An Improved V/F Control for High Performance Three Phase Induction Motor Drive

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Abstract **- The constant v/f control method is one of the most common speed control methods for Induction motors (IMs). In this paper the performance of constant v/f control method is improved by full compensation of the stator resistance voltage drop by the injection of low frequency boost voltage to achieve the rated torque-speed characteristic at any speed below rated speed. Also simple frequency compensation based on estimation of air-gap power and a linear motor torque-speed approximation is introduced. The dynamic performance of IM for proposed system is studied by MATLAB/SIMULINK under different load and speed variations. Further the proposed system is compared with the previous work. The simulation results show that the speed accuracy of the proposed method is improved effectively, even at low speed.**

Index Term – v/f control, constant flux, slip frequency compensation, torque and speed.

I. INTRODUCTION

Although the constant volts per hertz (v/f) control method is one of the most common variable-speed control methods for induction motors, a little has been published about it. Its practical application at low frequency is still challenging due to the following reasons: firstly, the influence of the stator resistance where at low frequency the voltage drop across it leads to decrease the air gap flux so the motor performance will be deteriorated. . Secondly, the nonlinear behaviour of the pulse-width modulation voltage-source inverter in the low voltage range makes it difficult to use constant v/f drives at frequency below 3 Hz [1]. Also, load increase or frequency decrease leads to lower the speed control accuracy with limited starting torque. One of the main drawbacks of the V/f control method appears when the drive system needs a fast dynamic response.

Different techniques have been proposed to improve the performance of the constant v/f control method for IM control, such as stator resistance compensation method, which consists of boosting the stator voltage by the magnitude of the current resistance IR drop. Vector compensation requires measurement of both voltage and current and
The stator resistance voltage drop was fully compensated by modifying the stator voltage and the slip frequency is compensated based on a nonlinear torque-speed estimate [1]. Slip compensation results in increasing the operating frequency (speed).

An auto boost voltage method was proposed to compensate the voltage drop across the stator leakage impedance and slip frequency compensation method to decrease the speed error by calculating the d-q currents of IM [2].The popular methods of an automatic torque boost for v/f inverters are introduced, that is the closed-loop magnitude flux control [3-5] .

Fully compensation for the stator resistance voltage drop (torque-boost) by modifying the stator flux and the simple frequency compensation based on the estimation of the air gap power and a linear torque speed approximation was also introduced [6]. In [7] torque control is performed by a magnetic flux compensation control loop and a current distortion correction control loop so that the motor can automatically generate the torque corresponding to the load torque. Two simple stator resistance voltage drop compensation methods based on IM model in rotating reference frame were proposed to maintain the stator flux magnitude constant in steady state [8]. In [9] an auto boost controller was designed to overcome the decrease in voltage of the stator resistance and modified flux observer with high-pass filter was employed to estimate the slip frequency.

The direct and quadrature component of the stator current in the stator voltage oriented reference frame was calculated to implement the vector compensation for stator resistance drop [10]. A novel open loop scalar control method for induction motor where the rotor flux vector is estimated to decouple the stator current. The slip frequency and the current resistant (IR) stator voltage drop were estimated and compensated based on the flux and torque component of the stator current in the rotor flux oriented reference frame [11].

Two techniques to improve the performance of the inverter-induction motor drive system with constant v/f ratio controller were presented; the first one is to keeping the maximum torque constant for all operating frequencies and equal to its rated value. The second is maintaining the flux constant at all operating frequencies and equal to its nominal value

[12]. A modified approach involving the injection of a low frequency boost voltage was developed, which offers the opportunity to realize maximum torque from zero to rated speed [13].

In this paper a proposed method to compensate the voltage drop across the stator resistance by injection of a low frequency boost voltage to keep the magnetizing flux at its rated value is presented. Also a slip frequency compensation method is presented here by detecting the stator currents and calculating the air gap power then the torque is produced. A linear relation between torque and slip frequency is assumed. Finally, the corresponding slip frequency is added to the supply frequency command to compensate the drop in motor speed due to load variations. To stabilize the system, a first-order lags is introduced in the feedback loop of slip frequency compensator. The performance of IM under proposed model is studied by using MATLAB/SIMULINK under load and speed variations. Also comparison between proposed system and previous work is presented. The simulation results show that the speed accuracy is improved effectively by the proposed method for various speeds and loads, even at low speed range.

