to set speed.
Effe = Efficiency of the machine

The slip and speed is calculated by using equations (8) and (9).The various stages involved in computing losses are as follows,

Power input to stator (P_1) = $3V_sI_s\cos\phi$
Stator losses = Cu loss + Iron loss
= $(3I_s^2R_s) + (2.5\%\ P_{in})$
Power input to rotor (P_2) = P_1 – Stator losses
Mechanical power output (P_m) = $P_1 \times$ Efficiency
Rotor losses = $P_2 - P_m$

4. Block Diagram

The proposed scheme consist of a slip estimator in which the slip is calculated using the available data's such as stator voltage, stator current, rotor resistance and reactance, efficiency. The estimated speed is compared with the set speed and a conventional PI controller is used for speed control which controls the PWM generator. The inverter controls the stator voltage and frequency of the machine according to the commanded speed.

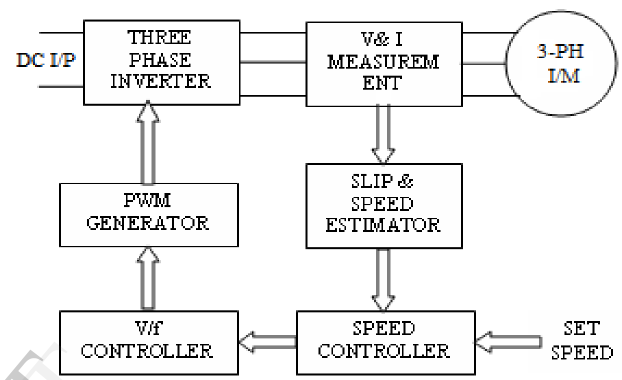

Figure.4. Block diagram for the proposed scheme

A conventional PI controller is used as speed controller. It is one of the common approaches used for speed control of industrial drives because of its simplicity. The Kp and Ki values are selected as 0.5 and 0.077 respectively based on the system response and controller parameters. A slip speed regulator is included at the output of PI controller for reducing the steady state error at all speeds.

Compensation for the stator resistance voltage drop is done by adding a voltage component proportional to the measured stator current. This method provides the torque even under low speeds

In figure.5 the block diagram for stator IR compensation is shown in which F_{ref} is the reference frequency corresponding to the set speed, I_{rms} is the measured stator current, R_s is the stator resistance, V_{rat} the rated supply voltage and F_{rat} the rated frequency. This entire block controls the modulation index (MI) of the inverter. The mathematical calculation involved in stator compensation is simple and they can be performed by using low end microcontrollers which supports in low cost applications.

