

Comparison study of Non-Adaptive and Adaptive Backstepping in Control of Permanent Magnet Synchronous Motor

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ABSTRACT: This paper addresses the comparison study between non-adaptive and adaptive backstepping control of the permanent magnet synchronous motor (PMSM) using a three level inverter (NPC). First, a non-adaptive backstepping approach is designed by defining the virtual control variables and selecting the Lyapunov functions. Secondly, the adaptive backstepping is investigated by deriving the control laws and parameters adaptation. The proposed strategy is regulating the rotor speed according to stator resistance and load torque parameters adaptation that estimated in real time. Therefore, the ability of disturbances rejection is improved. Simulation results show a signify static error in tracking speed in case of non-adaptive, while adaptive method is robust against load disturbances and parameter variations.

KEYWORDS: PMSM, Adaptive Backstepping, Parameters estimation, speed control.

I. INTRODUCTION

Since the permanent magnet synchronous motor (PMSM) with high efficiency, high torque inertia ratio, and high power density, it is widely used in electric vehicles [1], industrial robots [2], machine tools, and other high-performance motor drive system.

High-performance PMSM drive systems generally use vector control, which can achieve excellent static and dynamic speed performance, but the accuracy of field-oriented motor parameters susceptible to change, and motor speed control using a PI controller is seems not robust also to load torque disturbances.

In recent years, in order to overcome the time varying parameters and load disturbance on the motor drive system, some of the non-linear control methods are applied to control of permanent magnet synchronous motor, such as linear state feedback resolve decoupling control [3-4], variable structure control [5-6], disturbance rejection control [7] and backstepping control [8-9], etc. In this paper, the backstepping control method is chosen due to easy implementation with adaptive parameter estimation system to reduce uncertainty influencing disturbances. This control is designed by introducing virtual control variables and choosing an appropriate Lyapunov function to guarantee the asymptotic convergence of virtual control, and gradually the final export control law and parameter adaptive law.

This paper is organized as follows: The modelling of the permanent magnet synchronous motor is presented in the second section, the neutral point clamped converter is depicted in the third section, and the non-adaptive and adaptive-backstepping control is shown in the fourth section. Finally, simulation results are carried out in Matlab/Simulink.

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II. PMSM MOTORMODEL

PMSM is described in synchronous d-q frame by the following mathematical model [10]:

$$v_d = R_s i_d + \frac{d\phi_d}{dt} - \omega \phi_q \quad (1)$$

$$v_q = R_s i_q + \frac{d\phi_q}{dt} + \omega \phi_d \quad (2)$$

$$\phi_d = L_d i_d + \phi_f \quad (3)$$

$$\phi_q = L_q i_q \quad (4)$$

The electromagnetic torque is defined by:

$$T_e = \frac{3}{2} p [\phi_f i_q + (L_d - L_q) i_d i_q] \quad (5)$$

The mechanical equation is given by:

$$J \frac{d\omega_r}{dt} = T_e - B\omega_r - T_L \quad (6)$$

Where:

v_d, v_q d and q axis stator voltages;

i_d, i_q d and q axis stator currents;

ϕ_d, ϕ_q d and q axis stator flux;

L_d, L_q d and q axis stator inductances;

T_e, T_L electromagnetic and load torque;

R_s stator resistance;

ϕ_f flux linkage created by rotor magnets;

J moment of inertia;

B coefficient of viscosity;

p number of poles pairs;

ω electrical frequency;

ω_r rotor speed;

Electrical frequency and rotor speed are linked by the following equation:

$$\omega = p\omega_r \quad (7)$$

Hence, the state equation of the PMSM are deduced:

$$\begin{cases} \frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \frac{pL_q}{L_d} \omega_r i_q + \frac{1}{L_d} v_d \\ \frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - \frac{pL_d}{L_q} \omega_r i_d - \frac{p\phi_f}{L_q} \omega_r + \frac{1}{L_q} v_q \\ \frac{d\omega_r}{dt} = \frac{3p}{2J} [\phi_f i_q + (L_d - L_q) i_d i_q] - \frac{B}{J} \omega_r - \frac{T_L}{J} \end{cases} \quad (8)$$

III. NEUTRAL POINT CLAMPED CONVERTER

A. Configuration of NPC converter

The configuration of the NPC converter is illustrated in Fig. 1. Each leg is composed of four IGBTs connected in series. The bus voltage is divided in two by using two equal capacitors. Each leg is expected to be completed by two clamp diodes. For one phase, when IGBT Q1 and Q2 are turned on, the output is connected to V_p ; when Q2 and Q3 are on, the output is connected to V_o ; and when Q3 and Q4 are on, the output is connected to V_n . Switching states of the IGBTs are listed in Table I.