II. STATOR VOLTAGE COMPENSATION

The block diagram for proposed system is shown in Fig 1. To achieve maximum torque from zero to rated speed ,The V/f ratio is increased to keep magnetizing flux at its rated value at low speed to compensate the voltage drop across stator resistance .the stator voltage is modified according to (1)[13].

$$V_s = V_0 + K * a \quad (1)$$

Where

$$a=\frac{f_e^*}{f_{rated}} = \frac{w_e^*}{w_{e\,rated}} = \frac{w_e^*}{w_{base}}$$

$$w_e^* = 2\pi f_e^*$$

V_0 Is off-set voltage chosen to give rated magnetizing flux at zero speed and the term ($K*a$) is a Frequency dependent component.

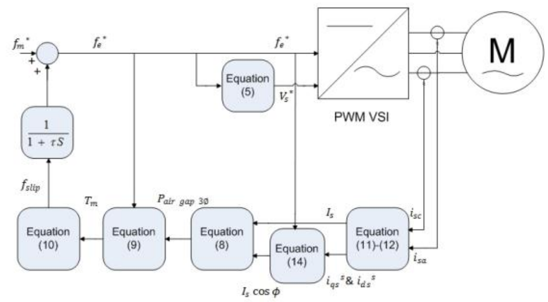

Fig. 1 Block diagram of proposed system

Where even at zero Frequency. “V_0” Compensates for the drop in stator impedance to make the magnetizing flux equal to its Rated value. To find the value of V_0 and K consider the exact equivalent circuit as shown in Fig 2.
From Fig 2,

$$V_s = aE_{ar} + (I_m + I'_r)(r_s + JaX_{ls}) \quad (2)$$

Where

$$I_m + I'_r = \left(\frac{E_{ar}}{JX_m} + \frac{aE_{ar}}{\frac{r'_r}{s} + JaX'_{lr}}\right) \quad (3)$$

Consequently,

$$V_s = aE_{ar} + \left(\frac{E_{ar}}{JX_m} + \frac{aE_{ar}}{\frac{r'_r}{s} + JaX'_{lr}}\right)(r_s + JaX_{ls}) \quad (4)$$

Where:

$$s = s_r/a$$

- s_r- Motor Rated slip
- S - Motor Slip
- X_{ls}- Stator leakage reactance (Ω)
- X_{lr}- Referred rotor leakage reactance (Ω)
- r_s- Stator resistance (Ω)
- r'_r- Referred rotor resistance (Ω)
- X_m- Magnetizing reactance (Ω)
- V_s -Stator voltage (volt)
- E_{ar}-Rated Induced e.m.f in stator (volt)

Equation (4) is evaluated to find the relation between V_s and "a" as ‘‘a’’ varies in the range $0.1 \le a \le 1$. The result is shown in Fig 3.

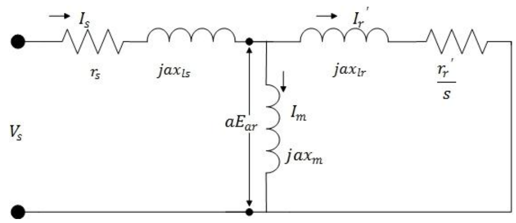

Fig.2 Steady state Equivalent Circuit of a Squirrel Cage Induction Motor for variable voltage and frequency control

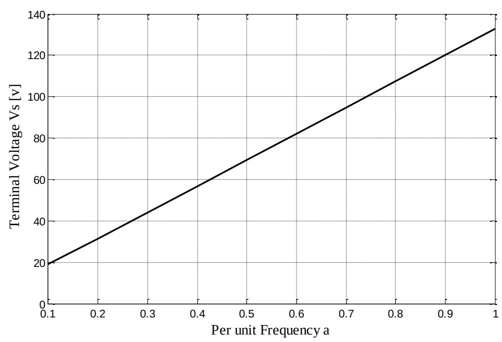

Fig. 3 Look-Up Plot for Modified V/F Control

V_0 Is obtained by back extrapolating the straight line to zero and determining the point of intersection at a=0. The constant, K, is the slope of Fig 3. For the motor parameter shown in appendix I the slope K is obtained as 126.4790 and V_0 obtained as 6.3115V then, (1) modifies to

$$\mathbf{V_s = 126.4790 * a + 6.3115} \quad (5)$$

The research in [13] introduced a modified closed loop v/f control method which provides a boost-voltage at low frequency therefore; compensation for the stator impedance drop is shown in Fig 4. This method introduced the pattern of gain design PI controller .in order to design PI controller, adequate knowledge for motor model is required. Also it requires speed sensors. However controlled IMs drives without mechanical speed sensors at the motor shaft have the attractions of low cost and high reliability. Therefore, to overcome on the above problems a slip frequency compensation method is presented as shown in Fig 1. .

