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Speed Control of 3 Φ Induction Motor Using Volts Hertz Control Method

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Abstract: This paper deals with design and analysis of a three phase induction motor drive using IGBT's at the inverter power stage. The hardware implementation of volts hertz control method is done using dsPIC30F2010 digital signal controller. The dsPIC30F2010 contain extensive DSP functionality within high performance 16-bit microcontroller architecture. Using proposed method speed of induction motor can be varied from 13Hz to 50Hz. The Closed-loop speed control method for induction motor that provides high output torque and nearly 2% steady-state speed error at any frequency is presented.

Keywords: Constant V/f, digital signal controller, voltage boost, induction motor.

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1. INTRODUCTION

The motor control industry is a strong aggressive sector. Each industry to remain competitive must reduce costs but also has to answer to power consumption reduction and EMI radiation reduction issues imposed by governments and power plant lobbies. To preserve the environment and to reduce green house effect gas emission, governments around world wide are introducing regulation requiring white good manufactures and industrial factories to produce more energy efficient appliances. This is the reason why appliance designer's and semiconductor suppliers are now interested by the design of low cost and energy efficient variable speed drives. The results of these constraining factors are the need of enhanced algorithms [8].

When power is supplied to an induction motor at the recommended specifications, it runs at its rated speed. With tremendous advances in power electronics devices over last couple of years, the speed and torque control are now commonly accomplished by supplying variable voltage and variable frequency via an adjustable frequency control to an IM [1]. These electronics not only control the motor's speed, but can improve the motor's dynamic and steady state characteristics [4][10]. In addition electronics can reduce the system's average power consumption and noise generation of the motor. Induction motors are designed to operate at a constant input voltage and frequency. We can effectively control an Induction motor in a closed loop speed application if the frequency of the motor input voltage is varied [3]. As you decrease the frequency of the drive voltage, you also need to decrease the amplitude by a proportional amount. Otherwise, the motor will consume excessive current at low input frequencies. This control method is called "Volts Hertz Control" [2][4][8]. In practice, a custom Volts-Hertz profile is developed that ensures that motor operates correctly at any speed setting.

This application describes the design of a 3-phase induction motor drive with volts hertz control in closed loop (V/Hz) using 16 bit high-performance digital signal controllers. The system is designed as motor control system for driving medium power, 3-phase AC induction motors [7][8]. The dsPIC30F2010 devices contain extensive Digital Signal Processor (DSP) functionality within high-performance 16-bit microcontroller (MCU) architecture. The use of this 16 bit digital signal controllers yields enhanced operations, fewer system components, lower system cost and increased efficiency [5].

The various graphs/waveforms are analyzed and studied on storage oscilloscope. The closed loop hardware control of the motor is developed and the results are studied and analyzed [3] [9].

2. ANALYSIS OF THE EQUIVALENT CIRCUIT MODEL

The fundamental steady-state equivalent circuit of the induction motor is shown in Figure 1. The rotating air gap flux induces an emf E_s in the stator winding. This emf has the value of applied voltage V_s minus the voltage drop due to the stator leakage impedance, I_s $(R_s + jX_{sl})$ [2,4]. If the rotating flux wave has a sinusoidal space distribution and the flux linking each stator turn has a sinusoidal time variation, the instantaneous flux linking a full span stator turn is

$$\Psi = \Psi_m \operatorname{Sin}\omega t. \qquad (1)$$

The induced emf per turn is,

$$E_s = N * \frac{d\Psi m}{dt}$$

$$E_s = E_{ag\,*}\,\text{Cos}\omega t.$$

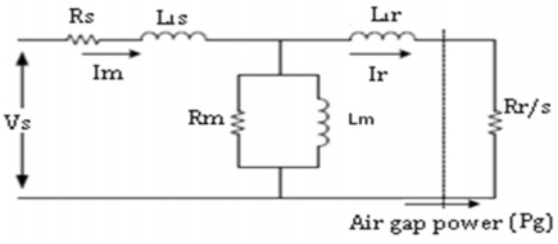

Figure 1: Equivalent Circuit of Induction Motor

Where $$E_{ag} = N * \omega_* \Psi_m \qquad (2)$$

$$E_{ag} \propto f * \Psi_m$$

The air gap flux rotating at ω_s cuts the stationary rotor again and an emf Er is induced in the rotor. Since rotor is short circuited, this induced emf sets up a current I_r given by