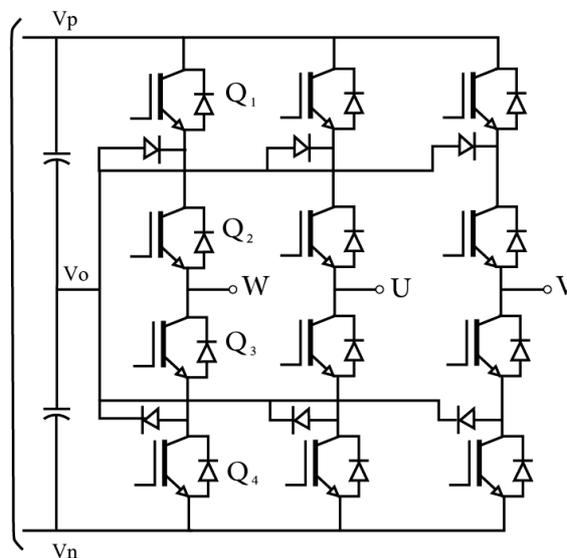


Fig. 1. Configuration of NPC converter.

TABLE I. SWITCHING STATES

IGBT	$V_{out}=V_p$	$V_{out}=V_o$	$V_{out}=V_n$
Q1	on	off	off
Q2	on	on	off
Q3	off	on	on
Q4	off	off	on

B. Sinusoidal Modulation using Multiple Carrier Waves (SPWM)

The multilevel SPWM modulation method is based on the comparison between the sinusoidal reference and many vertically shifted carriers' signals. For two level, the scheme is illustrated in Fig. 2. During a PWM period, if the modulation wave is greater than the upper carrier wave, switch Q1 is on and Q3 is off. In contrast, if the modulation wave is greater than the lower carrier wave, switch Q2 is on and Q4 is off.

IV. BACKSTEPPING CONTROL OF PMSM

A. Non adaptive case

In this mode of control, the parameters of the system are assumed known. The goal is to track the reference rotor speed; we begin by defining the speed error.

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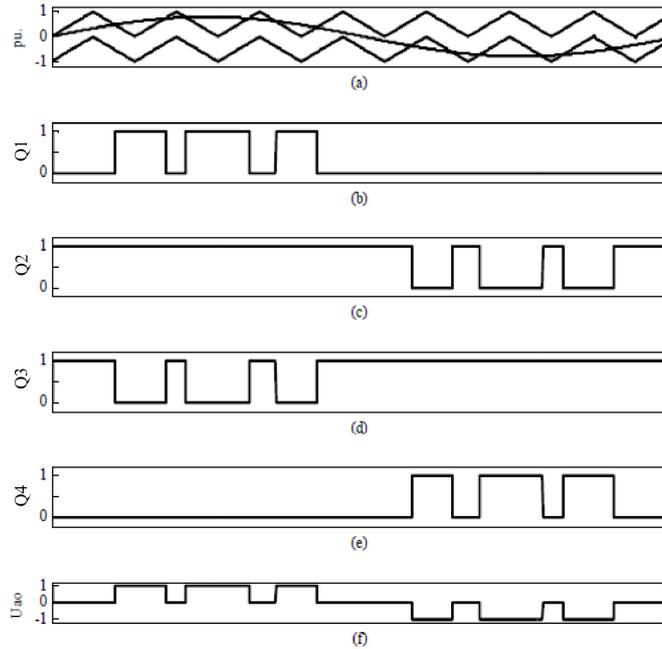


Fig. 2. (a) SPWM scheme for three-level NPC inverter, (b)-(e) the gate signals for switches Sa1, Sa2, Sa3, and Sa4, (f) output phase voltage

$$e_{\omega} = \omega_r^* - \omega_r \quad (9)$$

Where ω_r^* is the reference rotor speed and the dynamics of the error is:

$$\dot{e}_{\omega} = \dot{\omega}_r^* - \dot{\omega}_r \quad (10)$$

The dynamics of error is calculated by replacing the term of the derivative of rotor speed, and neglecting the dynamics of the desired speed:

$$\dot{e}_{\omega} = -\frac{1}{J} \left[\frac{3p}{2} \left[\varphi_f i_q + (L_d - L_q) i_d i_q \right] - B\omega_r - T_L \right] \quad (11)$$