III. SLIP FREQUENCY COMPENSATION

The slip frequency which varies directly, proportional to the motor torque is estimated. After keeping the stator flux magnitude to be constant, the air- gap power, motor torque and slip frequency value can be calculated as in (8)-(10) respectively .Due to positive feedback instability in the system is happened the system of a first-order lags is introduced in the feedback loop of slip frequency compensator [6].

$$P_{Air-gap\ 3\phi} = 3\left[V_s I_s \cos\phi - I_s^{\,2} R_s\right] - P_{core} \quad (8)$$

$$T_m = \frac{P}{2}\frac{P_{Air-gap\ 3\phi}}{w_e^{\,*}} \quad (9)$$

$$w_{slip} = \left(\frac{w_{sR}}{T_{mR}}\right) * T_m \quad (10)$$

$$, f_{slip} = \frac{w_{slip}}{2\pi}$$

Where:

- w_{sR} - Rated slip speed in rad/sec
- T_{mR} -Rated torque in Nm
- f_{slip} -Slip frequency
- P -number of poles

Calculation of $I_s \cos\phi$:

By using the zero crossing method to calculate the power factor, this method gives poor results due to the measured current contains high-frequency noise that makes it difficult to identify the exact point of zero crossing [1]. The problem is eliminated by transforming current on stationary reference frame into synchronous rotating reference frame. The RMS value of the stator current I_s is calculated by using Space vector quantities of current, which is expressed as:

The three sinusoidal phase current i_{sa}, i_{sb} and i_{sc} can be combined to space vector $\vec{i_s}(t)$ circulating with the stator frequency f_s where $\gamma=2\pi/3$ (rad) [14-15].

$$\vec{i_s} = \frac{2}{3}(i_{sa} + i_{sb}e^{j\gamma} + i_{sc}e^{j2\gamma})$$

By using relative transform matrix as shown in (11) $\vec{i_s}$ can be resolved to tow components in q-d stationary axes.

$$\begin{bmatrix} i_{qs}^{\ s} \\ i_{ds}^{\ s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{-\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad (11)$$

Hence the magnitude and RMS value of vector $\vec{i_s}$ will be:

$$|\vec{i_s}| = \sqrt{i_{qs}^{\ s\,2} + i_{ds}^{\ s\,2}} \quad (12)$$

$$I_s = \frac{|\vec{i_s}|}{\sqrt{2}}$$

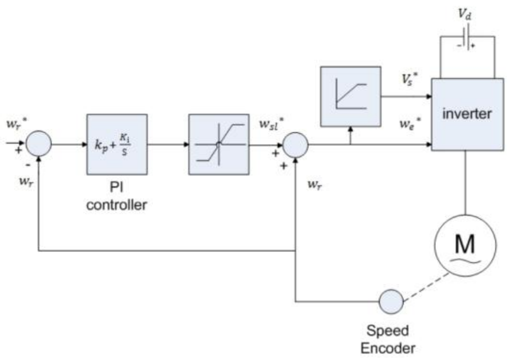

Fig .4 Closed-Loop Speed Control Scheme with Volts/Hertz and Slip Regulation

$I_s \cos\phi$ is calculated as in (13) after transforming the stator current on synchronous rotating reference frame as shown in Fig 5 can be used to calculate $I_s \cos\phi$ (real part of I_s) as shown in (14).

$$\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} = \begin{bmatrix} \cos(w_e t) & -\sin(w_e t) \\ \sin(w_e t) & \cos(w_e t) \end{bmatrix} \begin{bmatrix} i_{qs}{}^{s} \\ i_{ds}{}^{s} \end{bmatrix} \tag{13}$$

$$I_s \cos\phi = \frac{i_{qs}}{\sqrt{2}} \tag{14}$$

The core loss can be calculated corresponding to (15)

$$P_{coreR} = K_h B_R{}^2 f_e{}^* + K_e B_R{}^2 f_e{}^{*2} \tag{15}$$

Where K_e and K_h factors depend on the core type B_R is the rated flux density and $f_e{}^*$ the stator frequency.

