IPMSM Drive with MLI-Based Third Harmonic Injection for Broad Speed Range Operation

K LALAIAH[1]| N SHIVA PRASAD[2]|NALAPATLA BHAVYA [3]| G PRANEETH [4]
1&2 Assistant Professor, EEE department, Brilliant Grammar School Educational Society's Group of Institutions, Hyderabad, TS.
3&4 UG SCHOLARS, EEE department, Brilliant Grammar School Educational Society's Group of Institutions, Hyderabad, TS.

ABSTRACT: The nonlinear controller for the wide speed range activity of the internal permanent magnet synchronous motor (IPMSM) drive is presented in this study. It is based on third harmonic infusion (THI). Steady engine boundaries result in an inappropriate regulator execution due to appealing immersion. Accordingly, a flexible nonlinear regulator based on back stepping is developed for an IPMSM drive in order to achieve high power execution while adjusting to boundary vulnerabilities. To increase the DC transport use and provide a wider working tempo range, a sinusoidal THI method is coordinated. Using the hesitancy force and field debilitating, the field control provides a wider speed range. The Lyapunov solidness measure is used to demonstrate the security of the control law state factors, and Barbalat's lemma is used to ensure the drive's global asymptotic steadiness. The suggested drive's viability is tested through simulation. The suggested THI-based nonlinear regulator is shown along with a nonlinear regulator without THI and a conventional benchmark-tuned PI regulator. Fast intermingling to order speed, decrease in speed motions over the appraised speed and an obvious decrease in stage current with THI is accomplished through the proposed drive.

KEYWORDS: THI, IPMSM, MLI, Lyapunov stability.

I.INTRODUCTION: The interior permanent magnet synchronous motor (IPMSM) has been becoming a popular choice for ac drives as it offers high efficiency, low noise, robustness, high power density and small air gap [1,2]. IPMSM machines are particularly attractive due to rotor construction, as it offers magnetic saliency due to the arrangements of the magnets (either axially or radially) which results additional torque known as reluctance torque [3]. Due to nonlinear behavior of winding currents, magnetic saturation of the rotor core, cross coupling effects, and parameter dependency on temperature variations, the effective control of high performance drive is affected [4,5]. System performance degrades with the classical PI controllers having constant gains [6,7]. In order to ensure proper control during full operating speed of the machines, motor parameters must be estimated online.

Adaptive back-stepping is well suited for this purpose where system nonlinearities and uncertainties have been incorporated in the design stage which tend to vary with operating conditions [8,9]. Magnetic saliency features of the IPMSM are used to indirectly control the d-axis flux by controlling d-axis current [10]. To linearize torque equation, is considered zero by most of the researchers which simplifies supervision technique but resulting higher resistive losses and poor efficiency at light loads [11]. Moreover, with =0 control techniques, motor air-gap flux cannot be controlled which restricts the operating speed of the motor to rated speed and the reluctance torque cannot be utilized. By employing maximum torque per ampere (MTPA) and field weakening (FW) techniques motor can be operated over wide speed range [12-14]. But both MTPA and FW schemes are parameter dependent and hence, the performance is affected by the variations of d-axis and q-axis inductance unless these parameters are estimated online. Therefore, a control technique is required for variable speed drives where speed should follow the specified reference trajectory, regardless of load disturbances, parameter variations and model uncertainties. In [14] FW control strategy of IPMSM is proposed to achieve constant output power but the motor parameters remain constant which degrades the drive performance. Authors in [15] reported MTPA and FW algorithms to expand the operating speeds but it does not mathematically demonstrate the global asymptotic stability.

