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High Order Disturbance Observer Based PI-PI Control System With Tracking Anti-Windup Technique for Improvement of Transient Performance of PMSM

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ABSTRACT This paper focuses on designing a disturbance observer-based control (DOBC) system for PMSM drives. The cascade structure of the discrete-time PI-PI control system with tracking anti-windup scheme has been designed for both loops. In this study, high order disturbance observer (HODO) based control is used to improve the speed tracking performance of the control system for the PMSM prototyping kit regardless of the disturbance and unmodelled dynamics. The motion equation was modified in the HODO in which torque losses due to the drug resulting from the time-varying flux, hysteresis, and friction have been taken into account to estimate the total disturbance. The HODO does not require the derivatives of the disturbance to be zero, like in the traditional ones. It demonstrates its ability to estimate along with a load torque the high order disturbances caused by a cogging torque and a high-frequency electromagnetic noise in the PMSM system. In the real-time experiments, the proposed algorithm with HODO achieves less speed errors and faster response comparing with the baseline controller. The performances with proposed and baseline control have been evaluated under mechanical speed and load torque variation cases. The experimental results have proved the feasibility of the proposed control scheme. The proposed disturbance observer-based control system was implemented with a Lucas-Nuelle 300 W PMSM prototyping kit.

INDEX TERMS Disturbance observer based control, high-order disturbance observer, PI controller, PMSM, cascaded PI-PI, load torque observer.

I. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have been preferred than other type of electric motors. In comparison with DC motors, it is beneficial due to the special characteristics such as compact structures, high air-gap flux density, high power density, high torque to inertia ratio; but comparing with induction motors, it has higher efficiency [1]. However, it has been reported [2]–[7], that the PMSMs with nonlinear multivariable structure, external disturbance, noise, and uncertainties, cannot be easily controlled precisely [8], [9].

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Direct torque control (DTC) is one of approaches to simplify the control system in PMSM control applications. While field-oriented control (FOC) provides smooth starting, fast acceleration and four-quadrant operation, DTC simplifies motor modelling and hence reduces complexity of control system [10]. In the contrast, DTC method provides lower torque and inherits current ripples [11], [12]. Several FOC based sliding mode control (SMC) strategies have been proposed to optimize performance of the speed controller. While the 1st order SMC based composite control system has been designed with extended sliding mode observer (ESMO) [13], sliding mode observer (SMO) for load torque disturbance compensation have been synthesized with proportional-integral (PI-PI) control systems [14].

The cascade PI-PI control is an effective closed-loop control system for PMSM. This control architecture has direct access to limit armature current via simple saturation block. Typically, excessive currents come from a dramatic increase/decrease of motor speed and then armature voltages. In this cascade PI-PI control, the inner loop controls armature currents/torque whereas outer loop regulates the speed of motors by providing the current/torque reference. The limited current/torque reference in outer loop can facilitate current constraints. Therefore, it is essential to make sure that the inner loop response should be faster than outer loop to guarantee quick limiting overcurrent and stability in closed-loop scheme [15].

Due to so-called windup phenomena in traditional PI, the controller's performance is not satisfactory for PMSM drives applications. These phenomena is characterized by long periods of overshoot, which results in poor control performance and even makes the overall system unstable. Therefore, modern PI-PI control system for motor drives are typically equipped with various anti-windup (AW) techniques to reduce integral effect on control system performance. The effectiveness of back-calculation based tracking gains AW scheme's performance has been experimentally demonstrated among other anti-windup techniques such as, simple limited integration, limited output with dead zone element, and conditioned integration. These types of anti-windup technique were successfully tested for angular position control of a servo system [16] and for PMSM control [17].

PI speed controller equipped with anti-windup scheme demonstrates good performance in both transient and steady-state times than with conventional forms [17]–[19]. However, tuning gains of PI controller is tedious and time-consuming work. The defining of optimal gains for PI-PI control system based on analyzing plant's dynamics with step response method is most common among others, which was first presented by Ziegler and Nichols in 1942. The detailed information about this method and other methods to determine optimal gains of PI controller can be found in [18].

Another problem of traditional PI controllers is its sensitivity to uncertainties, disturbances, and unmodeled dynamics in the system, which degrade its performance [15]. There are several approaches to tune the gains of control systems for gaining robustness of control systems, namely, model-based and model-free one. The model-based adaptive PID speed control scheme, which consists a decoupling, PID, and supervisory terms has been developed in [5]. The adjustment of control gains is based on the gradient descent method and calculated online. Because of nonlinearities of PMSM [2], [4], the decoupling terms have been introduced to compensate them in feed-forward manner. However, this control gains tuning procedure highly depends on the knowledge of the model. Artificial neural network (ANN) based auto-tuning the gains of PID is another way to control PMSM without prior knowledge of the system model. In [20], a training algorithm for PID controller gains based on recursive least square was developed to update the gains online.

The main advantage of use PI based control system is its ability to facilitate zero steady-state errors in finite time under low-frequency disturbances and model uncertainties while the system's closed-loop stability is ensured. Sliding-mode control (SMC) [13], [21], H-infinity control [22], methods are considered as robust to the model uncertainty and modelling errors. However, these methods are too complicated and based on the knowledge of the model of the PMSM [23]. Also, SMC based control inherits so called chattering phenomenon and fully eliminating it hardly to achieve [24], [25]. On the other hand, intelligent and predictive controls implementation require high performance calculation processor in each time instance which is costly [26]. Finally, adaptive controller is difficult to follow all mathematical procedures because they are not straightforward [27].

Disturbance observer-based control (DOBC) can be used to estimate disturbance and then compensate it for the system [28]. The motion dynamics of PMSM is complex and intrinsically nonlinear. Therefore, for the high precision control of PMSM is a rather challenging task. In this study, high order disturbance observer (HODO) based control used to improve transient performance of the control system for PMSM regardless of the disturbances and unmodelled dynamics. In this study, the motion equation was modified in HODO observer in which torque losses due to eddy currents [29]–[31], hysteresis and friction have been taken into account as in the PMSM applications [32], [33]. Note that the total disturbance estimation is based on the estimation of the mechanical speed of PMSM. Because of various sources of the disturbance reduce the produced torque and generate ripples in the system response, they can be compensated with use of disturbance observer based control methods to achieve high performance. Recently, HODO type of observer has been utilized to estimate fast-varying disturbance such as aerodynamic torque, and synthesized with various baseline control methods in the renewable energy generation application [35]–[38]. This observer is free from assumption that the disturbance varies slowly which was obligatory condition for the traditional disturbance observer [28], [34]. Moreover, the same type of observer was effectively used for parameters uncertainty estimation. However, this observer is less effective for the electric machines with large inertia.

The main sources of high order disturbance in practical PMSM system are a cogging torque and a high-frequency electromagnetic noise [8]. The cogging torque is produced due to utilization of different materials in PMSM and uneven structure of windings of the motor, which induce various pulsating torques. The high-frequency electromagnetic noise associated with PWM technique for voltage control also has high order disturbance nature. Therefore, the sophisticated disturbance observer should be applied for these cases.