IV. SIMULATION

Digital Simulation are carried out for proposed constant v/f control of three phase induction motor using MATLAB SIMULINK and the parameter of motor used is shown in Appendix I and the core loss coefficientsK_e, K_h and B_R are entered at start of program. Fig (6)-(10) are the simulation results while the step load change at rated torque by +10 Nm at 1.5 sec and by -10 Nm at 4 sec for command speed 1200 rpm. Fig (11)-(20) gives the simulation results while the load change from rated torque to 130% of rated torque at 2 sec for 300 rpm and 1.5 sec for 100 rpm using the proposed system.

The simulation results show the motor with proposed system can drive the loads even at low speed range and at load greater than rated torque with speed error close to zero.

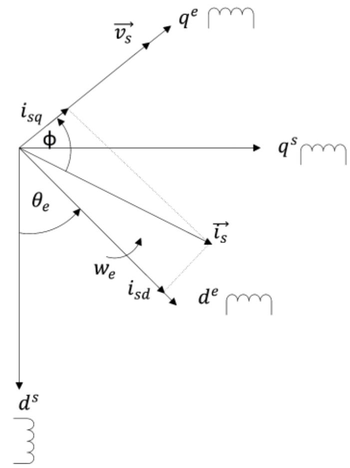

Fig. 5 Voltage and Current Components on Synchronous Rotating Reference Frame

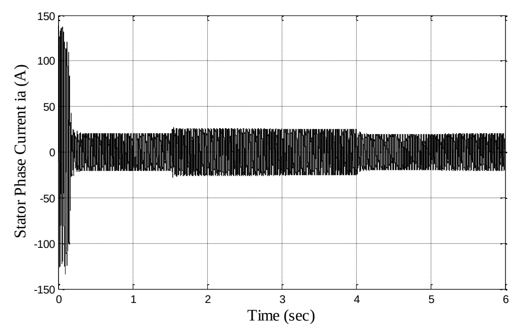

Fig. 6 Stator Current for load Torque Change by +10 Nm at 1.5 Sec and by -10 Nm at 4 Sec for Command Speed 1200 rpm

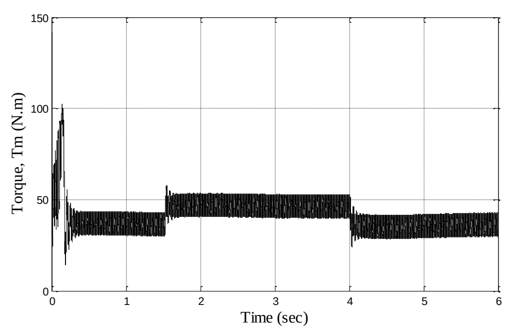

Fig. 7 Motor Torque for load Torque Change by +10 Nm at 1.5 Sec and by -10 Nm at 4 Sec for Command Speed 1200 rpm

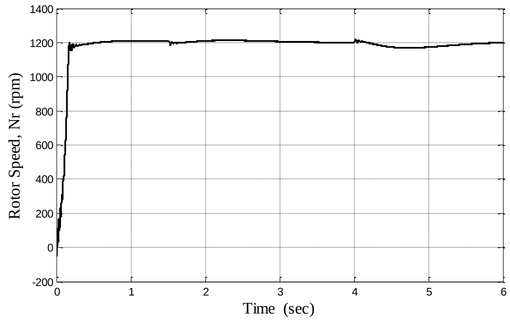

Fig. 8 Rotor Speed for load Torque Change by +10 Nm at 1.5 Sec and by -10 Nm at 4 Sec for Command Speed 1200 rpm

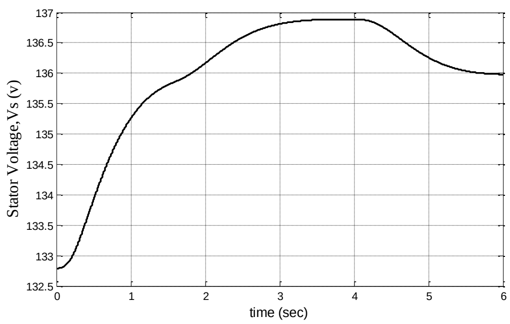

Fig. 9 Stator Voltage for load Torque Change by +10 Nm at 1.5 Sec and by -10 Nm at 4 Sec for Command Speed 1200 rpm