In most drive systems, modulation index (M) higher than one is undesirable as it causes the increased low frequency and baseband distortion in the phase current [16]. To avoid phase currents baseband distortion, linear modulation region is preferred by the researchers for pulse width modulation (PWM) based control schemes where 86.67% inverter supply potential is utilized for motor lineline potential [17]. Keeping control schemes in linear modulation region, inverter DC bus voltage utilization can be increased by 15.47% incorporating third harmonic injection (THI) which reduces the magnitude of the phase voltages [20]. In most cases the dc-link voltage of the inverter has lot of ripple as it is obtained from an uncontrolled rectifier fed by an alternating current (AC) source with peak voltage equals to that of the rated motor voltage. If THI is not used, the controller drives the converter outside of the linear modulation region, and hence, the control gets saturated during each PWM cycle and harmonic content is increased. If the third harmonic injection is utilized, it operates the converter within linear modulation range and cancels some harmonic content of the inverter output voltage and thus, the rotor flux aligns better with the controller reference frame which results in reduction of speed and torque ripples Therefore, in this paper a nonlinear speed controller coupled with sinusoidal THI is presented to achieve less speed ripple through reduction in stator current harmonics with increased inverter supply utilization. Existing nonlinear controllers didn't consider the variation of all motor parameters such as temperature fluctuations that alters the effective drive performance [22]. In this work the robustness of the controller is achieved by online estimation of stator resistance, load torque and d-q axis inductances through adaptive back stepping technique. The global asymptotic stability is assured through the application of criterion supported by Barbalat's lemma. Simulation results confirm the robustness, higher operating speed range with less speed oscillations, reduction in stator current and lowest torque ripples for the proposed THI based nonlinear control scheme as compared to the MLI, classical PI control and nonlinear control without THI.

II.LITARATURE SURVEY:

Tianfu Sun, MikailKoc, and Jiabin Wang, Due to parameter variations with stator currents, the derivatives of machine parameters with respect to current angle or d-axis current are not zero. However, these derivative terms are ignored by most of mathematical model based efficiency optimized control schemes. Therefore, even though the accurate machine parameters are known, these control schemes cannot calculate the accurate efficiency optimized operation points. In this paper, the influence of these derivative terms on maximum torque per ampere (MTPA) control is analyzed and a method to take into account these derivative terms for MTPA operation is proposed based on the recently reported virtual signal injection control (VSIC) method for interior permanent magnet synchronous machine (IPMSM) drives. The proposed control method is demonstrated by both simulations and experiments under various operating conditions on prototype IPMSM drive systems.

Md. Mizanur Rahman and M. Nasir Uddin, This paper presents a novel direct torque and flux control (DTFC) scheme of interior permanent magnet synchronous motor (IPMSM) drive. The conventional six-sector based DTFC scheme is modified with the proposed eighteen-sector based DTFC scheme in order to reduce the torque/flux ripple of the drive. Furthermore, the motor efficiency is optimized by reference flux estimation through an online loss minimization algorithm (LMA) so that the motor operates at minimum loss condition, which is not possible for conventional control where the reference flux remains constant. The complete drive is simulated using MATLAB/Simulink software and then a prototype is implemented using digital signal processor (DSP) board DS1104 for a laboratory 5-hp motor. Performance of the proposed DTFC scheme is investigated extensively at different operating conditions in both simulation and experiment. It is found from results that the proposed eighteen-sector based DTFC scheme incorporating LMA achieves the lowest possible torque ripples in steady state while maintaining high efficiency.

III. PROPOSED SYSTEM:

Therefore, in this paper, a nonlinear speed controller coupled with sinusoidal THI is presented to achieve less speed ripple through reduction in stator current harmonics with increased inverter supply utilization. Existing nonlinear controllers did not consider the variation of all motor parameters, such as temperature fluctuations that alters the effective drive performance [22]. In this paper, the robustness of the controller is achieved by online estimation of stator resistance, load torque, and d–q axis inductances through an adaptive backstepping technique. The global asymptotic stability is assured through the application of criterion supported by Barbalat’s lemma. The effectiveness of the proposed drive is experimentally verified for a laboratory 3.73 kW motor using a DSP board DS1104. Both simulation and experimental results confirm the robustness, higher operating speed range with less speed oscillations, reduction in stator current, and lowest torque ripples for the proposed THI-based nonlinear control scheme as compared to the classical PI control and nonlinear control without THI.