Motivated by [17] and inspired by [34], in this study, PI-PI control scheme with novel anti-windup algorithm is combined with HODO for speed control the prototyping kit PMSM. The HODO has been adopted to compensate the total disturbance with the aim of improving tracking performance and achieving asymptotic stability of the closed-loop system. Also, the detailed mechanical motion equation of PMSM has been modified in the HODO to accurately estimate the total disturbance associated with a cogging torque and a high-frequency electromagnetic noise in the PMSM system. Also, in the motion equation the torque losses due to drag resulting from time-varying flux, static moment of friction, and hysteresis also have been taken into account. The PI controllers are equipped with discrete-time tracking anti-windup scheme to handle windup phenomena. The proposed control method demonstrates superior tracking performance than the control system without disturbance observer. To the best of the authors' knowledge, PI controller with discrete-time tracking anti-windup scheme synthesized with high-order disturbance observer has not been studied for PMSM applications.

II. CONTROL SYSTEM DESIGN

A. SYSTEM MODEL

The mathematical description of PMSM system is as following

$$\begin{cases} \dot{\omega} = k_1 i_q - k_2\omega - k_3 d \\ \dot{i}_q = -k_4 i_{qs} - k_5\omega + k_6 V_q - \omega i_d \\ \dot{i}_d = -k_4 i_d + k_6 V_d + \omega i_q \end{cases} \tag{1}$$

where

$$k_1 = \frac{3}{2}\frac{1}{J}\frac{z_p^2}{4}\lambda_m;\quad k_2 = \frac{(c_{ed}+b)}{J};\ k_3 = \frac{2}{3z_p\lambda_m};$$
$$k_4 = \frac{R_s}{L_s};\quad k_5 = \frac{\lambda_m}{L_s};\ k_6 = \frac{1}{L_s};\ k_7 = \frac{1}{J}.$$

where

ω— electrical speed, RPM

i_q— q-axis current,

i_d— d –axis current, A

λ_m— permanent magnet flux coefficient, Wb V_d and V_q - d-axis and q-axis voltages, V

z_p— number of poles,

R_s— stator resistance, Ohm

L_s— stator inductance, H

J— rotor inertia, kg $\cdot$ cm^2

b— viscous damping coefficient, Nm/(rad/s)

c_{ed}— eddy currents coefficient, Nm/(rad/s)

d – total high order disturbance, Nm.

$(\dot{.}\,\dot{.})$ denotes derivative of argument function.

In this control system, the time varying magnetic flux due to eddy currents, friction and hysteresis cause torque losses, which are also considered in the motion equation. The eddy currents are induced when a nonmagnetic, conductive material is moving in a magnetic field [29]–[31]. The eddy

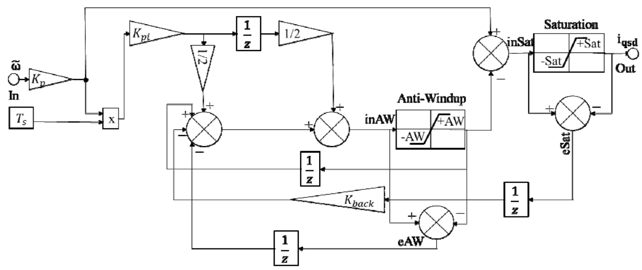

FIGURE 1. Discrete-time PI controller with tracking anti-windup scheme.

currents circulate in the rotor's conductive material and dissipate causing a repulsive force between the magnet and the conductor. Hence, the mechanical or produced torque considers losses due to static moment of friction, hysteresis, and drag resulting from time-varying flux. Equation (2) presents the total disturbance d in the mechanical motion equation including load torque T_L, which will be estimated based on the estimation of the mechanical speed of PMSM via HODO observer. Thus, the total disturbance d in the system can be defined as

$$d = \frac{1}{J}\left(\frac{z_p T_L}{2} + \left(C_{hy}+C_f\right)\,\mathrm{sign}\,(\omega) + z_p d_{ed}\frac{\dot{\Psi}_{dq}\Psi_{dq}}{\left|\Psi_{dq}\right|^2}\right) \tag{2}$$

T_L— rated load torque, Nm C_f— static moment of friction, Nm C_{hy}— hysteresis losses coefficient, N$\cdot$ m

d_{ed}— eddy currents damping coefficient, (Nm/(rad/s))

Ψ_{dq}— d-q frame magnetic flux linkage, Wb In (1), it should be noted that ω, i_{ds}, i_{qs} are states; V_{ds} and V_{qs} are the control inputs, and d is the total disturbance including load torque T_L. To design a DOBC with HODO, the following assumptions are established. Also, note that the permanent magnets' flux in (1) is aligned with only the d-axis.

Assumption 1: ω, i_{qs}, and i_{ds} are measurable.

Assumption 2: $\dot{d} \neq 0$

Note that in many existing disturbance observers, the disturbance is assumed to be slowly varied, i.e., its time derivative is zero. In the proposed HODO, this constraint is released.

B. BASELINE DISCRETE-TIME CASCADE PI-PI CONTROL SYSTEM

For the baseline speed controller implementation the total disturbance value and PMSM's parameters are not needed due to model free nature of PI control algorithm. Then PI-PI cascade closed-loop control is sufficient to achieve satisfactory performance for speed regulation. The control objective in this case is to achieve a specified tracking performance by means of the PI controller and facilitate zero errors in finite time. The speed loop controller can be formulated with the following formulas based on Fig. 1.

$$|inSat = 0|\,,\ \text{and}\ |inAW = 0|\,\{out = 0\} \tag{3}$$
$$|inSat \geq \mp Sat|\,,\ \text{and}\ |inAW \geq \mp AW|\,\{out = \mp Sat\} \tag{4}$$
$$|inSat < \mp Sat|\ \text{and}\ |inAW \geq \mp AW|\ @comma$$

$$\left\{\mathrm{out} = \tilde{\omega}\mathrm{K_p} - (\mp\mathrm{AW})\right\} \tag{5}$$

$|\mathrm{inSat} < \mp\mathrm{Sat}|$ and $|\mathrm{inAW} < \mathrm{AW}|$,

$$\left\{\begin{array}{l}\mathrm{out} = \tilde{\omega}\mathrm{K_p} - (\frac{1}{2}\frac{1}{z}\mathrm{K_{pi}}\tilde{\omega}\mathrm{K_p}\mathrm{T_s} + (\frac{1}{2}\mathrm{K_{pi}}\tilde{\omega}\mathrm{K_p}\mathrm{T_s} \\ +\frac{1}{z}\mathrm{inAW} - \frac{1}{z}\mathrm{eSatK_{back}} - \frac{1}{z}\mathrm{eAW}))\end{array}\right\} \tag{6}$$

where

inSat– input of saturation block
$\mp Sat$– output of saturation block
out– output of PI controller
inAW– input of anti-windup block
$\mp AW$– output of anti-windup block
eSat– error of saturation block
eAW– error of anti-windup block
$\tilde{\omega}$– speed error, rad/s
$\mathrm{K_p}$– proportional gain
$\mathrm{K_{pi}}$– proportional-integral gain
$\mathrm{T_s}$– sampling time
$\frac{1}{z}$– unit delay
$\mathrm{K_{back}}$– back-calculation gain

III. DISTURBANCE OBSERVER BASED CONTROL

A. BASIC CONCEPT OF DOBC

Linear plant in the time domain is characterized by the following system of equations

$$\begin{aligned}\dot{x} &= \mathrm{Ax} + \mathrm{Bu} + \mathrm{Dd} \\ \mathrm{y} &= \mathrm{Cx}\end{aligned} \tag{7}$$

where x, u, d are the state, input, and disturbance vectors; A, B, C, D denote coefficient matrices of the system.