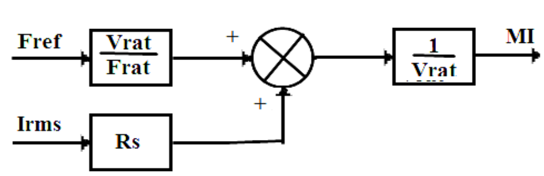

Figure.5. Stator resistance compensation

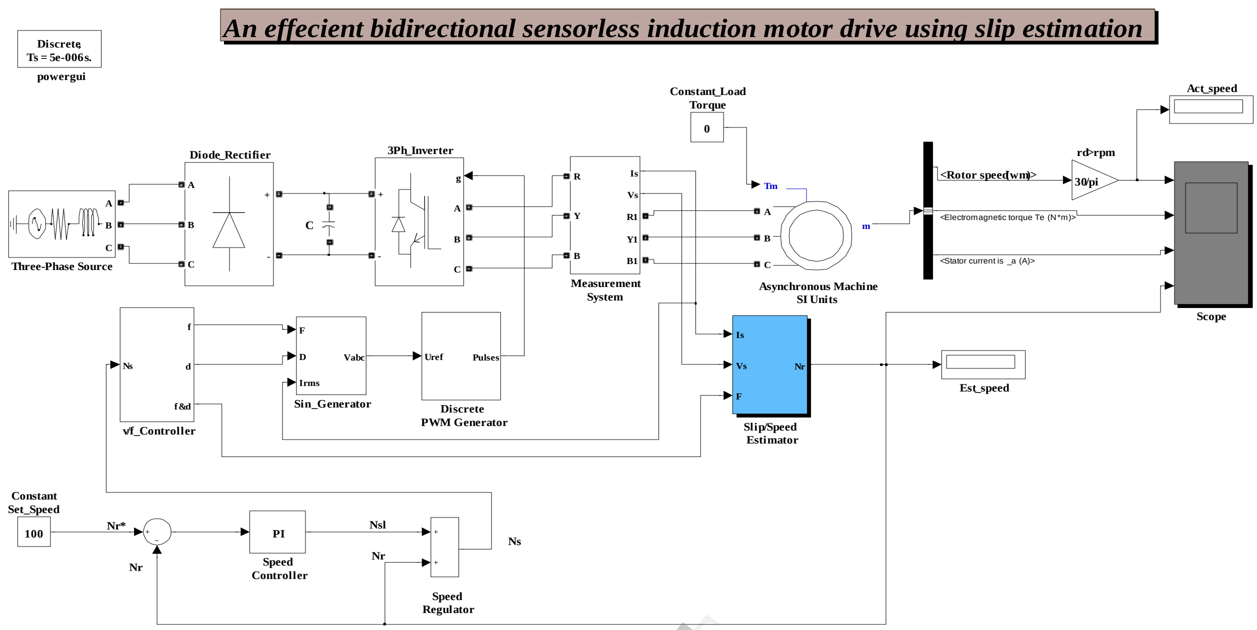

Figure.6. Simulation model using MATLAB

5. Simulation of Proposed Scheme

A model for the proposed induction motor drive was designed using MATLAB/SIMULINK software as shown in figure.6.The data of the induction machine used for simulation is given in table-1.

Table .1. Machine Data

PARAMETERS	VALUES
Power: HP (KW)	5.4 (4)
Rated voltage	400V
Speed	1430 RPM
Rotor type	Squirrel Cage
Stator Resistance &Inductance	R_s=1.405 ohms L_s=5.839mH
Efficiency	90%

Simulation is done for both forward and reverse directions and from the results it was observed that the actual speed of the motor is very close to the set speed with low steady state error.

The simulation was also done under no load condition and with a load torque of 10 NM and the speed is found to be precisely under control even at very low speeds.

6. Results and Discussion

The results of the proposed scheme were depicted from figure-7 to figure-11 for various cases such as, starting, speed change in both forward and reverse directions, sudden reversal and load impact.

6.1. Case-1: No load starting (Forward)

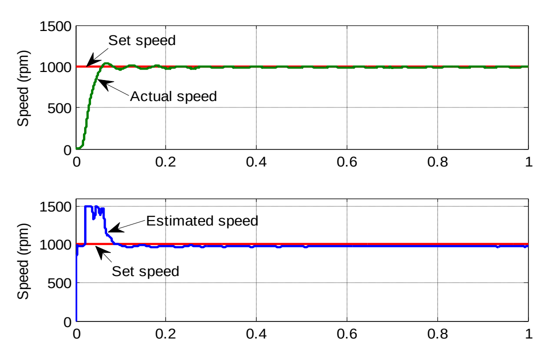

Figure.7. Estimated speed and Actual speed for reference speed 1000 Rpm

From figure.7 it was proved that for a set speed of 1000rpm under no load condition the estimated speed shoots up at starting and settles down to the set speed after 0.3 sec

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The actual sped of the rotor has a smooth increase in speed and settles to reference speed after 0.3 sec. The response was found to be identical but negative for reverse operation.

6.2. Case-2: No load step speed change (Forward)

Figure.8 depicts the response of the drive for step speed change in forward direction. Initially the reference speed was 500rpm and the speed was suddenly raised to 1000rpm and is maintained for 1 sec then it was reduced back to 500rpm.

The plot of estimated and actual speed found to be very close to each other and steady state is attained after 0.5sec for both speeds.

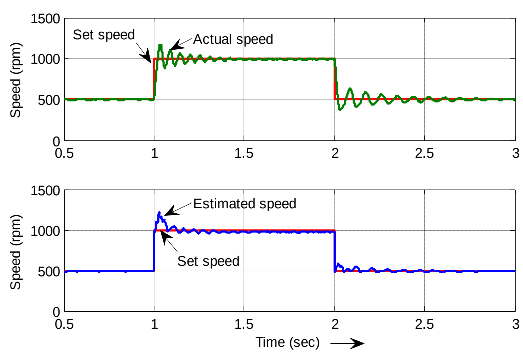

Figure.8. Estimated speed and Actual speed for step speed change in forward direction

6.3. Case-3: No load step speed change (Forward to Reverse)

The response of drive for speed change from forward to reverse direction with a reference speed of 500rpm was shown in figure.9. There was a good agreement between the estimated and actual speed even for sudden speed reversal.

