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# Dynamic Input Current Low-Frequency Ripple Evaluation and Reduction by Inverter with Variable-Speed, Sensor less Induction Motor Drive

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## ABSTRACT:

*The control of IM variable speed drives often requires control of machine currents, which is normally achieved by using a voltage source inverter. We propose a modified control scheme that includes the torque control and a current regulated PWM inverter to avoid the undesirable trips due to transient currents. In this system, two PI controllers are used to regulate the average value of torque and speed. The output of the P-I regulators forms the q-axis reference in a synchronously rotating reference frame. The open loop control strategy in an existing v/f drive can be replaced by the proposed close-loop control strategy without requiring any additional power components or the physical sensors. The proposed strategy appears to be a good compromise between the high-cost, high-performance field-oriented drives and the low-cost, low-performance v/f drives. In this paper, a new speed sensorless control strategy for IM is proposed that includes the speed control, torque control and current regulation. The drive is operated under torque control with an phase voltages, line currents, flux, torque and rotor speed. An active or passive-type low-pass filter (LPF) with narrow bandwidth is used to filter out the high frequency components in the ac current waveform.*

## INTRODUCTION

The widespread industrial use of induction motor (IM) has been stimulated over the years by their relative cheapness, low maintenance and high reliability. The control of IM variable speed drives often requires control of machine currents, which is normally achieved by using a voltage source inverter. A large number of control strategies have been registered so far. The volts per hertz (v/f) IM drives with inverters are widely used in a number of industrial applications promising not only energy saving, but also improvement in productivity and quality.

The low cost applications usually adopt v/f scalar control when no particular performance is required. Variable-speed pumps, fans are the examples. For those applications which require higher dynamic performance than v/f control, the dc motor like control of IM that is called, the field oriented control (FOC) is preferred. During the last few years, a particular interest has been noted on applying speed sensor less FOC to high performance applications that is based on estimation of rotor speed by using the machine parameters, instantaneous stator currents and voltages.

## PROPOSED SCHEME

Fig. 1 shows the block diagram of the proposed scheme. It consists of a speed (frequency loop), a torque loop, and a current regulator. The output of speed/frequency regulator represents the torque reference for the torque loop. The torque regulator generates the q-axis current command $i_{qe}^*$ The d axis current command $i_{qe}^*$ is directly generated from the reference rotor flux $\psi_r^*$ as given by (1. This eliminates an additional PI controller and reduces the computational burden. These dc commands expressed in synchronously rotating reference after transformation to the three phase current commands are than compared with the actual three phase currents (reconstructed waveforms) to generate the switching signals for the inverter. In the proposed scheme, all the feedback signals including the stator currents and stator voltages are estimated/ reconstructed from the dc link quantities.

$$i_{de}^* = \frac{\psi_r^*}{L_m} \qquad (1)$$

## RECONSTRUCTION OF STATOR VOLTAGES & CURRENTS FROM DC LINK

As indicated in the stator flux, torque and speed can be derived from the stator voltages and currents expressed in d-q reference frame. The phase currents and voltages are related to the dc link current and voltage by inverter switching states. A voltage source inverter-IM drive is shown in Fig. 2 where Vdc is the dc link voltage, Idc is the instantaneous dc link current and ia, ib, ic are the instantaneous three-phase winding currents. Generally, IGBTs associated with snubber protection and feedback diode are used as switch in inverters. When a switch is being turned-on and the conducting diode at the same leg is being blocked off by this turn-on, because of the reverse recovery effect of diode, this leg is in fact shorted through at this moment such that a positive current spike will appear at the dc link side. To establish the basic relationship between dc link current, winding currents and inverter switching pattern, the switches shown in Fig. 2 are considered as ideal; the diode recovery effect and the snubber action are not considered.

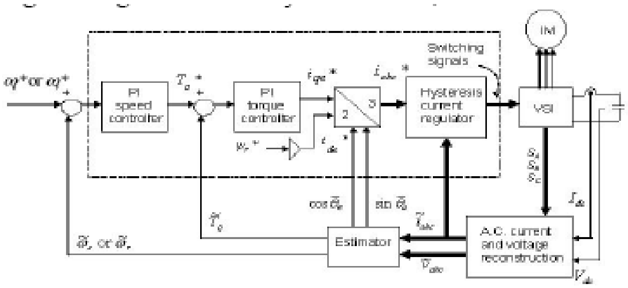


Figure 1. Block diagram of the proposed scheme.