The design procedure of disturbance observer based control (DOBC) consists of integrating the baseline speed controller and disturbance observer to compensate for the total disturbance in the control law [34].

Suppose the control law of the baseline controller u^* is given by the following equation

$$\mathrm{u}^* = \mathrm{f(x)} \tag{8}$$

By assuming that the disturbance in the state input in the same channel is zero, composite control law of the stated DOBC above is expressed as follows

$$\mathrm{u} = \mathrm{u}^* + \hat{\mathrm{d}} = \mathrm{f}\,(\mathrm{x}) + \hat{\mathrm{d}} \tag{9}$$

Because DOBC is flexible, it can be combined with various control schemes to improve its ability to reject disturbance.

Then estimated error of total disturbance is

$$\tilde{\mathrm{d}} = \hat{\mathrm{d}} - \mathrm{d} \tag{10}$$

where superscript ^and ∼ denotes the estimated and error values, respectively. From (9) it can be stated the following

$$\mathrm{Dd} = \dot{\mathrm{x}} - \mathrm{Ax} - \mathrm{Bu} \tag{11}$$

B. COGGING TORQUE AS FAST VARYING DISTURBANCE IN PMSM SYSTEM

The model based control techniques are effective way to handle complex system. However, various sources of disturbance, coming from cogging torque, flux harmonics may influence in practical PMSM system to design ideally controllable MIMO system with high performance [8]. These types of the disturbances with high order nature are difficult to model and hence should be estimated by sophisticated disturbance observer separately in PMSM applications.

The utilization of different materials for the rotor in PMSM, the structure of windings of the motor may induce various pulsating torques, which is also called cogging. This happens due to interaction of the rotor magnetic flux and angular variations in the stator magnetic reluctance. It should be noted that cogging torque is presented even if power source is disconnected and defined as

$$\mathrm{d_T^{cog}} = \sum\nolimits_{i=1}^{\infty} \mathrm{d_T^{cogi}}\sin(\mathrm{iN_c}\theta_\mathrm{e}) \tag{12}$$

where $\mathrm{N_c}$ is the least common multiple between the number of slots and pole pairs, θ_e is the electrical angle expressed as $\theta_\mathrm{e}\,(\mathrm{t}) = \theta_\mathrm{e}\,(\mathrm{t_0}) + \int_{t_0}^{t} z_p\omega(\tau)d\tau$ and $\mathrm{d_T^{cogi}}$ is the amplitude of the i-order harmonic cogging torque.

The flux density of the materials used for the magnet in PMSM is mostly changed by the temperature variation. The resultant demagnetization phenomenon of permanent magnets due to rise of temperature has a significant impact on the maximum torque capability and the efficiency of PMSM. The flux linkage between the rotor and stator magnets can be expressed as

$$\lambda_\mathrm{m} = \sum\nolimits_{i=0}^{\infty} \lambda_\mathrm{mi}\cos(6\mathrm{i}\theta_\mathrm{e}), \tag{13}$$

where λ_mi is the amplitude of the 6^{th}-order harmonic flux. According to the definition of electromagnetic torque, $\mathrm{T_e} = \frac{3}{2}\mathrm{z_p}\lambda_\mathrm{m}\mathrm{i_{qs}}$, it is indicated that the effect of flux harmonics can be represented as follows:

$$\mathrm{d_T^{flux}} = \frac{3}{2}\mathrm{z_p}\mathrm{i_{qs}}\sum\nolimits_{i=0}^{\infty} \lambda_\mathrm{m}\cos(6\mathrm{i}\theta_\mathrm{e}), \tag{14}$$

The main disturbances of PMSM system are cogging torque and flux harmonics. These disturbances cause ripples and hence errors in the speed response in the steady state and bigger errors during transient times. These internal disturbances along with external ones such as friction and load torque are always presented in the system; therefore, they should be compensated with comprehensive disturbance observer, which will be presented in the next subsection. Further, the aforementioned disturbances will be considered as total disturbance.

Note that there is another source of high-order disturbance of PMSM drives, it comes from the PWM inverter.

C. HIGH ORDER DISTURBANCE OBSERVER DESIGN

While speed controller in the conventional PI-PI control is easy to implement with fixed gains, the tracking accuracy can be degraded under various operational conditions. The total disturbance including load torque T_L is assumed to be slowly varying in time. Thus, under this assumption the effectiveness of a disturbance observer in terms of accuracy can be relaxed. The suddenly activated load torque does not affect to the stability of the operation process. Therefore, to improve the performance of the PI speed controller with tracking back-calculation anti-windup scheme, HODO observer can be integrated to compensate the disturbances. The HODO observer is constructed based on the mechanical motion in the system (1).

The original concept of a HODO design is presented for wind speed estimation in renewable energy generation application [35]–[38] even for the case of fast-varying disturbance. HODO is considered as a cost efficient solution with acceptable range of accuracy in estimating aerodynamic torque. Using inappropriate observers leads to poor performance of whole control system. The high-quality observer along with robust controller can provide better performance in speed control of PMSM under various disturbances.

To estimate the total disturbance d including load torque T_L, the first equation of (1) should be recalled,

$$\dot{\omega} = k_1 i_{qs} - k_2\omega - k_3 d \tag{15}$$

Then high order disturbance observer is designed as

$$\begin{cases} \dot{\hat{\omega}} = k_1 i_{qs} - k_2\omega - k_3\hat{d} \\ \hat{d} = L_{11}g_1 + L_{12}g_2 + L_{13}g_3 \\ g_1 = -\dfrac{(\omega - \hat{\omega})}{k_7} \\ \dot{g_2} = g_1 \\ \dot{g_3} = g_2 \end{cases} \tag{16}$$

where L_{11}, L_{12}, L_{13} are observer gains for estimation the total disturbance.

Theorem 1: With observer gains L_{1k}, L_{2k}, L_{3k} ($k = 1, 2, 3$) are chosen such that the following polynomial is stable by the Hurwitz's criterion

$$r(s) = s^{k_1+1} + L_1 s^{k_1} + L_2 s^{k_1-1} + \cdots + L_{k_1} \tag{17}$$

Then the estimated disturbance asymptotically converges to the true value.

Proof: This is straightforward to see that if $(k+1)^{th}$ time derivative of disturbance is zero, $d^{(k+1)} = 0$, then the Theorem 1 is hold. More details on how to choose the gains to achieve stability and less steady-state errors in estimation with HODO observer are given in [35]–[38].