$$I_r = \frac{E_r}{Z_r}$$

$$\Psi m \propto \frac{E_m}{\omega} \qquad (3)$$

When ratio is constant, the constant air gap flux is obtained [4]. A simple per phase equivalent circuit model of an induction motor is a very important tool for analysis and performance prediction under steady-state conditions. Figure 1 Shows the development of a per phase transformer-like equivalent circuit [7]. The various power expressions can be written form the equivalent circuit of Figure 1 as follows:

Output power: $$P_o = Pg - P_{lr} = 3I_r^2 R_r\left(\frac{1-s}{s}\right) \qquad (4)$$

Since the output power is the product of developed torque T_e and speed ωm, T_e can be expressed as

$$T_e = \frac{Po}{\omega_m} \qquad (5)$$

$$T_e = \frac{3}{\omega_m} I_r^2\; R_r\left(\frac{1-s}{s}\right) = \left(\frac{p}{2}\right) I_r^2\;\frac{R_r}{s\omega_e} \qquad (6)$$

If the core loss resistor R_m has been dropped and the magnetizing inductance L_m has been shifted to the input. This approximation is easily justified for an integral horsepower machine, where $(R_s + j\omega_e L_{ls}) << \omega_e L_m$.

The current I_r is figured out by:

$$I_r = \frac{V_s}{\sqrt{\left(R_s + \frac{R_r}{s}\right)^2 + \omega e^2\left(L_{Is} + L_{lr}\right)^2}} \qquad (7)$$

Substituting Equation (7) in (6) yields

$$T_e = 3\left(\frac{p}{2}\right)\frac{R_r}{s\omega_e}\,\frac{V_s^2}{\left(R_s + \frac{R_r}{s}\right)^2 + \omega_e^2\left(L_{ls} + L_{lr}\right)^2} \qquad (8)$$

A further simplification of the equivalent circuit can be made by neglecting the stator parameters R_s and L_{ls}. Then, the equation (8) can be simplified as

$$T_e = 3\left(\frac{p}{2}\right)\left(\frac{V_s}{\omega_e}\right)^2\left(\frac{\omega_{sl} R_r}{R_r^2 + \omega_{sl}{}^2 L_{lr}{}^2}\right) \qquad (9)$$

In a low-slip region, (9) can be approximated as

$$T_e = 3\left(\frac{p}{2}\right)\frac{1}{R_r}\left(\Psi_m\right)^2 \omega_{sl} \qquad (10)$$

Where $R_r^2 >> \omega_{sl}^2 L_{lr}^2$ Equation (10) is critical for analysis because it indicated that at constant flux, the torque is proportional to slip frequency, or at constant slip frequency, torque is proportional to flux [7].

3. START-UP CONSIDERATION FOR INDUCTION MOTOR DRIVES

There are some important considerations during starting of Induction motor drives. The two of most important ones are

A. Soft –Start B. Voltage boost

3.1. Soft–Start

For static Inverter based Induction motor drives it is important to keep starting current drawn by motor within its rated value. This can achieved by

$$I_r \propto \Psi_m f_{sl} \;\text{ and }\; T_e \propto f_{sl}$$

From above two equations it is clear that if slip frequency at start or throughout all acceleration period is kept below or equal to rated slip frequency, the motor current can be kept under control.

At start s = 1 Therefore $I_r \propto f$

This suggest that starting current I_{rstart} can be limited by selecting appropriate

$f = f_{start}$ $I_s = \sqrt{I_r^2 + I_m{}^2}$ Since I_m is constant (Ψ_m = constant)