Considering sinusoidal induced EMF with no damper winding on rotor and negligible core losses, state model of an IPMSM drive is derived from synchronous machine can be obtained by as follows [23]:

$$\frac{di_d}{dt}=\frac{1}{L_d}[v_d\text{-}R_s i_d+P\omega_r L_q i_q] \quad (1)$$
$$\frac{di_q}{dt}=\frac{1}{L_q}[v_q\text{-}R_s i_q\text{-}P\omega_r L_d i_d\text{-}P\omega_r\psi] \quad (2)$$
$$\frac{d\omega_r}{dt}=\frac{1}{J}[T_e\text{-}T_L\text{-}B_m\omega_r] \quad (3)$$
$$T_e=\frac{3P}{2}[\psi i_q+(L_d-L_q)i_d i_q] \quad (4)$$
$$T_e=T_L+B_m\omega_r+J\omega_r \quad (5)$$

where, , are d-q axis components of stator voltages; , are d-q axis components of stator currents; , are d-q axis components of stator inductances; is rotor magnetic flux linkage; P is the number of motor pole pairs; is the actual rotor speed; is the stator per phase resistance ; is the electromagnetic developed torque; is the load torque; J is the rotor inertia constant and, Bm is the friction damping coefficient. Flux weakening technique involves d- and q-axis current interacting components; reluctance torque as shown by the second term of Eqn.(4) which provides the exact speed control over an extended operating speed range [11]. Due to nonlinear nature and variations of dynamic operating conditions, motor parameters are not constant. Traditionally, is controlled to control the motor speed while is maintained zero to make controller development easier. However, with this assumption motor cannot be operated above rated speed as the flux cannot be controlled for IPMSM and at the same time reluctance torque cannot be utilized. For expanded operating region, MTPA is utilized to determine d-axis current within the rated speed and FW above the rated speed while parameters are estimated online. Control laws for d-q axis command voltages are achieved through the proposed nonlinear controller. Furthermore, PWM technique is used where sinusoidal THI is applied for translated d-q axis command voltages with the scaled third harmonic [31].

A. Controller Design

Motor actual speed converges to the command speed and speed tracking is achieved where error dynamics (speed) is specified as:

$$e_\omega=\omega_r^*\text{-}\omega_r \quad (6)$$

Where, e_w = speed error and = speed reference. Then, from (3), and (6) one can get:

$$\dot{e_\omega}=\frac{1}{J}[B_m\omega_r+T_L-\frac{3P}{2}(\psi i_q+(L_d-L_q)i_d i_q)] \quad (7)$$

Where, = rate of change of speed error (error dynamic). To fulfil the speed tracking objectives, derivative of the initial Lyapunov function, is given by:

$$\dot{V}=e_\omega\dot{e_\omega}=\frac{e_\omega}{J}[B_m\omega_r+T_L-\frac{3P}{2}(\psi i_q+(L_d-L_q)i_d i_q)] \quad (8)$$

To ensure the stability of (8), and is identified as virtual control variable. The stabilizing function and are selected such that (8) becomes negative semi-definite. Initially, the reluctance torque is neglected (=0) to ensure the stability of (8) and is chosen as:

$$i_d^{*}=0 \text{ and } i_q^{*}=\frac{2}{3P\psi}(B_m\omega_r+T_L+k_\omega J e_\omega) \qquad (9)$$

where, is closed-loop feedback gain, and is the command currents, replacing (9) into (8):

$$\dot{V}=-k_\omega e_\omega^2 \qquad (10)$$

Speed tracking requirements of (10) are fulfilled assuming . For proper tracking, corresponding current error variables are defined as:

$$e_d=i_d^{*}-i_d \qquad (11)$$
$$e_q=i_q^{*}-i_q \qquad (12)$$

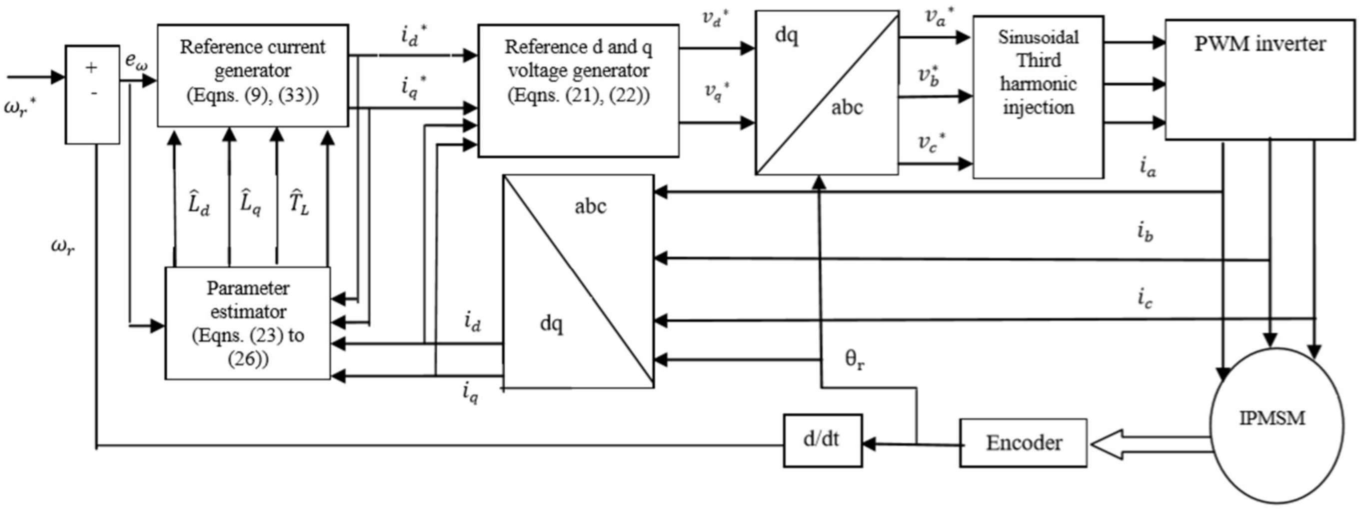


Fig.1: Sinusoidal third harmonic injection based nonlinear control of IPMSM drive for wide speed range operation.

For stabilizing the derivatives of the error dynamics of (11) and (12) are defined as:

$$\dot{e_d}=\frac{1}{L_d}[R_s i_d-P\omega_r L_q i_q-v_d] \qquad (13)$$

$$\dot{e_q}=\frac{2(B_m-k_\omega J)}{3P\psi J}(T_e-T_L-B_m\omega_r)+\frac{1}{L_q}(R_s i_q+P\omega_r L_d i_d+P\omega_r\psi-v_q) \qquad (14)$$

Temperature variation affects the stator resistance and due to magnetic saturation of the rotor core, the air gap flux linkage changes which mainly affects the value of q-axis inductance thus the value of should be estimated online in order to achieve the desired tracking objectives. Thus, variation of d-axis inductance and stator resistance should be estimated online. The estimation of unknown parameters can be done by exploiting the features of adaptive backstepping approach. Precise tracking also needs load torque estimation to adapt with changing loading conditions. Therefore, parameters are estimated adaptively as:

$$e_D = \hat{L}_d - L_d \quad (15)$$
$$e_Q = \hat{L}_q - L_q \quad (16)$$
$$e_L = \hat{T}_L - T_L \quad (17)$$
$$e_R = \hat{R}_s - R_s \quad (18)$$

Where the estimated d- and q- axis inductances; , are the estimated load torque and estimated stator resistance. New Lyapunov function including the speed, currents and estimated quantities can be defined as:

$$V_1 = \frac{1}{2}\left(e_\omega^2 + {e_d}^2 + {e_q}^2 + \frac{1}{\gamma_1}e_D^2 + \frac{1}{\gamma_2}e_Q^2 + \frac{1}{\gamma_3}e_L^2 + \frac{1}{\gamma_4}e_R^2\right) \quad (19)$$