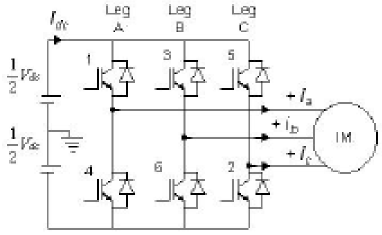


Figure 2. Voltage source inverter fed induction motor drive

### A. Space-Vectors

During normal state, there are eight switching states of inverter which can be expressed as space voltage vector (SA,SB,SC) such as shown in table

| Sa | Sb | Sc |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 0 | 1 |

| | | |
|---|---|---|
| 0 | 1 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 0 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |
| 1 | 1 | 1 |

SA =1 means upper switch of leg A is on while the lower one is off, and vice versa. The same logic is applicable to SB and SC also. Amongst above eight voltage vectors, (0,0,0) and (1,1,1) are termed as zero vectors while the other six as active vectors. The switching vectors describe the inverter output voltages

## B. Basic Principle of Phase Voltage & Line Current Reconstruction

For different voltage vectors, the phase voltage that will appear across stator winding can be determined by circuit

observation. This is summarized in Table 1. It is assumed that the stator winding is star connected. From this table, the expressions for the reconstruction of three phase voltages are as follows (assuming no dwelling time):

$$\tilde{v}_a = \frac{V_{dc}}{3}(2S_A - S_B - S_C) \tag{2}$$

$$\tilde{v}_b = \frac{V_{dc}}{3}(-S_A + 2S_B - S_C) \tag{3}$$

$$\tilde{v}_c = \frac{V_{dc}}{3}(-S_A - S_B + 2S_C) \tag{4}$$

The stator voltages as expressed in stationary d-q frame are:

$$\tilde{v}_{qs}{}^{s} = \tilde{v}_a = \frac{V_{dc}}{3}(2S_A - S_B - S_C) \tag{5}$$

$$\tilde{v}_{ds}{}^{s} = \frac{1}{\sqrt{3}}(\tilde{v}_b - \tilde{v}_c) = \frac{V_{dc}}{\sqrt{3}}(S_B - S_C) \tag{6}$$

TABLE I. DC LINK CURRENT & PHASE VOLTAGES

| *Voltage Vector* $(S_A, S_B, S_C)$ | $v_a$ *(V)* | $v_b$ *(V)* | $v_c$ *(V)* | $I_{dc}$ *(A)* |
|---|---|---|---|---|
| (0,0,0) | 0 | 0 | 0 | 0 |
| (0,0,1) | $-V_{dc}/3$ | $-V_{dc}/3$ | $2V_{dc}/3$ | $+ i_c$ |
| (0,1,0) | $-V_{dc}/3$ | $2V_{dc}/3$ | $-V_{dc}/3$ | $+ i_b$ |
| (0,1,1) | $-2V_{dc}/3$ | $V_{dc}/3$ | $V_{dc}/3$ | $- i_a$ |
| (1,0,0) | $2V_{dc}/3$ | $-V_{dc}/3$ | $-V_{dc}/3$ | $+ i_a$ |
| (1,0,1) | $V_{dc}/3$ | $-2V_{dc}/3$ | $V_{dc}/3$ | $- i_b$ |
| (1,1,0) | $V_{dc}/3$ | $V_{dc}/3$ | $-2V_{dc}/3$ | $- i_c$ |
| (1,1,1) | 0 | 0 | 0 | 0 |

The relationship between the applied active vectors and the phase currents measured from the dc link is also shown in Table 1. It is clear that at-most, one phase current can be related to the dc.-link current at every instant.

The Reconstruction of phase currents from the dc-link current can be achieved easily only if two active vectors are present for at least enough time to be sampled. Fortunately, as indicated in, for most PWM strategies, two phase currents can be sampled by looking at the dc link current over every PWM period. If the PWM frequency is high enough, the phase current does not change much over one PWM period. Hence, a reconstructed current derived from the dc link current gives a reasonable approximation of the actual current. In terms of switching states and Idc, the three ac line currents can be derived as follows

$$\tilde{i}_a = I_{dc}(S_A - \frac{S_B}{2} - \frac{S_C}{2}) \tag{7}$$

$$\tilde{i}_b = I_{dc}(-\frac{S_A}{2} + S_B - \frac{S_C}{2}) \tag{8}$$

$$\tilde{i}_c = I_{dc}(-\frac{S_A}{2} - \frac{S_B}{2} + S_C) \tag{9}$$

The stator currents as expressed in stationary d-q frame are:

$$\tilde{i}_{qs}^{s} = \tilde{i}_{a}\,; \quad \tilde{i}_{ds}^{s} = \frac{1}{\sqrt{3}}(2\tilde{i}_{b} + \tilde{i}_{a}) \qquad (10)$$

$$\text{or } \tilde{i}_{qs}^{s} = \tilde{i}_{a}\,; \quad \tilde{i}_{ds}^{s} = \frac{-1}{\sqrt{3}}(2\tilde{i}_{c} + \tilde{i}_{a}) \qquad (11)$$

$$\text{or } \tilde{i}_{qs}^{s} = -(\tilde{i}_{b} - \tilde{i}_{c})\,; \quad \tilde{i}_{ds}^{s} = \frac{1}{\sqrt{3}}(\tilde{i}_{b} + \tilde{i}_{c}) \qquad (12)$$

### C. Filter Stage

The dc link current Idc consists of a train of short duration pulses and has information about the stator currents of all the three phases. By using (7)-(9), these pulses can be segregated into three ac line currents. Generally, an active or passive-type low-pass filter (LPF) with narrow bandwidth is used to filter out the high frequency components in the ac current waveform thus obtained from Idc. This filter actually works as an integrator. However, a LPF causes phase lag and amplitude attenuation that vary with fundamental frequency. In this paper, we propose the use of band-pass filter with adaptable gain to overcome this problem. The transfer function of the filter is given below:

$$y = \left[\left(\frac{sT}{1+sT}\right)\left(\frac{T}{1+sT}\right)\right]x \qquad (13)$$

where x, y and T are input, output and time constant of the band-pass filter. For sT >>1; (1+sT) Therefore,

$$y = \frac{1}{s}x \qquad (14)$$

## ESTIMATION OF FEEDBACK SIGNALS FROM RECONSTRUCTED QUANTITIES:

The feedback signals required to simulate the proposed scheme i.e., flux, torque and rotor speed are estimated as:

Estimation of Flux

The stator flux in stationary d-q frame $\psi_{ds}^{s}, \psi_{qs}^{s}$ and thus $\psi_{s}$ can be obtained on integration of the phase voltage minus voltage drop in the stator resistance Rs [1]:

$$\tilde{\psi}_{ds} = \int\left(\tilde{v}_{ds}^{s} - R_{s}\tilde{i}_{ds}^{s}\right)dt \qquad (15)$$

$$\tilde{\psi}_{qs} = \int\left(\tilde{v}_{qs}^{s} - R_{s}\tilde{i}_{qs}^{s}\right)dt \qquad (16)$$

$$|\tilde{\psi}_{s}| = \sqrt{\tilde{\psi}_{ds}^{2} + \tilde{\psi}_{qs}^{2}} \qquad (17)$$

$$\cos\tilde{\theta}_{e} = \frac{\tilde{\psi}_{ds}}{|\tilde{\psi}_{s}|}\,; \quad \sin\tilde{\theta}_{e} = \frac{\tilde{\psi}_{qs}}{|\tilde{\psi}_{s}|} \qquad (18)$$

where is the stator flux angle with respect to the q-axis of the stationary d-q frame.

Estimation of Torque

The electromagnetic torque can be expressed in terms of stator

currents and stator flux as follows:

$$\tilde{T}_{e} = \frac{3P}{4}\left(\tilde{\psi}_{ds}\tilde{i}_{qs}^{s} - \tilde{\psi}_{qs}\tilde{i}_{ds}^{s}\right) \qquad (19)$$

Estimation of Synchronous Speed &Rotor Speed

The synchronous speed $\tilde{\omega}_{e}$ can be calculated from the expression of the angle of stator flux as:

$$\tilde{\theta}_{e} = \tan^{-1}\frac{\tilde{\psi}_{ds}}{\tilde{\psi}_{qs}} \qquad (20)$$

$$\tilde{\omega}_{e} = \frac{d\tilde{\theta}_{e}}{dt} \qquad (21)$$

To obtain the rotor speed $\tilde{\omega}_{r}$, simple slip compensation can be derived using the steady-state torque speed curve for the machine being used:

$$\tilde{\omega}_{sl} = K_{s}\tilde{T}_{e} \qquad (22)$$

where Ks is the rated slip frequency/rated torque and it can be derived from the name plate of the machine. Alternately, if the rotor flux r ψ is assumed as constant, the slip speed can also be calculated as:

$$\tilde{\omega}_{sl} = \frac{R_{r}'}{L_{r}'}\frac{\tilde{i}_{qs}^{s}}{\tilde{i}_{ds}^{s}} \qquad (23)$$