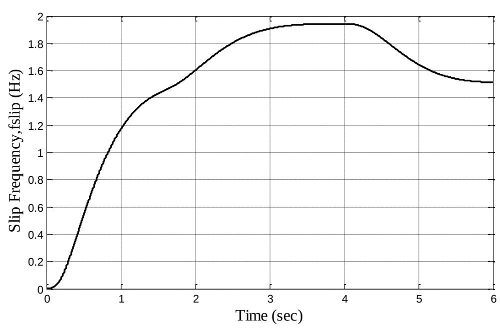

Fig. 10 Slip Frequency for load Torque Change by +10 Nm at 1.5 Sec and by -10 Nm at 4 Sec for Command Speed 1200 rpm

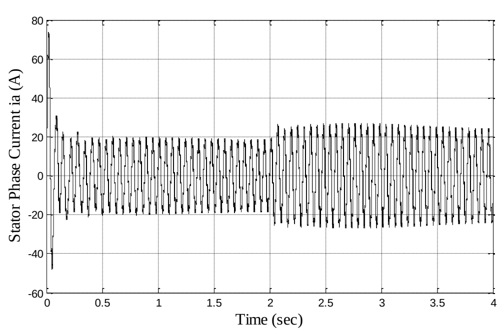

Fig. 11 Stator Current for load Torque Change from rated value to 130% of rated value at 2 Sec for Command Speed 300 rpm

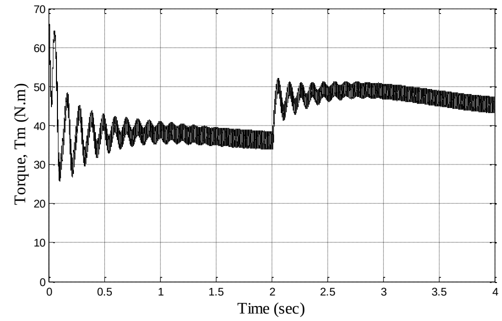

Fig. 12 Motor Torque for load Torque Change from rated value to 130% of rated value at 2 Sec for Command Speed 300 rpm

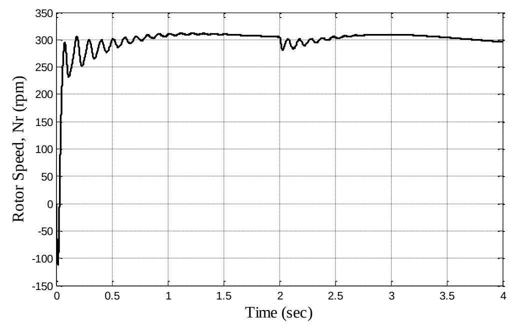

Fig. 13 Rotor Speed for load Torque Change from rated value to 130% of rated value at 2 Sec for Command Speed 300 rpm

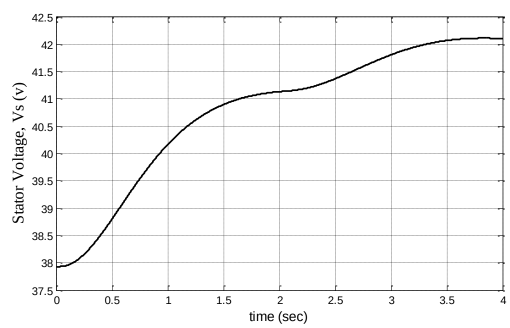

Fig. 14 Stator Voltage for load Torque Change from rated value to 130% of rated value at 2 Sec for Command Speed 300 rpm

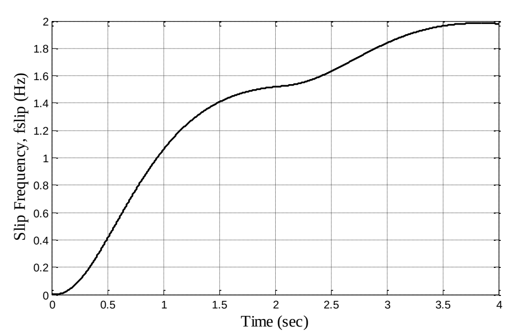

Fig. 15 Slip Frequency for load Torque Change from rated value to 130% of rated value at 2 Sec for Command Speed 300 rpm