The derivative of the Lyapunov's function in (19) is as follows:

$$\dot{V}_1 = e_\omega \dot{e}_\omega + e_d \dot{e}_d + e_q \dot{e}_q + \frac{1}{\gamma_1}e_D \dot{e}_D + \frac{1}{\gamma_2}e_Q \dot{e}_Q + \frac{1}{\gamma_3}e_L \dot{e}_L + \frac{1}{\gamma_4}e_R \dot{e}_R$$

$$= \frac{e_\omega}{J}\left[-e_L - k_\omega J e_\omega + \frac{3P}{2}\psi e_q + \frac{3P}{2}(L_d - L_q)e_d i_q\right] + \frac{e_d}{L_d}\left[R_s i_d - P\omega_r L_q i_q - v_d\right] + e_q\left[\frac{2(B_m - k_\omega J)}{3P\psi J}(T_e - T_L - B_m\omega_r) + \frac{1}{L_q}(R_s i_q + P\omega_r L_d i_d + P\omega_r \psi - v_q)\right] + \frac{1}{\gamma_1}e_D \dot{e}_D + \frac{1}{\gamma_2}e_Q \dot{e}_Q + \frac{1}{\gamma_3}e_L \dot{e}_L + \frac{1}{\gamma_4}e_R \dot{e}_R \quad (20)$$

To establish the global asymptotic stability of the drive, control voltages and are chosen from (20) by setting the terms multiplied with the d-axis current error (e_d) and qaxis current error (e_q) to zero so that the derivative of the Lyapunov's function (e_r) becomes negative definite.

$$v_d = \hat{R}_s i_d - P\omega_r \hat{L}_q i_q + K_d e_d \hat{L}_d + \frac{3P}{2J}\hat{L}_d(\hat{L}_d - \hat{L}_q) i_q e_\omega \quad (21)$$

$$v_q = \frac{2\hat{L}_q(B_m - k_\omega J)}{3P\psi J}\left[\frac{3P}{2}\left(\psi i_q + (\hat{L}_d - \hat{L}_q) i_d i_q\right) - \hat{T}_L - B_m\omega_r\right] + \hat{R}_s i_q + P\omega_r \hat{L}_d i_d + P\omega_r\psi + K_q e_q \hat{L}_q + \frac{3P}{2J}\psi e_\omega \hat{L}_q \quad (22)$$

where, , and are closed-loop feedback constants and , , and are adaptive gains. The values of the closed-loop feedback constants and adaptive gains constants are selected by trial and error method so that at rated condition drive system follows the command speed while the updated motor values are close to the nominal values [32]. Substituting (21) and (22) into (20), parameters are predicted online based on adaptive back stepping can be defined as:

$$\dot{e}_L = -\gamma_3\left[-\frac{e_\omega}{J} + \frac{2e_q(B_m - k_\omega J)}{3P\psi J}\right] \tag{23}$$

$$\dot{e}_R = \gamma_4\left[\frac{e_d i_d}{L_d} + \frac{e_q i_q}{L_q}\right] \tag{24}$$

$$\dot{e}_D = -\gamma_1\left[-\frac{3P e_\omega e_d i_q}{2J} - \frac{e_q(B_m - k_\omega J) i_d i_q}{\psi J} - \frac{e_q P \omega_r i_d}{L_q}\right] \tag{25}$$

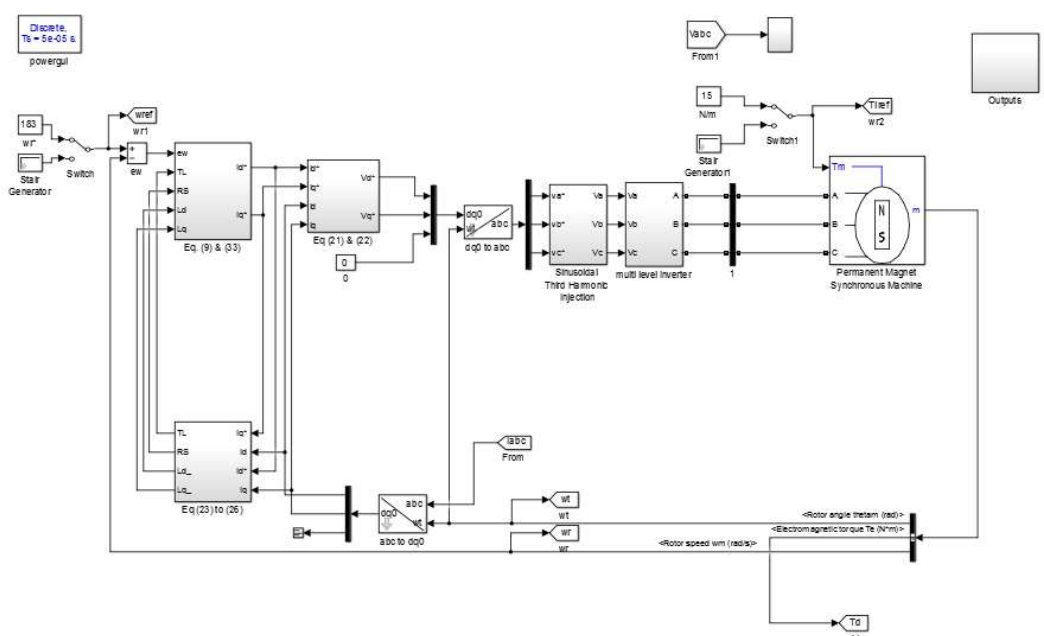
$$\dot{e}_Q = -\gamma_2\left[\frac{3P e_\omega e_d i_q}{2J} + \frac{e_q(B_m - k_\omega J) i_d i_q}{\psi J} + \frac{e_d P \omega_r i_q}{L_d}\right] \tag{26}$$