Considering the dynamics error of rotor speed, the d-q axis currents are chosen as virtual control; to ensure the stability we chose the following Lyapunov function:

$$V_1 = \frac{1}{2} e_{\omega}^2 \quad (12)$$

The dynamics of Lyapunov function is calculated using Eq.(11):

$$\dot{V}_1 = e_{\omega} \dot{e}_{\omega} = \frac{e_{\omega}}{J} \left[-\frac{3p}{2} \left[\varphi_f i_q + (L_d - L_q) i_d i_q \right] + B\omega_r + T_L \right] \quad (13)$$

The tracking of reference is done by chosen the following stabilizing functions:

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$$i_d^* = 0 \quad (14)$$

$$i_q^* = \frac{2}{3p\phi_f} [B\omega_r + T_L + k_\omega J e_\omega] \quad (15)$$

Where $k_\omega > 0$ is the closed loop feedback constant.

Substituting Eq.(14) and Eq.(15) into Eq.(13), we get:

$$\dot{V}_1 = -k_\omega e_\omega^2 \quad (16)$$

Since the stator currents are not our control, we define the currents errors:

$$e_d = i_d^* - i_d \quad (17)$$

$$e_q = i_q^* - i_q \quad (18)$$

Substituting Eq.(14) and Eq.(15) into Eq.(11), the dynamics of rotor speed error becomes:

$$\dot{e}_\omega = \frac{1}{J} \left[\frac{3p}{2} \phi_f e_q + \frac{3p}{2} (L_d - L_q) i_q e_d - k_\omega J e_\omega \right] \quad (19)$$

In the next step, the dynamics the stabilizing error is computed:

$$\dot{e}_d = \frac{di_d^*}{dt} - \frac{di_d}{dt} = \frac{R_s}{L_d} i_d - \frac{pL_q}{L_d} \omega_r i_q - \frac{1}{L_d} v_d \quad (20)$$

$$\begin{aligned} \dot{e}_q &= \frac{di_q^*}{dt} - \frac{di_q}{dt} = \frac{2}{3p\phi_f} [B\dot{\omega}_r + \dot{T}_L + k_\omega J \dot{e}_\omega] \\ &+ \frac{R_s}{L_q} i_q + \frac{pL_d}{L_q} \omega_r i_d + \frac{p\omega_r \phi_f}{L_q} - \frac{v_q}{L_q} \\ &= \frac{2(k_\omega J - B)}{3p\phi_f J} \left(\frac{3p}{2} \phi_f e_q + \frac{3p}{2} (L_d - L_q) i_q e_d - k_\omega J e_\omega \right) \\ &+ \frac{R_s}{L_q} i_q + \frac{pL_d}{L_q} \omega_r i_d + \frac{p\omega_r \phi_f}{L_q} - \frac{v_q}{L_q} \end{aligned} \quad (21)$$

To ensure the global stability of the system, we define the following Lyapunov function:

$$V_2 = \frac{1}{2} (e_\omega^2 + e_d^2 + e_q^2) \quad (22)$$

Its derivative along the trajectories (19), (20), and (21) is calculated as follows:

$$\begin{aligned} \dot{V}_2 &= e_\omega \dot{e}_\omega + e_d \dot{e}_d + e_q \dot{e}_q \\ &= -k_\omega e_\omega^2 - k_d e_d^2 - k_q e_q^2 + \frac{e_\omega}{J} \left[\frac{3p}{2} \phi_f e_q + \frac{3p}{2} (L_d - L_q) i_q e_d \right] \\ &\quad + e_d \left[\frac{R_s i_d}{L_d} - \frac{pL_q \omega_r i_q}{L_d} - \frac{v_d}{L_d} + k_d e_d \right] \\ &\quad + e_q \left[\frac{2(k_\omega J - B)}{3p\phi_f J} \left(\frac{3p}{2} \phi_f e_q + \frac{3p}{2} (L_d - L_q) i_q e_d - k_\omega J e_\omega \right) \right. \\ &\quad \left. + \frac{R_s i_q}{L_q} + \frac{pL_d \omega_r i_d}{L_q} + \frac{p\omega_r \phi_f}{L_q} - \frac{v_q}{L_q} + k_q e_q \right] \end{aligned} \quad (23)$$