D. DISTURBANCE COMPENSATION

As $B \neq D$, the disturbance affects to state input through the different channel. In order to derive synthesized control law of HODO based speed controller, dynamics of the system is written as

$$\dot{x} = Ax + B(u + \frac{D}{B}d) \tag{18}$$

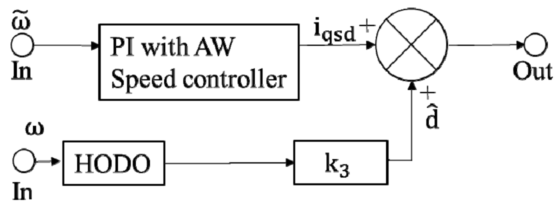

FIGURE 2. **The total disturbance compensation in the speed controller of the proposed control design.**

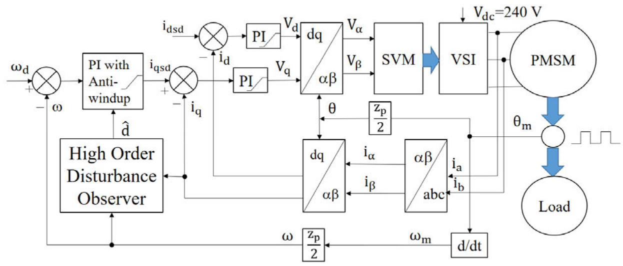

FIGURE 3. **Proposed DOBC based control method structure.**

The discrete PI speed and current controllers with tracking back-calculation based anti-windup scheme serves as baseline controller. The design procedures of the controllers have been thoroughly studied in [11], [26], and [27]. According to (9), the synthesized control law of HODO based PI-PI control system is

$$i_{qsd} = K_p(\omega - \omega_d) + K_I \int_{i=0}^{\infty} (\omega - \omega_d)dt + k_3\hat{d} \tag{19}$$

where ω_d – desired speed, RPM; speed error is $\tilde{\omega} = \omega - \omega_d$; and d-axis reference current is $i_{dsd} = 0$.

The estimated total disturbance is compensated in the speed loop of the proposed control design (Fig. 2).

E. HODO BASED DISCRETE-TIME PI WITH TRACKING ANTI-WINDUP SCHEME

In Fig. 3, the architecture of the proposed DOBC control to compensate the total disturbance is shown. While the inputs of saturation (inSat) block is between its limits, the estimated total disturbance, $\hat{d}$ is injected to the outputs of anti-windup, AW to be compensated in the speed loop of the proposed control system. Otherwise, the outputs of the speed controller is equal to $\mp$Sat and the estimated value does not affect to reference q-axis current in steady state.

The logic of the proposed speed controller is explained briefly below. When the posed conditions of the equations (3) and (4) are true the proposed controller's outputs will not exceed the limits of the saturation block or zero.

$$|inSat = 0|\,,\ \text{and}\ |inAW = 0|\,\{out = 0\} \tag{20}$$

$$|inSat \geq \mp Sat|\,,\ \text{and}\ |inAW \geq \mp AW|\,\{out = \mp Sat\} \tag{21}$$

When the posed conditions in the equations (5) and (6) are true the proposed speed controller will be completed with the compensating term $k_3\hat{d}$.

$$|\mathrm{inSat} < \mp\mathrm{Sat}| \text{ and } |\mathrm{inAW} \geq \mp\mathrm{AW}|,\quad \left\{\mathrm{out} = \mathrm{eK_p} - (\mp\mathrm{AW}) + k_3\hat{\mathrm{d}}\right\} \tag{22}$$

$$|\mathrm{inSat} < \mp\mathrm{Sat}| \text{ and } |\mathrm{inAW} < \mathrm{AW}|,\quad \left\{\begin{array}{l} \mathrm{out} = \mathrm{eK_p} - (\frac{1}{2}\frac{1}{\mathrm{z}}\mathrm{K_{pi}eK_pT_s} + (\frac{1}{2}\mathrm{K_{pi}eK_pT_s} \\ +\frac{1}{\mathrm{z}}\mathrm{inAW} - \frac{1}{\mathrm{z}}\mathrm{eSatK_{back}} - \frac{1}{\mathrm{z}}\mathrm{eAW})) + k_3\hat{\mathrm{d}} \end{array}\right\} \tag{23}$$

F. CLOSED-LOOP STABILITY ANALYSIS

First, let us consider the stability of anti-windup PI control without the HODO [39]. The output of the PI speed controller $\mathrm{i_{qs}}$ can be written as,

$$\mathrm{i_{qs}} = \mathrm{eK_p} + \mathrm{q} \tag{24}$$

where $\mathrm{e} = \omega_\mathrm{d} - \omega$ and q is the anti-windup integral state. According to [39], as the speed error dynamics is much slower than that of the integral state, the integral state q can be neglected, so controller output u is reduced to,

$$\mathrm{i_{qs}} = \mathrm{eK_p} \tag{25}$$

Therefore, there exists a speed error bound $\mathrm{I_b}$ which determines the operating regions of the PI controller, which can be defined as,

$$\mathrm{I_b} = \frac{\mathrm{I_{max}}}{\mathrm{K_p}} \tag{26}$$

where $\mathrm{I_{max}}$ is the maximum stator current. If $|\mathrm{e}| \leq \mathrm{I_b}$, the PI controller is in the linear region; otherwise, it is in the saturation region.

Define the Lyapunov function given by

$$\mathrm{V}(\mathrm{e}) = \frac{1}{2}\mathrm{e}^2 \tag{27}$$

On the other hand, we have,

$$\dot{e} = -\mathrm{k_1 i_{qs}} - \mathrm{k_2 e} + \mathrm{k_2}\omega_\mathrm{d} + \mathrm{k_3 d} \tag{28}$$

So the derivative of the Lyapunov function is,

$$\begin{aligned} \dot{V} &= \mathrm{e}\dot{e} \\ &= \mathrm{e}\left(-\mathrm{k_1 i_{qs}} - \mathrm{k_2 e} + \mathrm{k_2}\omega_\mathrm{d} + \mathrm{k_3 d}\right) \\ &\leq -\mathrm{k_2 e^2} - \mathrm{k_1 K_p}|\mathrm{e}|\,\mathrm{I_{max}} + |\mathrm{e}|\,(\mathrm{k_2}\omega_\mathrm{d} + \mathrm{k_3 d}) \end{aligned} \tag{29}$$

The tracking error is asymptotically converged to zero when $\dot{V} \leq 0$, which means the following condition is satisfied,

$$|\mathrm{e}| \leq \frac{1}{\mathrm{k_2}}\left(-\mathrm{k_1 K_p I_{max}} + \mathrm{k_2}\omega_\mathrm{d} + \mathrm{k_3 d}\right) \tag{30}$$

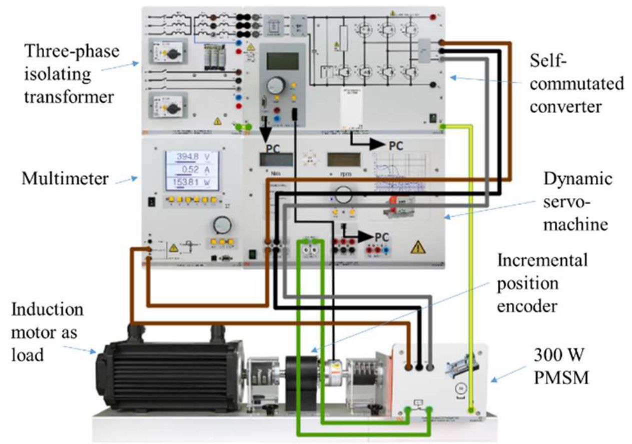

FIGURE 4. DSP based experimental setup for PMSM control (manufactured by Lucas-Nuelle gGmbH).