The parameter adaptation laws are implemented using the expressions in (23) to (26) to get the estimated values (, and). Based on command voltages as defined in (21) & (22) and update laws from (23) to (26), the Lyapunov derivative in (20) can be shown to be negative semi-definite with bounded state variable as:

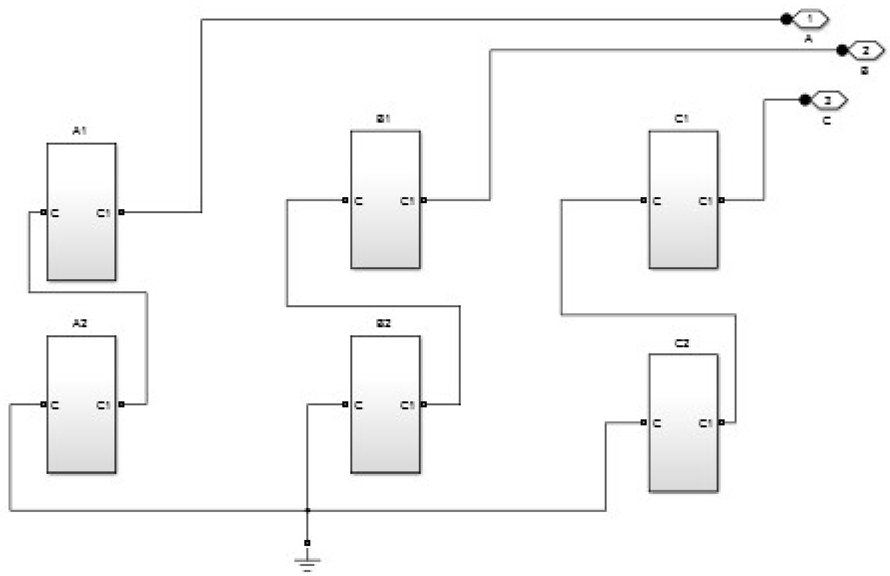
$$\dot{V}_I = -k_\omega e_\omega^2 - K_d {e_d}^2 - K_q {e_q}^2 \le 0 \tag{27}$$

Three criterion of Barbalat's lemma principle is used to establish asymptotic stability of the controller [24-25], and then applied to the (27). Validity of the conditions is checked as:
(19) cannot be less than zero; it is lower bounded. (b) (27) is negative semi-definite and less than or equal to zero. (c) (27) is a continuous function of time as it is a bounded function.
Then consequently, control laws are validated and global asymptotic stability of the proposed system is verified.