The above dynamics of Lyapunov function requires the following control:

$$\begin{cases} v_d = R_s i_d - pL_q \omega_r i_q + \frac{3pL_d}{2J} (L_d - L_q) i_q e_\omega + k_d L_d e_d \\ v_q = \frac{2L_q (k_\omega J - B)}{3p\phi_f J} \left(\frac{3p}{2} \phi_f e_q + \frac{3p}{2} (L_d - L_q) i_q e_d - k_\omega J e_\omega \right) \\ R_s i_q + pL_d \omega_r i_d + p\omega_r \phi_f + \frac{3p\phi_f L_q}{2J} e_\omega + k_q L_q e_q \end{cases} \quad (24)$$

Replacing Eq.(24) into Eq.(23), the dynamics of Lyapunov function becomes:

$$\dot{V}_2 = -k_\omega e_\omega^2 - k_d e_d^2 - k_q e_q^2 \leq 0 \quad (25)$$

Fig. 3 shows the block diagram of non-adaptive backstepping control of PMSM in tracking the rotor speed.

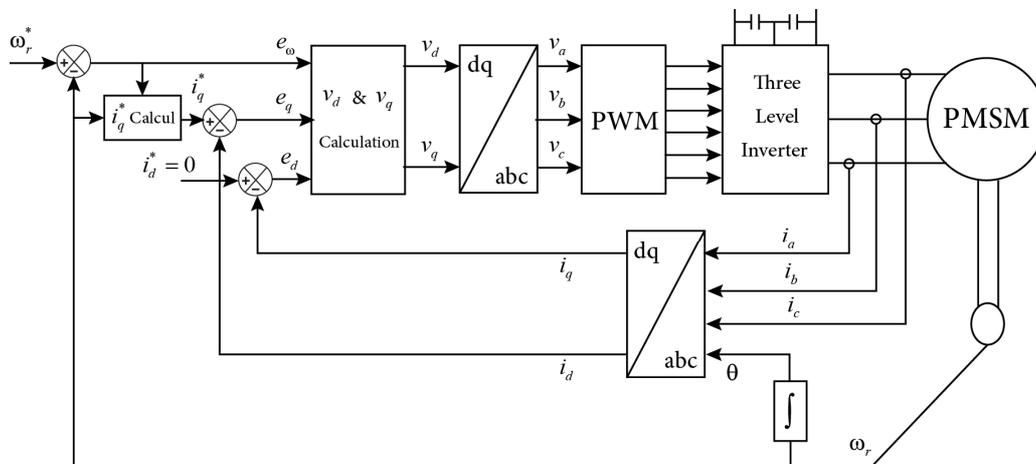


Fig. 3. Block diagram of non-adaptive backstepping control of PMSM

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B. Adaptive case

In non-adaptive backstepping control developed previously, it is assumed that the parameters are known. Nevertheless, this assumption is not always true, because the parameters change with different physical phenomenon, for example the resistance change with heating, and torque with the operating conditions. In the next step, we use adaptive backstepping technique to handle these uncertainties. The load torque cannot measured directly. Therefore, it is necessary to estimate them in Eq.(15):

$$\hat{i}_q^* = \frac{2}{3p\varphi_f} [B\omega_r + \hat{T}_L + k_\omega J e_\omega] \quad (26)$$

From Eq.(14) and Eq.(26), the new expression of the speed error is deduced as follows:

$$\dot{e}_\omega = \frac{1}{J} \left[\frac{3p}{2} \varphi_f e_q + \frac{3p}{2} (L_d - L_q) i_q e_d - k_\omega J e_\omega - \tilde{T}_L \right] \quad (27)$$

Where $\tilde{T}_L = \hat{T}_L - T_L$ is the load torque estimation error.