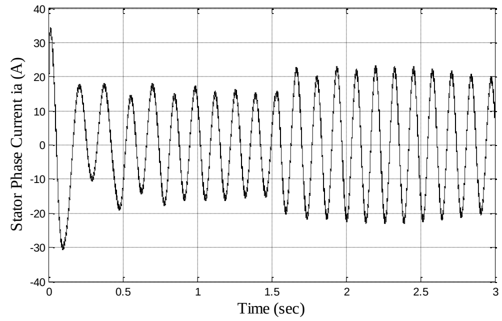

Fig. 16 Stator Current for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 100 rpm

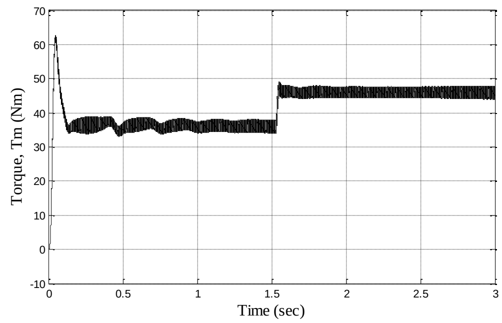

Fig. 17 Motor Torque for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 100 rpm

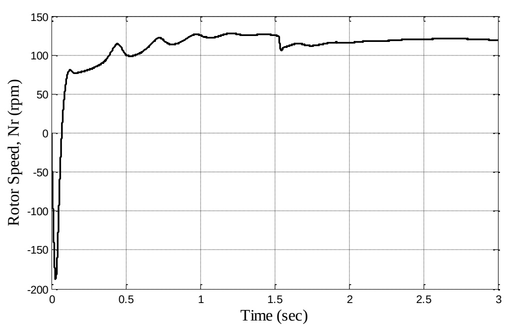

Fig. 18 Rotor Speed for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 100 rpm

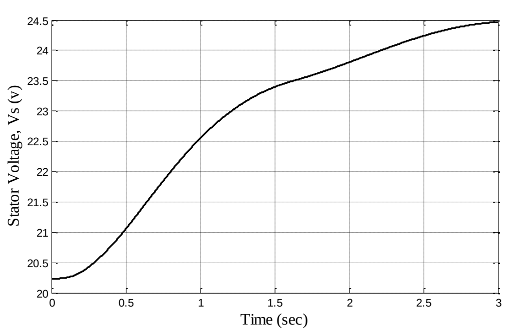

Fig. 19 Stator Voltage for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 100 rpm

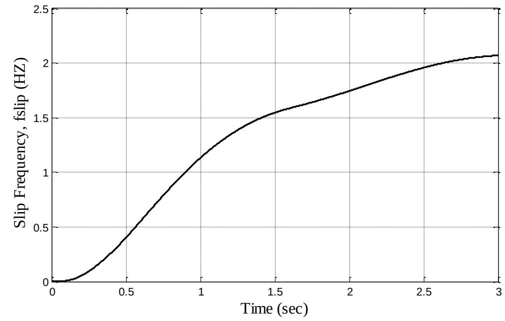

Fig. 20 Slip Frequency for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 100 rpm

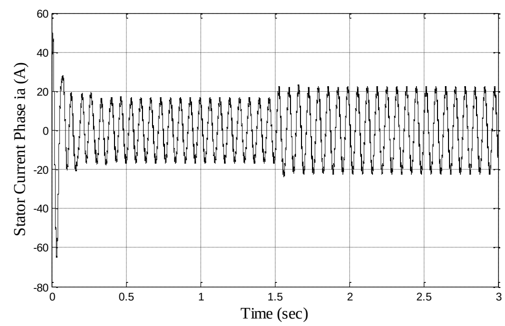

Fig. 21 Stator Current for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 300 rpm (previous work)

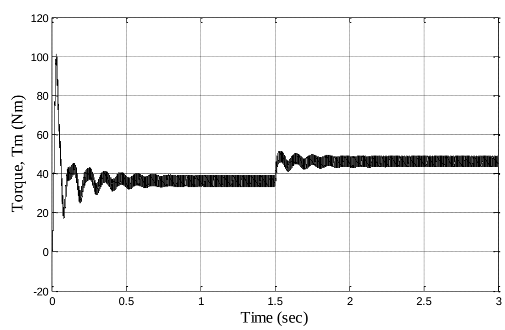

Fig. 22 Motor Torque for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 300 rpm (previous work)

Fig 9 and Fig 10 show that the stator frequency is increased corresponding to load increase; therefore the output voltage from inverter is increased to compensate the voltage drop on stator resistance.