3.2. Voltage Boost Required at Start

In order to operate the motor with desired speed/torque curve, we must apply proper voltage to motor at each frequency. According to equation (3) air gap flux is directly proportional to V_s/f. When ratio is constant, constant air gap flux is obtained. Around rated frequency it is valid that stator voltage drop, $I_s\,(R_s+\mathrm{j}X_{sl})$ is negligible. But the stator voltage drop developed by the rated current stays constant even though output frequency is reduced because as frequency reduces, stator parasitic impendence starts looking more resistive. As a result percentage of input voltage dropped across it increases. This drop occupies large portion of terminal voltage. The air gap emf and flux decreases significantly, causing torque reduction. This problem can be resolved by boosting the voltage above Volts/Hertz ratio under low frequency [2] [4]. From the per phase equivalent circuit of the three phase Induction motor as shown in Figure 1.

$$V_s = E_{ag} + I_s\,(R_s + X_{sl})$$

Drop across $I_s\,X_{sl}$ can be neglected and also $I_s = I_r$

$$V_s = E_{ag} + I_r\;R_s$$

According to equation 2

$$V_s = 2\pi\,f\,N\,\Psi_m + I_r\;R_s$$

$$V_s = k\,f + I_r\;R_s$$

To keep flux Ψ_m constant V_s/f ratio is kept constant. Therefore V_s increases proportionally with frequency f.

$$V_s - I_r\,R_s = k\,f$$

But $$Vs' = V_s - I_r\,R_s$$

Therefore $$\frac{Vs'}{f} = k$$

This suggest that to $\dfrac{Vs'}{f}$ ratio constant $\left(\dfrac{V_s - I_r\,R_s}{f}\right)$ must be kept constant. The drop $I_r R_s$ increases with increase in I_r or motor torque. This means that if we are required to produce full torque at low speed, we must have a significant volts hertz “boost” at low speeds. Since required boost voltage depends upon individual motor and load characteristics, if motor load is constant fixed boost voltage is used. In case of varying load fixed boosting can produce undesirable results; therefore for varying load auto boosting using IR compensation is used [2] [4].

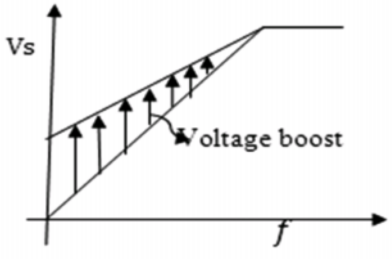

Figure 2: Voltage Boost Required to keep Constant Ψ_m to Compensate (Ir R_s) Drop

IR drop at rated frequency and full load is 4% of phase voltage and effect on air gap flux relatively insignificant. However at one tenth of rated frequency with constant Volts/Hertz’s supply, the IR drop at rated current is 40% of applied voltage causing significant reduction in the air gap emf and flux [10].

4. CONFIGURATION OF THE PROPOSED SYSTEM

The constant volts hertz control methods is the most popular method of scalar control, it controls the magnitude of the variables like frequency, voltage or current [10]. The command and feedback signals are DC quantities and are proportional to the respective variables. The purpose of the volts per hertz control scheme is to maintain the air-gap flux of AC Induction motor constant in order to achieve higher run-time efficiency [2] [4]. The magnitude of stator flux is proportional to the ratio of stator voltage & frequency. If ratio is kept constant the stator flux remains constant & motor torque will only depend upon slip frequency. The control system is illustrated in Figure 3. When stator frequency fails under a given frequency threshold (boost frequency), the voltage magnitude must be kept at given level called boost voltage to keep rotor flux magnitude constant. V_{boost} means small voltage is added to dc voltage reference to compensate stator resistance drop at low frequency. At opposite when frequency becomes higher than rated value, the voltage magnitude is kept at rated value. The stator flux is no more constant & torque decreases. The characteristic is defined by the base point of the motor. Below the base point the motor operates at optimum excitation because of the constant V/f ratio. Above this point the motor operates under-excited because of the DC-bus voltage limit. If speed is changed by maintaining V/f ratio constant, then maximum torque remains same [1] [3].