The rotor speed is than given by,

$$\tilde{\omega}_{r} = \tilde{\omega}_{e} - \tilde{\omega}_{sl} \qquad (24)$$

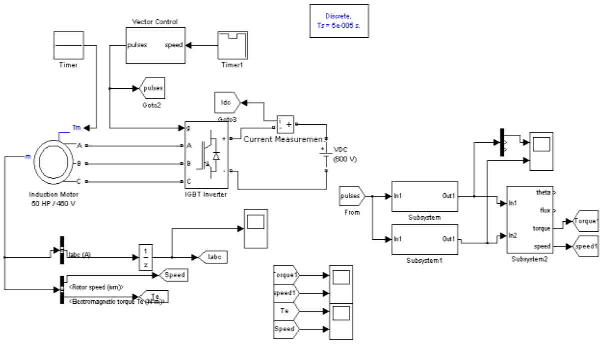
## PROPOSED CONTROL STRATEGY

Majority of IM drives are of open-loop, constant-v/f, voltage source- inverter type. These drives are cost effective but they offer sluggish response. Due to high current transients during the torque changes, they are subject to undesirable trips. To avoid the un-necessary trips, the control parameters like acceleration/deceleration rate has to be adjusted (reduced) according to the load. This results in underutilization of torque capability of the motor. Thus the drawback of v/f drive can be attributed to lack of torque control.

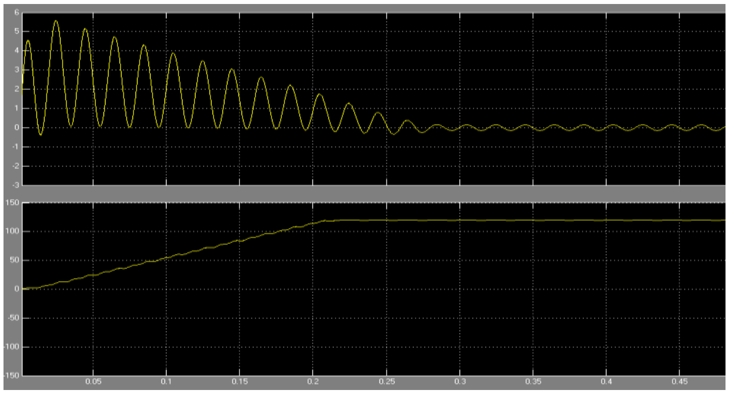
This is the reason why open-loop, constant-v/f drives are mostly used in low performance fan and pump type loads. In this paper, we propose a modified control scheme that includes the torque control and a current regulated PWM inverter to avoid the undesirable trips due to transient currents. As shown in Fig.1, the feedback signals i.e. torque and rotor speed are obtained from the dc link quantities and hence from the reconstructed line currents and phase voltages. The accuracy of reconstructed waveforms depends upon the sampling rate. Higher the sampling rate less is the error between the actual and reconstructed waveforms. In a hard switching inverter, the switching frequency is limited to a typical value of a few kHz.

This limits the sampling rate of dc current and hence the update rate of torque and rotor speed. Consequently, closing the loop directly on the instantaneous value of the estimated torque now becomes difficult because estimation error during a PWM cycle could become significantly high. In order to use the estimated torque in a more robust manner, a control strategy should use the averaged torque instead of the instantaneous value. This leads to the control strategy depicted in Fig.1. In this system, two PI controllers are used to regulate the average value of torque and speed. The output of the P-I regulators forms the q-axis reference in a synchronously rotating reference frame.