Therefore, the dynamics of errors are rewritten as:

$$\dot{e}_d = \frac{di_d^*}{dt} - \frac{di_d}{dt} = \frac{R_s}{L_d} i_d - \frac{pL_q}{L_d} \omega_r i_q - \frac{1}{L_d} v_d \quad (28)$$

$$\begin{aligned} \dot{e}_q &= \frac{di_q^*}{dt} - \frac{di_q}{dt} = \frac{2}{3p\varphi_f} [B\dot{\omega}_r + \dot{\hat{T}}_L + k_\omega J \dot{e}_\omega] \\ &+ \frac{R_s}{L_q} i_q + \frac{pL_d}{L_q} \omega_r i_d + \frac{p\omega_r \varphi_f}{L_q} - \frac{v_q}{L_q} \\ &= \frac{2(k_\omega J - B)}{3p\varphi_f J} \left(\frac{3p}{2} \varphi_f e_q + \frac{3p}{2} (L_d - L_q) i_q e_d - k_\omega J e_\omega \right) \\ &+ \frac{R_s}{L_q} i_q + \frac{pL_d}{L_q} \omega_r i_d + \frac{p\omega_r \varphi_f}{L_q} - \frac{v_q}{L_q} + \frac{2(B - k_\omega J)}{3p\varphi_f J} \tilde{T}_L \end{aligned} \quad (29)$$

The Lyapunov function that take into account the estimation errors of T_L and R_s is defined as:

$$V_2 = \frac{1}{2} \left(e_\omega^2 + e_d^2 + e_q^2 + \frac{1}{\gamma_1} \tilde{T}_L^2 + \frac{1}{\gamma_2} \tilde{R}_s^2 \right) \quad (30)$$

Where $\tilde{R}_s = \hat{R}_s - R_s$ is the stator resistance estimation error, γ_1 and γ_2 are a constants greater than zero.

Substituting Eq.(27), Eq.(28), and Eq.(29), we get:

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$$\begin{aligned} \dot{V}_2 &= e_\omega \dot{e}_\omega + e_d \dot{e}_d + e_q \dot{e}_q + \frac{1}{\gamma_1} \tilde{T}_L \dot{\tilde{T}}_L + \frac{1}{\gamma_2} \tilde{R}_s \dot{\tilde{R}}_s \\ &= -k_\omega e_\omega^2 - k_d e_d^2 - k_q e_q^2 + \\ &+ e_d \left[\frac{\hat{R}_s i_d}{L_d} - \frac{p L_q \omega_r i_q}{L_d} - \frac{v_d}{L_d} + \frac{3p}{2J} (L_d - L_q) i_q e_\omega + k_d e_d \right] \\ &+ e_q \left[\frac{2(k_\omega J - B)}{3p\phi_f J} \left(\frac{3p}{2} \phi_f e_q + \frac{3p}{2} (L_d - L_q) i_q e_d - k_\omega J e_\omega \right) \right. \\ &+ \frac{\hat{R}_s i_q}{L_q} + \frac{p L_d \omega_r i_d}{L_q} + \frac{p \omega_r \phi_f}{L_q} - \frac{v_q}{L_q} + \frac{3p}{2J} \phi_f e_\omega + k_q e_q \left. \right] \\ &+ \tilde{T}_L \left[-\frac{e_\omega}{J} + \frac{2(B - k_\omega J)}{3p\phi_f J} e_q + \frac{\dot{\tilde{T}}_L}{\gamma_1} \right] + \tilde{R}_s \left[-\frac{i_d e_d}{L_d} - \frac{i_q e_q}{L_q} + \frac{\dot{\tilde{R}}_s}{\gamma_2} \right] \end{aligned} \quad (31)$$

The control laws are designed according to Eq.(31):

$$v_d = \hat{R}_s i_d - p L_q \omega_r i_q + \frac{3p}{2J} (L_d - L_q) i_q e_\omega + k_d L_d e_d \quad (32)$$

$$\begin{aligned} v_q &= \frac{2L_q(k_\omega J - B)}{3p\phi_f J} \left(\frac{3p}{2} \phi_f e_q + \frac{3p}{2} (L_d - L_q) i_q e_d - k_\omega J e_\omega \right) \\ &+ \hat{R}_s i_q + p L_d \omega_r i_d + p \omega_r \phi_f + \frac{3p}{2J} \phi_f e_\omega + k_q L_q e_q \end{aligned} \quad (33)$$

Substituting Eq.(32) and Eq.(33) in Eq.(31), we get the simplified expression of Lyapunov function:

$$\begin{aligned} \dot{V}_2 &= -k_\omega e_\omega^2 - k_d e_d^2 - k_q e_q^2 + \\ &+ \tilde{T}_L \left[-\frac{e_\omega}{J} + \frac{2(B - k_\omega J)}{3p\phi_f J} e_q + \frac{\dot{\tilde{T}}_L}{\gamma_1} \right] \\ &+ \tilde{R}_s \left[-\frac{i_d e_d}{L_d} - \frac{i_q e_q}{L_q} + \frac{\dot{\tilde{R}}_s}{\gamma_2} \right] \end{aligned} \quad (34)$$