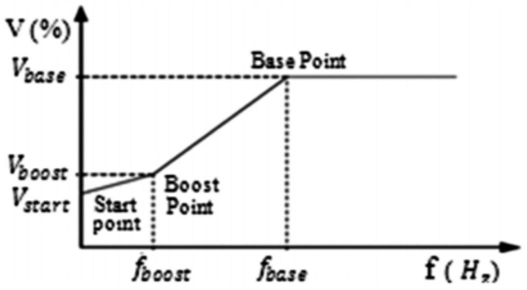

Figure 3: Voltage verses Frequency

Open-loop speed control of an induction motor provides a satisfactory variable speed drive when the transient performance characteristics are undemanding and when the motor operates at steady speeds for long periods. The demerit of this system is that it cannot be used in the presence of supply voltage fluctuations and loads disturbances. Also, when the drive requirements include rapid acceleration and deceleration, an open-loop system is unsatisfactory because the supply frequency cannot be varied quickly without exceeding the rotor breakdown frequency. However, when fast dynamic response and greater speed accuracy are needed, closed-loop control methods are essential, but a precise feedback system must be used to sense the rotor speed and adjust the inverter frequency accordingly [8] [9][10].

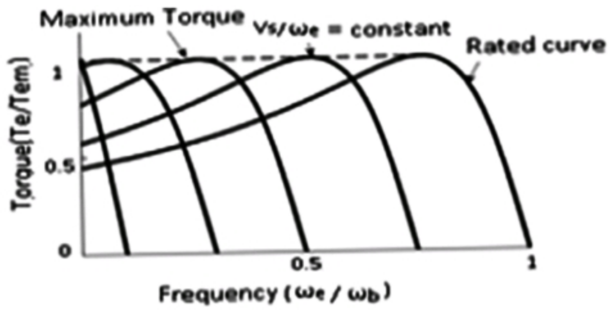

Figure 4: Torque-speed Curves with Low-speed Voltage Boost, Constant V/f Ratio

Figure 5 shows the block diagram of the Volts Hertz speed control method. The power circuit consists of a diode rectifier with single phase AC supply, capacitor filter, and PWM voltage-fed inverter [6] [7]. The frequency command ω^*_e is the control signal, neglecting the small slip frequency ω_{sl} of the machine. Based on volts hertz control theory the phase voltage command V^*_e can be generated from frequency command gain factor K, as shown, So that the flux Ψ_s remains constant.

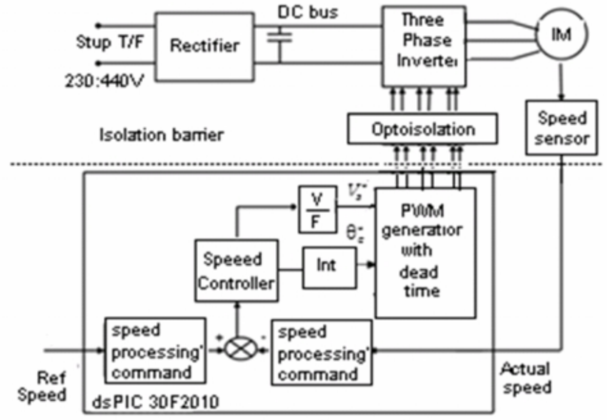

Figure 5: Block Diagram of Proposed Method

If the stator resistance and leakage inductance of the machine are neglected, the flux will also correspond to the air gap flux Ψ_m or rotor flux Ψ_r. At low speed areas, the stator resistance become significant and absorbs the major amount of the stator voltage, thus weakening the flux. Therefore, the boost voltage V_{boost} is added to compensate flux to keep it equal to rated flux and corresponding full torque become available at low frequency. The ω_e signal is integrated to generate the angle signal θ^*_e and the corresponding sinusoidal phase voltages are generated.

$$PWMA = \sqrt{2}\,V_s\,\mathrm{Sin}\theta_e^*$$

$$PWMB = \sqrt{2}\,V_s\,\mathrm{Sin}\left(\theta_e^* - \frac{2\pi}{3}\right)$$

$$PWMC = \sqrt{2}\,V_s\,\mathrm{Sin}\left(\theta_e^* - \frac{2\pi}{3}\right)$$

Then PWM controllers which are embedded in digital signal controller can generate control signals to drive the inverter [8].