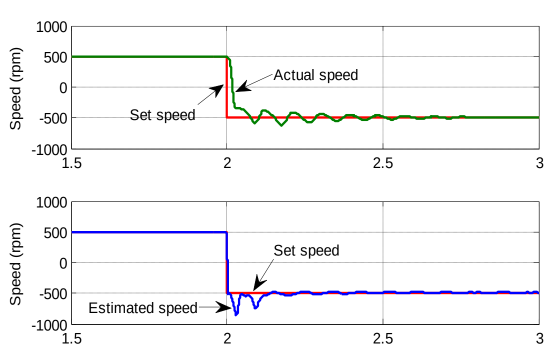

Figure.9. Estimated speed and Actual speed for speed change from 500 Rpm to -500 Rpm

6.4. Case-4: No load step speed change (Reverse)

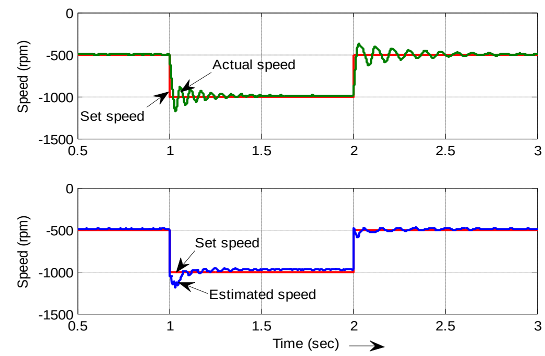

Figure.10. Estimated speed and Actual speed for step speed change in reverse direction.

The plots in figure.10 describe the drive response for step speed change in reverse direction. The response is similar to that shown in figure-9 but in reverse direction and it proves that the drive operation is satisfactory in both forward and reverse directions

6.5. Case-5: With load torque 10 NM (Forward)

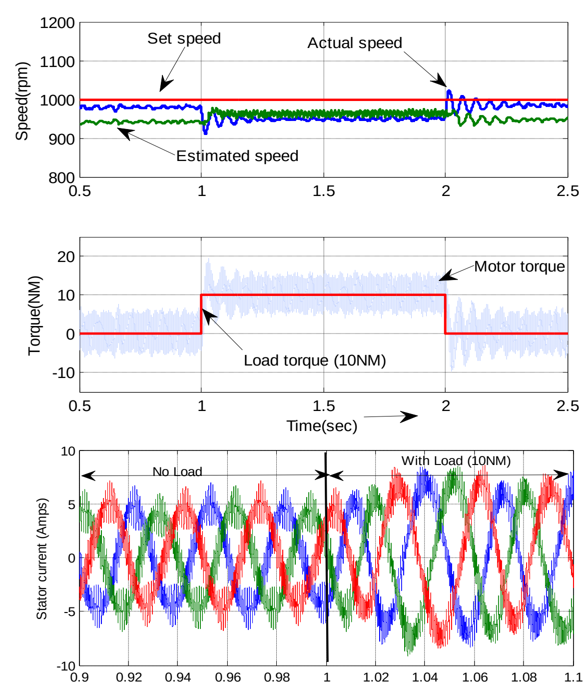

Figure.11. Estimated speed, Actual speed, Load torque, Motor torque and stator current for reference speed 1000 rpm and with load torque of 10NM.

For analyzing the performance of the drive on application of load, a load torque of 10NM was applied suddenly with a reference speed of 1000rpm.Figure.11depicts the drive response under loaded condition and was found to be satisfactory.

7. Conclusion

A new closed loop scalar controlled sensorless induction motor drive has been proposed. As the proposed method uses the machine name plate data's and the measured stator voltage and current it is very simple and cheap. It is capable of supplying load torque even under low speeds. The Simulation result shows that good closed loop regulation can be achieved. As there are no speed sensors, the cost towards sensors and cables are reduced and also the interference related to speed sensors are eliminated.

The proposed control scheme offer energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, centrifugal pump and compressor load applications. It is therefore concluded that instead of going for complex vector control we can incorporate the proposed scheme for some common industrial applications which is very simple in construction and very cheap.

8. References

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