Thereafter, the adaptation laws are deduced as follows:

$$\dot{\tilde{T}}_L = \gamma_1 \left[\frac{e_\omega}{J} - \frac{2(B - k_\omega J)}{3p\phi_f J} e_q \right] \quad (35)$$

$$\dot{\tilde{R}}_s = \gamma_2 \left[\frac{i_d e_d}{L_d} + \frac{i_q e_q}{L_q} \right] \quad (36)$$

V. SIMULATION RESULTS

Simulation of the proposed control approach are carried out in Matlab/Simulink software. Fig. 5 presents the Simulink block model of the entire system. The parameters of the permanent magnet synchronous motor are given in Appendix. The gains of adaptation laws are selected such as to ensure fast converge. Hence, $k_d = 400$, $k_q = 600$, $k_\omega = 1$, $\gamma_1 = 0.1$, $\gamma_2 = 0.00094$.

To test the performance of the proposed approaches two cases are considered: varying rotor speed while keeping the load torque constant, and varying load torque while keeping rotor speed constant.

A. Case 1: varying speed and keeping load torque constant

In this case, the rotor speed reference is set to 1200 rpm at $t=0s$, and it's increased to 1400 rpm at $t=0.3s$. However, the load torque is keeping equal to 6 N.m. as presented in Fig. 6. Fig. 7 shows the response of the rotor speed using Non-adaptive backstepping and Adaptive backstepping. It is obvious that the response of Non-adaptive backstepping has a large static error. Nevertheless, adaptive backstepping converges to its reference in 0.05s approximately. According to Fig. 8 and Fig. 9, equivalent stator currents present an overshoot, which lasts 0.02s for d-axis current and 0.03s for q-axis current. Estimated stator resistance is shown in Fig. 10.

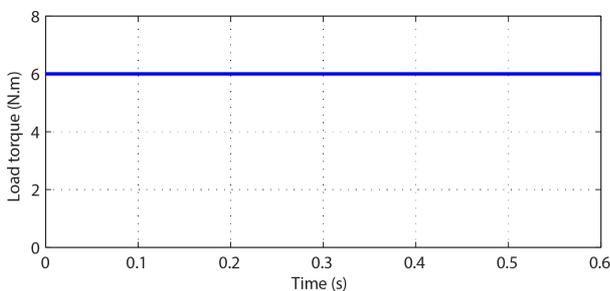


Fig. 6. Response of Load torque.

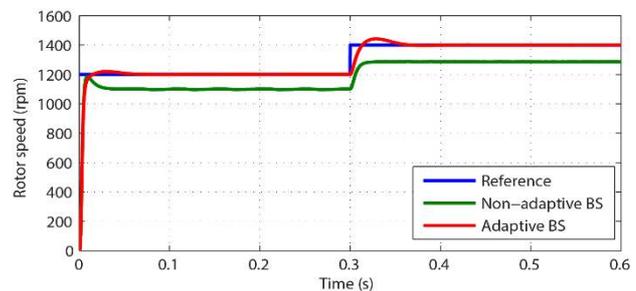


Fig. 7. Response of rotor speed.

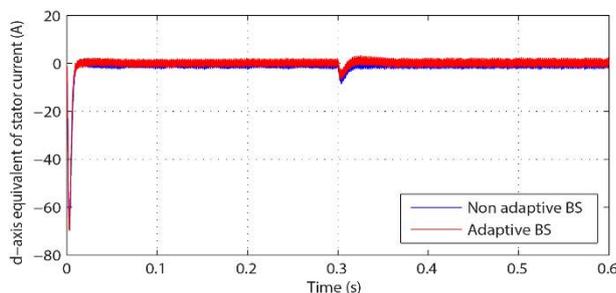


Fig. 8. Response d-axis equivalent stator current.