If the air gap flux of the machine is kept constant in the constant torque region, it can be shown that the torque sensitivity per ampere of stator current is high, permitting fast transient response of the drive with stator current control. In variable-frequency, variable-voltage operation of a drive system, the machine usually has low slip characteristics, giving high efficiency. With low-frequency voltage boosting, the machine can always be started at maximum torque, as shown in Figure 4. The absence of high starting current in a direct-start drive reduces stress and therefore improves the effective life of the machine [3] [9].

5. EXPERIMENTAL SETUP AND RESULTS

The performances of the proposed method have been experimentally tested for different value of speed from 400 rpm to 1500rpm for different value of load. The experimental results show the effectiveness of the proposed method. Even at low frequency operation, the speed control is realized under heavy load condition. Experimental results show that good speed control accuracy can be achieved by the proposed method. As it can be seen from Figure 6 and 7, for set rpm of 1360 and 900, the rpm of motor remains in the range of set rpm with an error of +/- 10rpm. Hence, the accuracy of approximately 98%. Figure 8 and 9 shows steady state stator current response for the load as 1Kg and 2Kg. It shows that stator current remains constant for different value of speed at rated torque [2] [4] [9]. Figure 10 shows that ratio of voltage and frequency remains constant and current also remains constant for different value of load [3] [7]. Experimental results for variable load and set speed as 1360rpm.

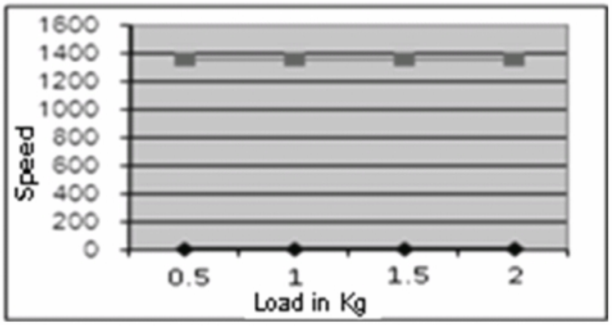

Figure 6: Characteristics of Actual rpm vs. Load for the Set Speed as 1360rpm

Experimental results for variable load and set speed as 900rpm

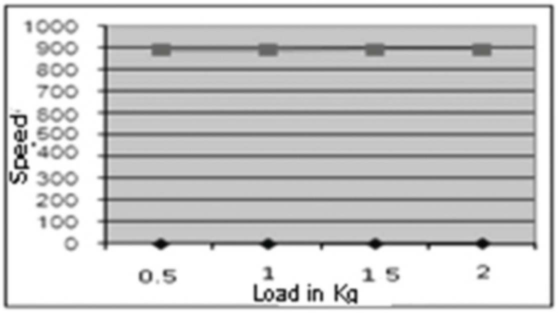

Figure 7: Charactristics of Actual RPM vs. Load for the Set Speed as 900rpm

Steady state stator current response for the load as 1 Kg.

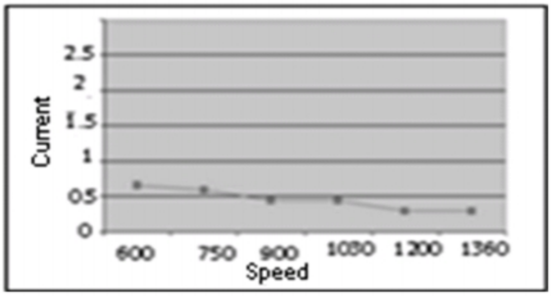

Figure 8: Characteristics of Stator Current vs. Speed for the Load as 1 Kg

Steady state stator current response for the load as 2 Kg.