The maximum error should be less than the error bound in (26) to guarantee that the PI controller will transfer from saturation region to the linear region, it means,

$$\omega_\mathrm{d} + \frac{\mathrm{k_3}}{\mathrm{k_2}}\mathrm{d} \leq \left(\frac{\mathrm{k_1 K_p}}{\mathrm{k_2}} + \frac{1}{\mathrm{K_p}}\right)\mathrm{I_{max}} \tag{31}$$

Now we consider the closed-loop stability. Let define the estimation error as

$$\mathrm{e_o} = \mathrm{d} - \hat{\mathrm{d}} \tag{32}$$

Then (28) becomes,

$$\dot{e} = -\mathrm{k_1 i_{qs}} - \mathrm{k_2 e} + \mathrm{k_2}\omega_\mathrm{d} + \mathrm{k_3}\hat{\mathrm{d}} + \mathrm{k_3 e_o} \tag{33}$$

Lemma 1([40]): Let us take into consideration a system as follows

$$\left\{\begin{array}{l} \dot{\mathrm{z}} = f(\mathrm{z}, \tilde{\mathrm{y}}) \\ \dot{\tilde{\mathrm{y}}} = g(\tilde{\mathrm{y}}) \end{array}\right. \tag{34}$$

where $\dot{\tilde{y}} = g(\tilde{y})$ has an asymptotically stable equilibrium at $\tilde{y} = 0$. If $\dot{z} = f(z, 0)$ has an asymptotically stable equilibrium at $z = 0$, then (34) has an asymptotically stable equilibrium at $(z, \tilde{y}) = (0, 0)$.

Theorem 2: With the given PI controller and observer, the tracking error e and estimation error eo asymptotically converge at zero.

Proof: Firstly, according to condition (31), the dynamics@comm

$$\dot{e} = -\mathrm{k_1 i_{qs}} - \mathrm{k_2 e} + \mathrm{k_2}\omega_\mathrm{d} + \mathrm{k_3 d} \tag{35}$$

has an asymptotically stable equilibrium at zero.

Secondly, in Theorem 1, it is proven that the estimation errors of the disturbance converge asymptotically to the stable equilibrium zero. Then, by referring to Lemma 1, it implies that tracking error e and estimation error $_\mathrm{eo}$ are asymptotically stable at zero.

TABLE 1. PMSM technical data.

Motor parameters	Symbol	Value
Rated speed	n_n (RPM)	6000
Rated torque	M_n (Nm)	0.97
Rated power	P_n (W)	300
Torque constant	K_{tRMS} (Nm/A)	0.41
Voltage constant	K_{eRMS} (Nm/A)	26.1
Permanent magnetic flux coefficient	λ_m (Vs)	0.089
Winding resistance Ph-Ph	R_s (Ohm)	4.74
Winding inductance Ph-Ph	L_s (mH)	8.6
Rotor's moment of inertia	J (kgcm^2)	0.33
Number of poles	z_p	8
Static moment of friction	C_f (Nm)	0.014
Hysteresis losses coefficient	C_{hys} (Nm)	0.08
Viscous damping coefficient	b (N·m/(rad/s))	0.002
Eddy currents coefficient	c_{ed} (Nm/(rad/s))	0.0015
Eddy currents damping coefficient	d_{ed} (Nm/(rad/s))	0.003

TABLE 2. Control system's parameters.

Controllers and Observers	Parameters and Gains
Speed controller PI gains	$K_p = 0.057, K_I = 0.04$
Current controllers PI gains	$K_p = 17.1, K_I = 0.0018$
$\hat{T}_L$ observer gains	L_{11}=500, L_{12}=250, L_{13}=100

IV. EXPERIMENTAL RESULTS

The experimental setup configuration is shown in Fig. 4. DSP based "Controlled permanent magnet servo drive with MATLAB/Simulink 300W" (manufactured by Lucas-Nuelle gGmbH) was used to test the proposed HODO based PI-PI control system with tracking anti-windup scheme. The experimental setup comprises surface mounted type PMSM that coupled with 1024 pulses incremental position encoder and servo-machine operated with ActiveServo software acting as a load. The control algorithm is written in Matlab/Simulink (R2016b) environment then the code generated by Code Composed Studio 5 is sent to servo-converter for real-time experiment control. Note, after loading the code, no modification of gains is allowed. For a new configuration and modification of gains, the code generation has to be performed again. The switching period of the self-commutated converter is set to 125 μs. The control routine frequency for the pulse width modulation technique (PWM) in the inverter is set to 8 kHz. The parameters of the PMSM are listed in Table 1.

To confirm the effectiveness of the proposed HODO-based controlled system design, let us consider a prototype of SPMSM with the following nominal parameters given in Table 1.

A space vector pulse width modulation (SVPWM) technique is used to regulate the phase currents flowing into the PMSM. For evaluation of performance of the proposed control scheme, in this paper, the experimental results of the baseline controller without HODO are compared with the results of the proposed HODO based PI-PI control system with tracking anti-windup scheme utilized. Two cases with speed variation and load torque disturbance have been investigated.

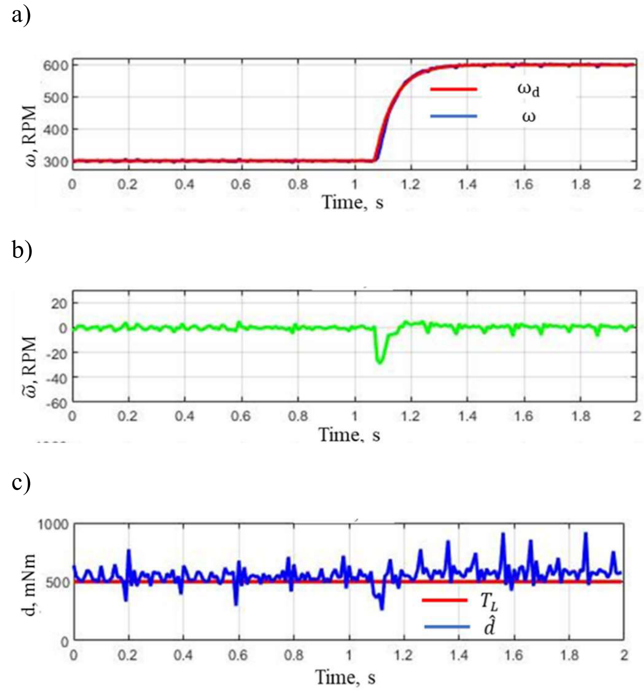

FIGURE 5. Experimental results of the proposed HODO based PI with novel anti-windup scheme for case 1. (a) Mechanical speed response of PMSM; (b) Mechanical speed error; (c) Estimated load torque disturbance.