Fig (21)-(26) gives the simulation results while the load change from rated torque to 130% of rated torque at 1.5 sec for 300 rpm and 100 rpm, respectively, for previous work in [13].

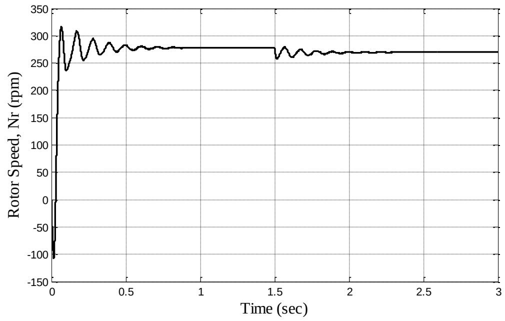

Fig. 23 Rotor Speed for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 300 rpm (previous work)

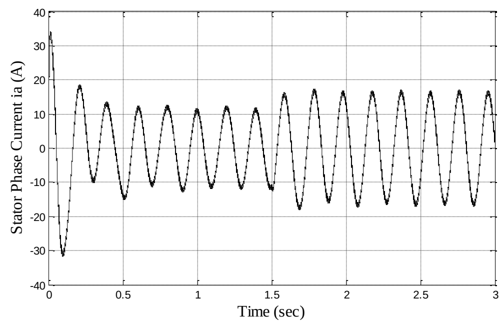

Fig. 24 Stator Current for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 100 rpm (previous work)

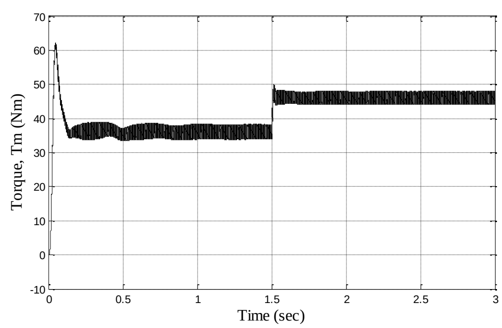

Fig. 25 Motor Torque for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 100 rpm (previous work)

Speed accuracy Comparison between proposed system and previous work for Load Change from Rated torque to 130% Rated torque at Command Speed 1200 rpm (60 Hz), 300 rpm (15 Hz) 100 rpm (5 Hz) is done and tabulated in Table I.

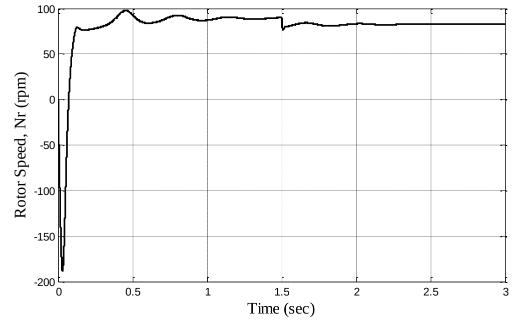

Fig. 26 Rotor Speed for load Torque Change from rated value to 130% of rated value at 1.5 Sec for Command Speed 100 rpm (previous work)

Table I

	Command Speed(rpm)	Steady state Speed(rpm)	Accuracy %
Proposed System	1200	1201	0.0833%
Previous Work	1200	1185	1.25%
Proposed System	300	302	0.66%
Previous Work	300	278	7.3%
Proposed System	100	116	16%
Previous Work	100	83	17%

CONCOLUSION

A proposed system for v/f control method improvement is presented via full compensation for the stator resistance voltage drop by injection of low frequency boost voltage .Also simple frequency compensation based on estimation of air-gap power and a linear motor torque-speed approximation is introduced. The dynamic performance of IM for proposed system is presented by MATLAB SIMULINK under different load and speed variations. The simulation results prove the speed accuracy of proposed method is improved over wide range of operating loads and speeds.

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Appendix I

The parameters of 3-phase IM that we used in simulation are shown in the table II.

Table II

Rated Voltage	230 V
Rated frequency	60 HZ
Number of poles	6
Rated Speed	1170 rpm
Stator Resistance	0.5 ohm
Rotor Referred Resistance	0.25 ohm
Stator Reactance	0.75 ohm
Rotor Referred Reactance	0.5 ohm
Magnetizing Reactance	100 ohm
Moment of inertia	0.02 Kg .m^2
Winding Connection	Star