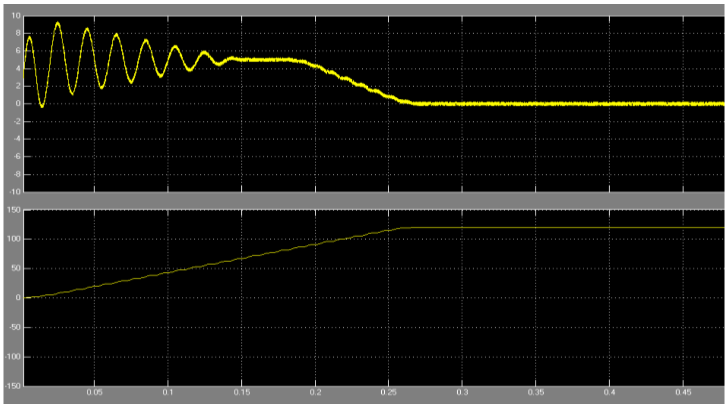
## MAT LAB DESIGN OF CASE STUDY AND RESULTS



**Free-acceleration characteristics:**

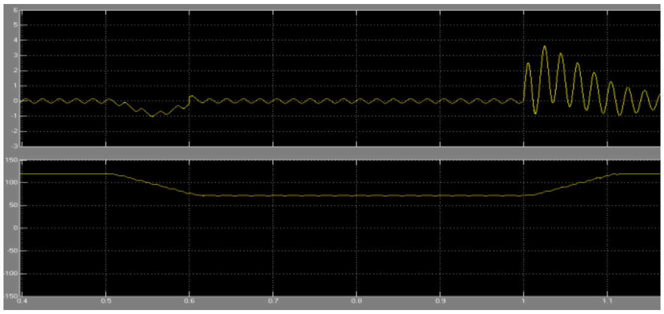


(a) Estimated values

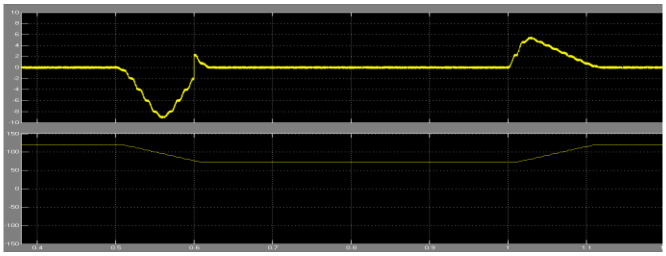


(b) Actual values

**Variation in rotor speed and electromagnetic torque for step changes in reference speed:**

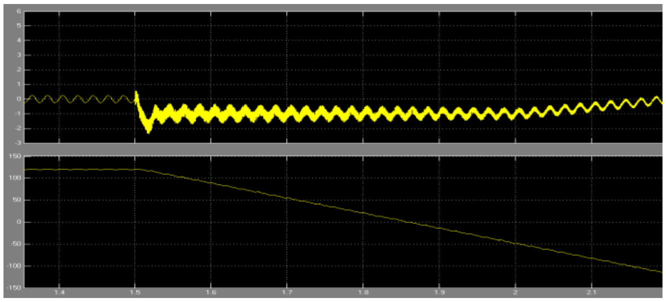


(a) Estimated values

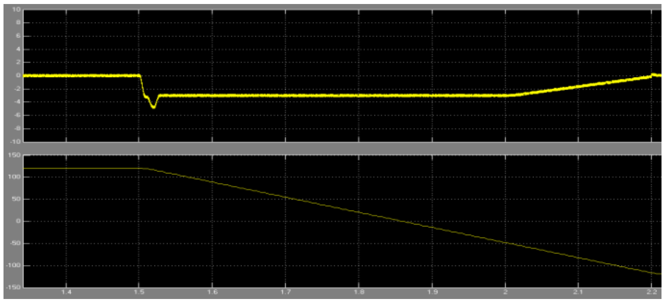


(b) Actual values

**Variation rotor speed and electromagnetic torque during reversal:**



(a) Estimated values



(b) Actual values

# CONCLUSION

In this paper, a new control strategy for induction motor drive is proposed. The drive is operated under torque control with an outer speed loop and is very similar to open-loop v/f drive in terms of power components and sensors required. Due to the inclusion of torque control loop, the drive response is fast and stable. Simulation results confirm the effectiveness of the proposed scheme. The technique uses only dc link voltage and dc link current measurements to generate the estimates of phase voltages, line currents, flux, torque and rotor speed. If the dc link voltage is assumed as constant, only one current sensor in the dc link is sufficient to give the estimates of all required feedback variables. Moreover, the same current sensor that is already available in the dc link of an open-loop v/f drive for protection purpose can be used. Thus the open loop control strategy in an existing v/f drive can be replaced by the proposed close-loop control strategy without requiring any additional power components or the physical sensors. The proposed strategy appears to be a good compromise between the high-cost, high-performance field-oriented drives and the low-cost, low-performance v/f drives.

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