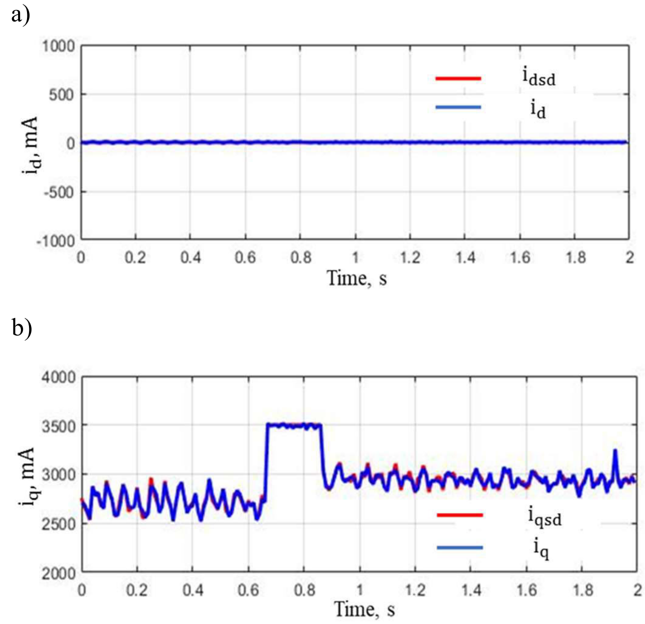

FIGURE 6. dq-axis currents of the proposed HODO based PI with novel anti-windup scheme for case 1. (a)i_{ds} and its desired value i_{dsd}; (b) i_{qs} and its desired value i_{qsd}.

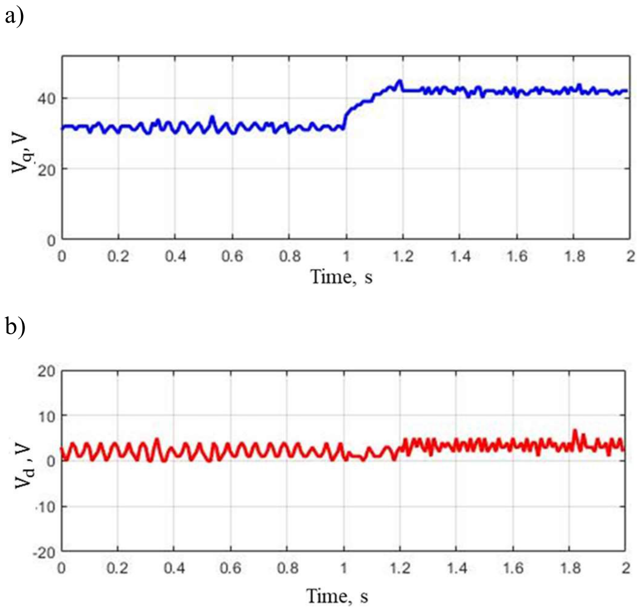

FIGURE 7. dq-axis voltages under proposed HODO based PI with novel anti-windup scheme for case 1. (a) control input on q-axis V_{qs}; (b) control input on d-axis V_{ds}.

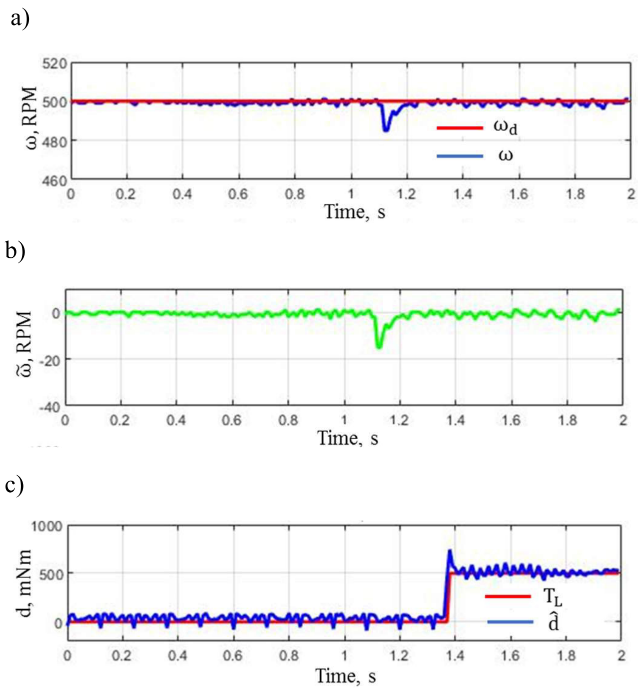

FIGURE 8. Experimental results of the proposed HODO based PI with novel anti-windup scheme for case 2. (a) Mechanical speed response of PMSM; (b) Mechanical speed error; (c) Estimated load torque disturbance.

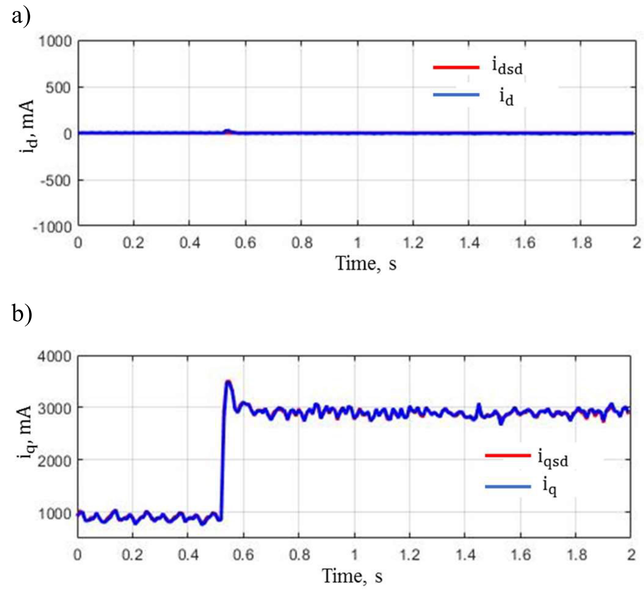

FIGURE 9. dq-axis currents of the proposed HODO based PI with novel anti-windup scheme for case 2. (a) i_{ds} and its desired value i_{dsd}; (b) i_{qs} and its desired value i_{qsd}.