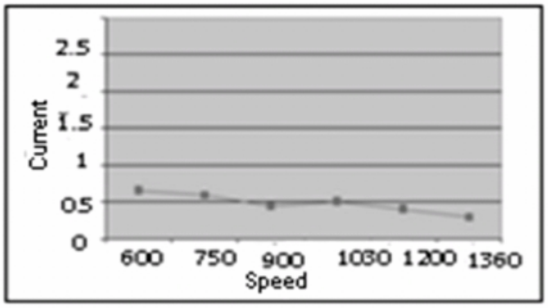

Figure 9: Characteristics of Stator Current vs. Speed for the Load as 2 Kg

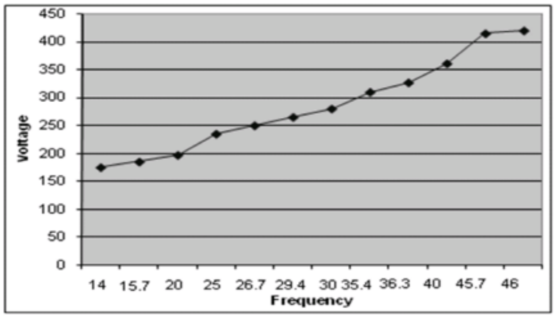

Figure 10: Stator Voltage Magnitude verses Frequency for the Load as 2 Kg

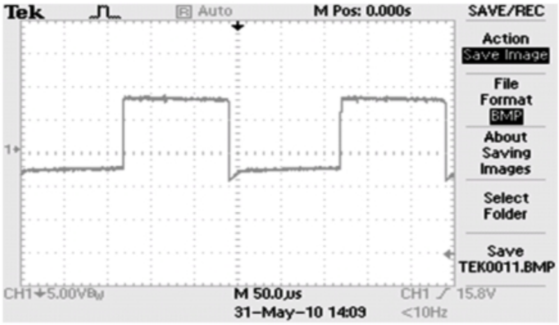

Figure 11: Gate Pulses for 1360rpm

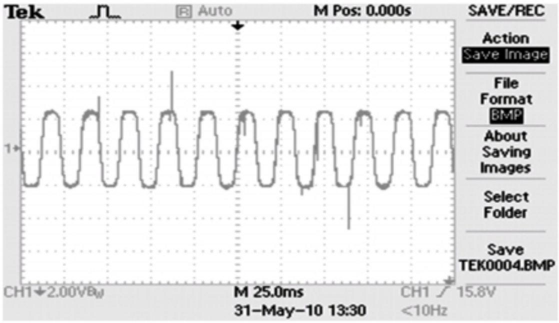

Figure 12: Current Waveforms for 1360rpm

Figure 11, 12 and 13 shows the gate pulse, current waveforms and inverter output voltage waveforms for set speed of 1360 rpm.

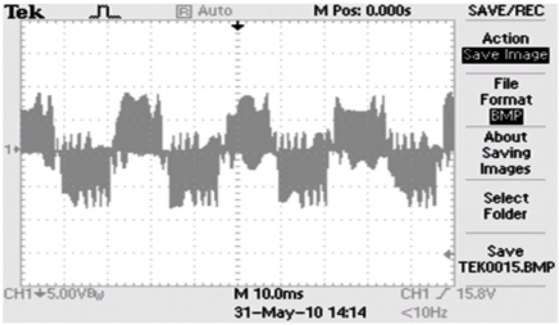

Figure 13: Waveforms of Inverter Output Voltage for 1360rpm

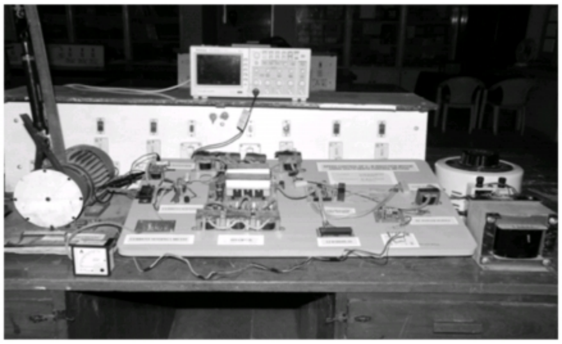

Figure 14: Photograph of Complete Hard Ware Set up

6. CONCLUSION

The paper describes the design of control stage and presents results obtained by motor. This type of motor control is well justified in applications requiring a constant *V/f* speed control such as pumps , machine tools , mills etc. An analysis of steady state equivalent circuit was done in order to establish the equations that justify use of the scalar control method.

In this proposed method, range of speed control is from 13Hz to 50Hz.The performances of the proposed method have been experimentally tested for different value of speed from 400 rpm to 1500 rpm for different value of load. The experimental results show the effectiveness of the proposed method. Even at low frequency of operation, the speed control is realized under heavy load condition. Experimental results show that good speed control accuracy can be achieved by the proposed method

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