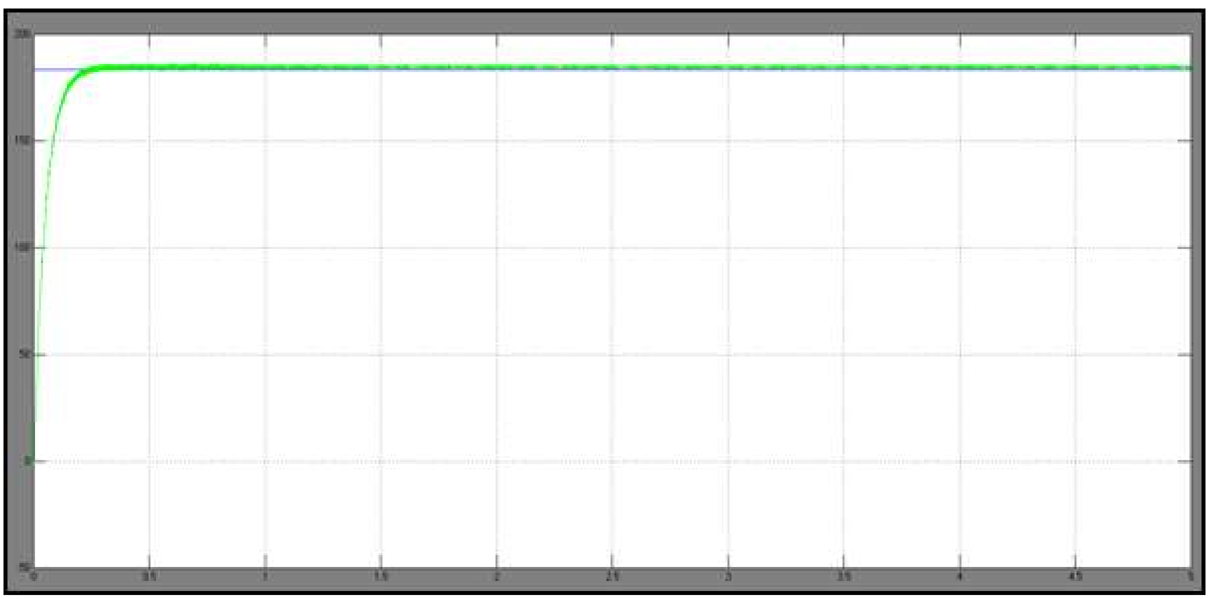
IV.SIMULATION RESULTS



PROPOSED SIMLINK DIAGRAM



MULTI LEVEL INVERTER



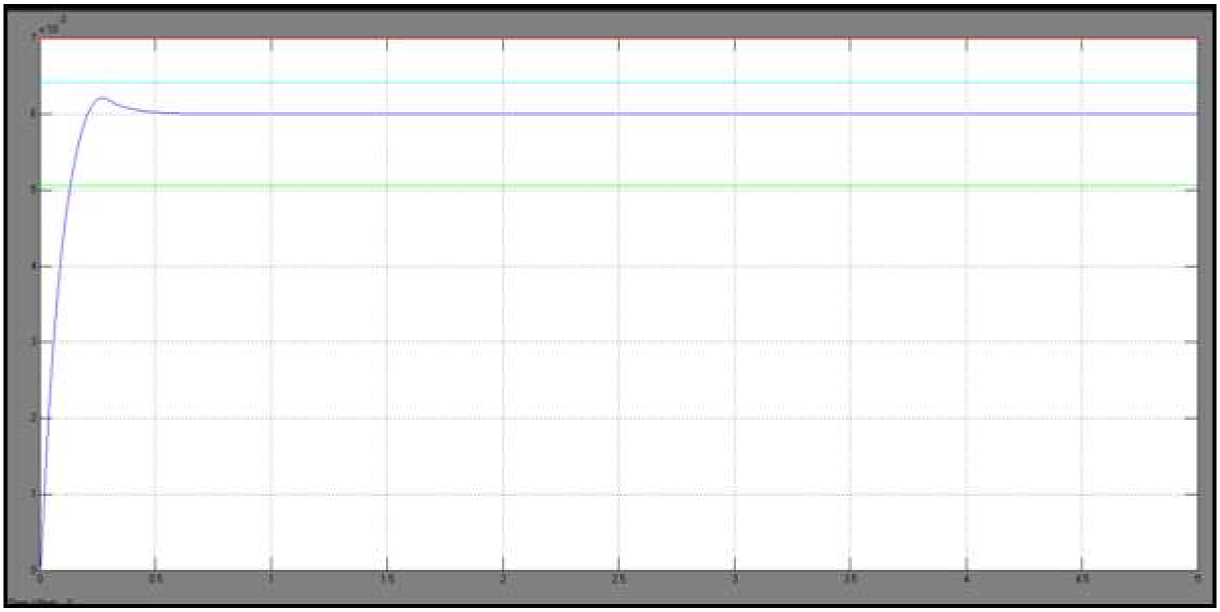
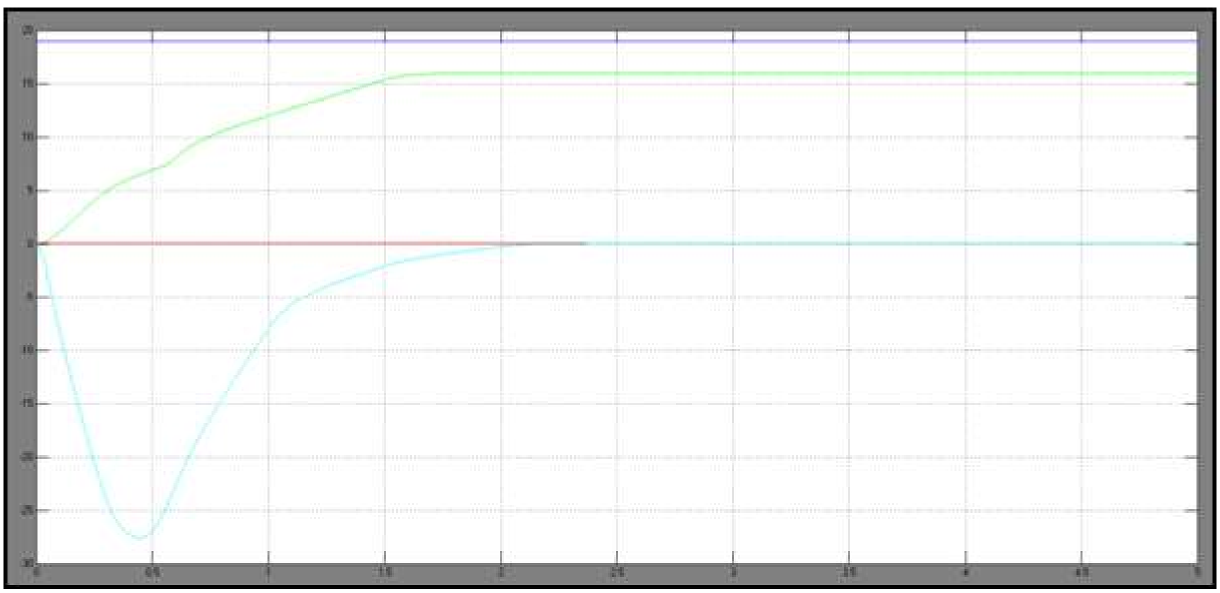


Fig. 3. Estimated and actual parameters. (a) Load torque and stator resistance. (b) d- and q-axis inductance.



V.CONCLUSION

This work presents a new sinusoidal third harmonic injection based nonlinear control of IPMSM drive that incorporates parameter uncertainty and field control. The stability of the control laws is confirmed using Lyapunov's stability criterion, which is backed by Barbalat's lemma, and an adaptive controller has been created taking into account all system nonlinearities. To improve the use of DC bus voltage, sinusoidal third harmonic voltages are introduced. To guarantee the use of reluctance torque below the rated speed and field weakening operation above the rated speed, field control is integrated. It has been confirmed that the suggested THI-based nonlinear control of the IPMSM drive is superior to the traditional benchmark tuned PI controller and nonlinear controller without THI in terms of load disturbance rejection and decreased steady-state speed oscillation under various operating conditions, both in simulation and in real time. Additionally, by lowering stator currents, the suggested controller reduces power losses. Simulation has confirmed a noticeable decrease in phase current with THI, a quick convergence to command speed, and a decrease in speed oscillations over the rated speed. Therefore, it has been determined that the suggested THI nonlinear controller based IPMSM drive is a viable option for real-time industrial drives in order to get good dynamic performance throughout a broad speed range.

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