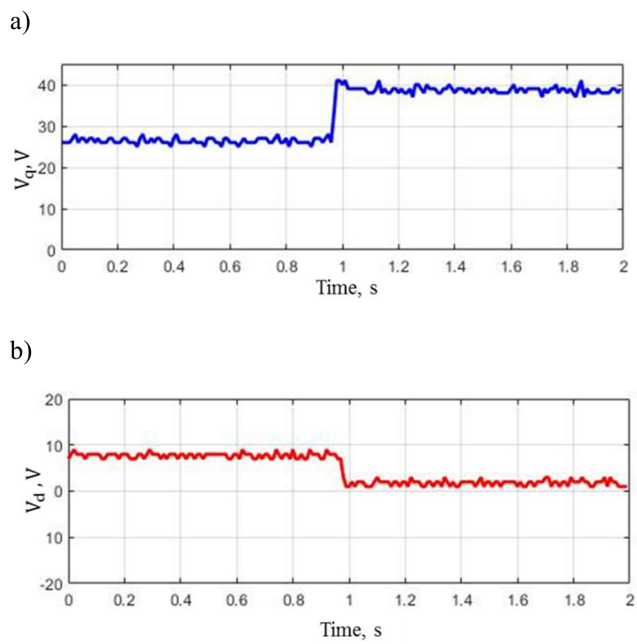

FIGURE 10. dq-axis voltages under the proposed HODO based PI with novel anti-windup scheme for case 2. (a) control input on q-axis V_{qs}; (b) control input on d-axis V_{ds}.

Case 1: Speed Transient Response with nominal parameters

1) The desired speed (ω_d): 300 RPM → 600 RPM.
2) Constant load torque $T_L = 0.5$ Nm.
3) No load torque disturbance.

Case 2: Load Torque Transient Response

1) The desired speed $\omega_d = 500$ RPM.
2) Load torque disturbance $T_L = 0.3$ Nm → 0.5 Nm.

The round or trapezoidal shaped reference speed has been chosen for PMSM, as it is more effective against wear of mechanical coupling of the prototype PMSM like in the industrial applications [28]. However, the load torque disturbance has been applied as step-wise.

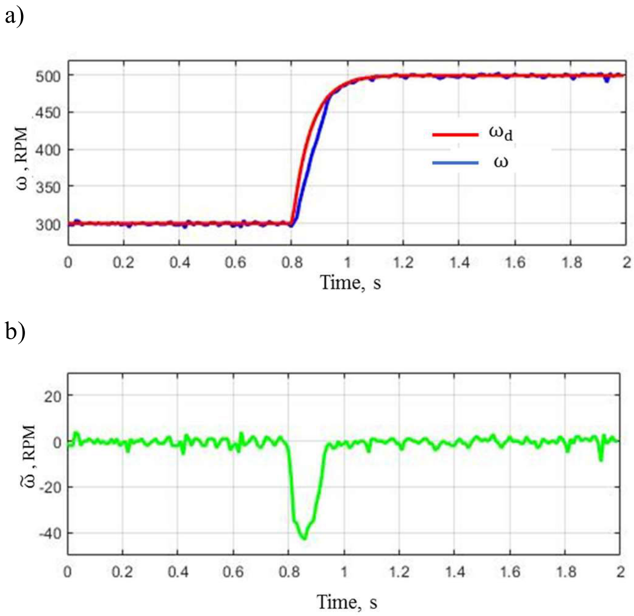

FIGURE 11. Experimental results of the baseline control for case 1. (a) Mechanical speed response of PMSM; (b) Mechanical speed error.

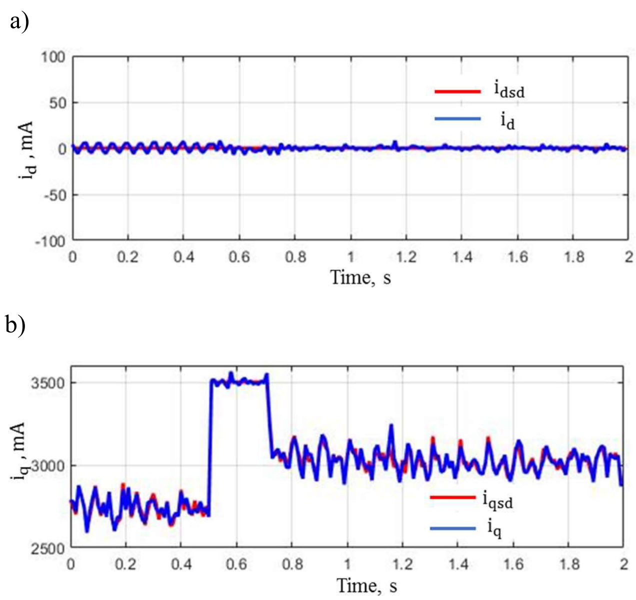

FIGURE 12. dq-axis currents of baseline control for case 1. (a) i_{ds} and its desired value i_{dsd}; (b) i_{qs} and its desired value i_{qsd}.

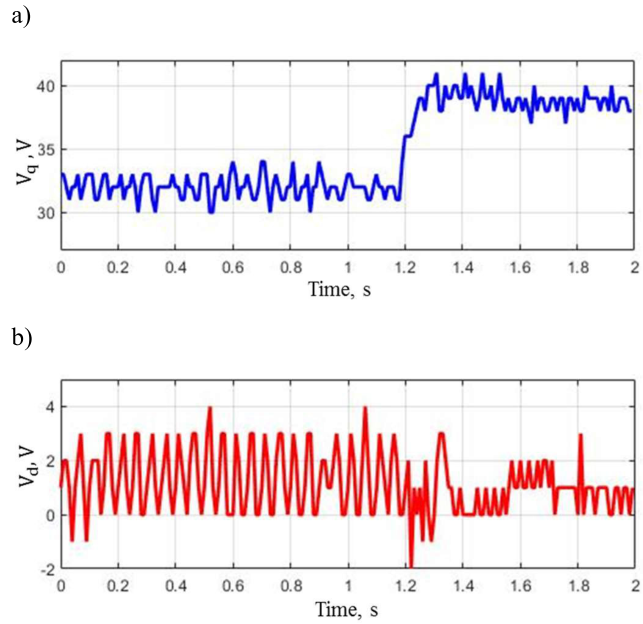

FIGURE 13. dq-axis voltages of the baseline control for case 1. (a) control input on q-axis V_{qs}; (b) control input on d-axis V_{ds}.

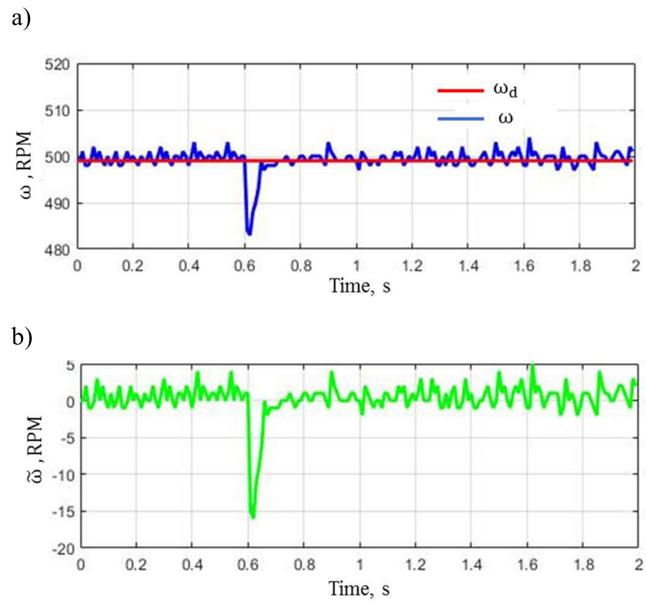

FIGURE 14. Experimental results of the baseline control for case 2. (a) Mechanical speed response of PMSM; (b) Mechanical speed error.

HODO has been synthesized with the baseline control system to compensate the total disturbance and improve transient performance. The speed response and the total disturbances estimation in the proposed control as well as other important variables' graphs are presented below.

Figs. 5-15 show the experimental results of the proposed control method under two operational cases to assess its performance against the baseline controller. The currents and the voltages have been measured and converted to d-q frame (i_{qs}, i_{ds}, V_{qs}, V_{ds}). The mechanical speed of PMSM (ω) as well as its tracking error ($\tilde{\omega}$) and the estimated total disturbances ($\hat{d}$) have been shown and compared with their reference values. Figs 5-7 are results under conditions in *Case 1*, while Figs 8-10 are outcomes obtained under *Case 2*. Also, in Figs 11-13, the results of baseline controller are shown under *Case 1* whereas the results for *Case 2* are presented in Figs 14-16. The detailed performance of the proposed control design is summarized in Table 3. Based on the

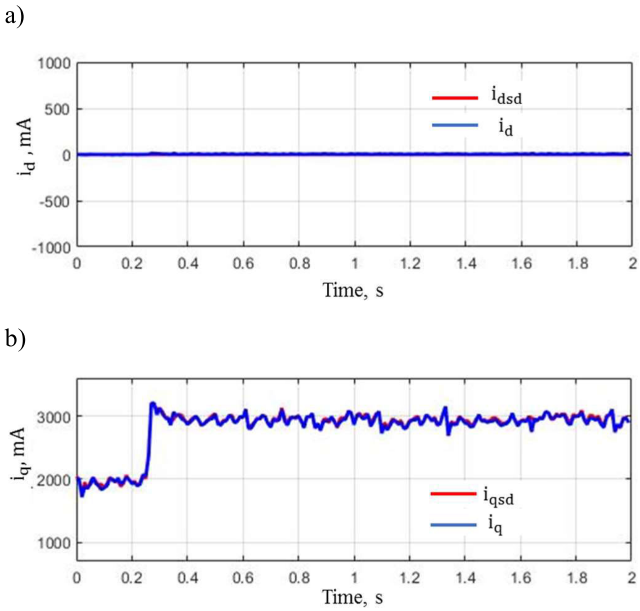

FIGURE 15. dq- axis currents of the baseline control for case 2. (a) i_{ds} and its desired value i_{dsd}; (b) i_{qs} and its desired value i_{qsd}.

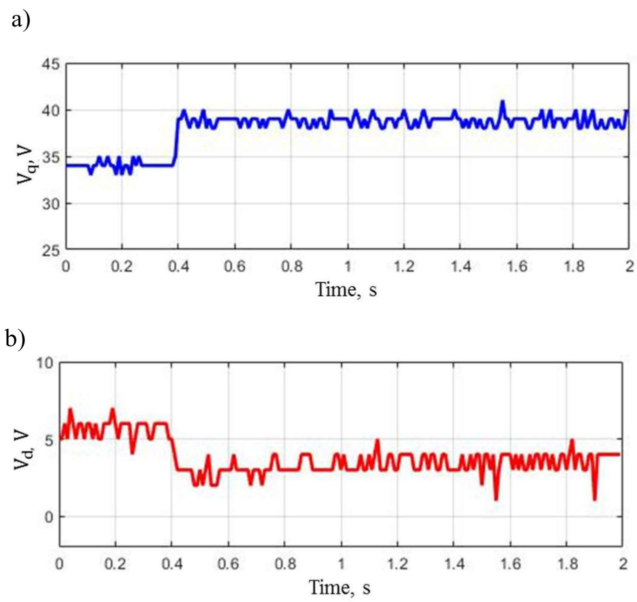

FIGURE 16. dq- axis voltages of the baseline control for case 2. (a) control input on q-axis V_{qs}; (b) control input on d-axis V_{ds}.

experimental results shown below, the settling time and absolute mean mechanical speed errors are improved considerably (settling time under *Case 1*: 6.7%, *Case 2*: 52.94%; absolute mean mechanical speed error under *Case 1*: 29.34%, *Case 2*: 17.01%). While maximum mechanical speed error under the proposed control in *Case 1* is decreased by 44.8%, in *Case 2* this criterion is decreased by 13.3%. The absolute mean of the total disturbances are 11.69% and 12.86% for *Cases 1* and *2*, respectively. The absolute mean of the total disturbances is calculated with respect to the reference load torque value, hence the big error value coming from the total disturbance.

TABLE 3. Performance of the proposed HODO based PI-PI with anti-windup control scheme.

Criteria and cases		PI with anti-windup	PI with anti-windup and HODO,%	Improved, %
Maximum speed error, rad/s	Case 1	42	29	44.8%
	Case 2	17	15	13.3%
Settling time, s	Case 1	0.3	0.28	6.7%
	Case 2	0.17	0.08	52.94%
Absolute mean of the total disturbances estimation error,%	Case 1	-	11.69%	n/a
	Case 2	-	12.86%	n/a
Absolute mean of the mechanical speed error,%	Case 1	-1.4838%	1.049%	29.34%
	Case 2	0.172%	0.147%	17.01%

There are no the overshoot in transient time due to the round shaped reference in both cases.

In the PMSM system, the total disturbance has been estimated with HODO which demonstrates fluctuations above load torque level, especially during the transient time (Fig. 5, c). The pulsating torques can be seen in the d-q currents plots, especially in q part (Fig. 6,b). In fact, the speed errors during the transient time for both cases with control system without disturbance observer are the most significant. However, the proposed control scheme can provide reduction of speed error not only during transient but also overall robust performance.

V. CONCLUSION

In this paper, disturbance observer based control for the PMSM prototyping kit is proposed. The cascade structure of discrete-time PI-PI control system equipped with tracking anti-windup scheme has been utilized for both loops. As the total disturbance estimation with HODO is based on the accurate prediction of the mechanical speed, the detailed motion equation of the PMSM has been derived. The motion equation in the proposed HODO includes terms associated with torque losses due to drag resulting from time-varying flux, friction, and hysteresis. It has demonstrated its ability to improve the speed tracking performance under the external disturbance and unmodelled dynamics associated with a cogging torque and a high-frequency electromagnetic noise in the PMSM system. The estimated total disturbance is compensated in the speed controller. A zero steady-state errors have been achieved in the real time experiment. The mechanical speed errors were minimized in both operation scenarios. The performances of the proposed and baseline control algorithms have been evaluated under mechanical speed and load torque variations. The performance of the novel control system has shown better robustness to the external disturbances.

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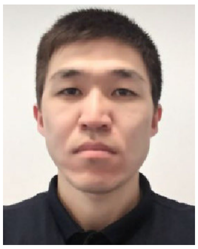

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