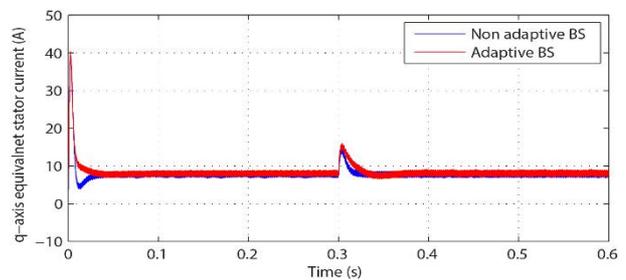


Fig. 9. Response q-axis equivalent stator current.

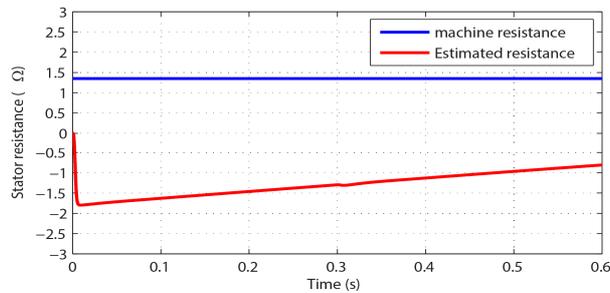


Fig. 10. Response of estimated stator resistance.

B. Case 2: varying load torque and keeping speed constant

In this case, the rotor speed reference is kept constant to 1400 rpm. However, the load torque is equal to 4 N.m and it's increased to 6 N.m at $t=0.3s$ as presented in Fig. 11. Fig. 12 shows the response of the rotor speed using the both approaches. One more time, it is clear that the response of non-adaptive backstepping has a large static error. While, adaptive backstepping converges to its reference in 0.05s approximately. Fig. 13 and Fig. 14 shows the response of d-q axis of equivalent stator current due to the change of load torque, and the estimated stator resistance is depicted in Fig. 15.

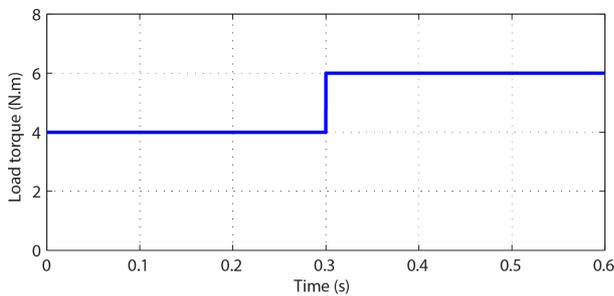


Fig. 11. Response of Load torque.

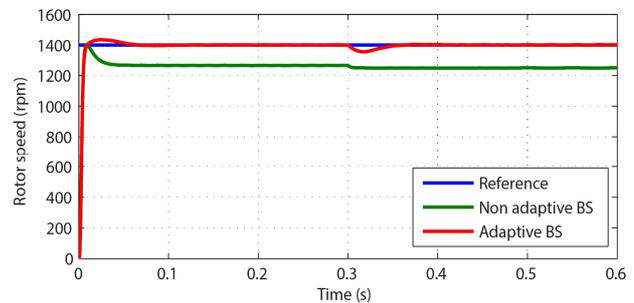


Fig. 12. Response of rotor speed.

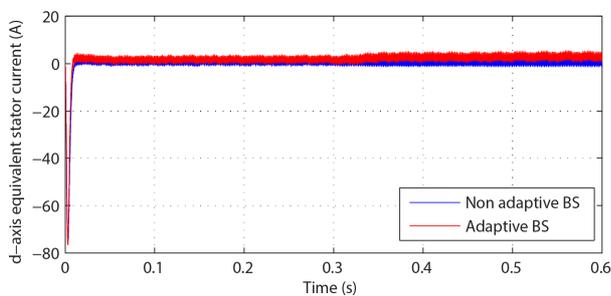


Fig. 13. Response d-axis equivalent stator current.

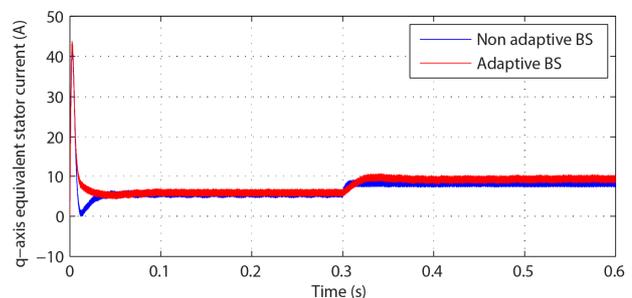


Fig. 14. Response q-axis equivalent stator current.

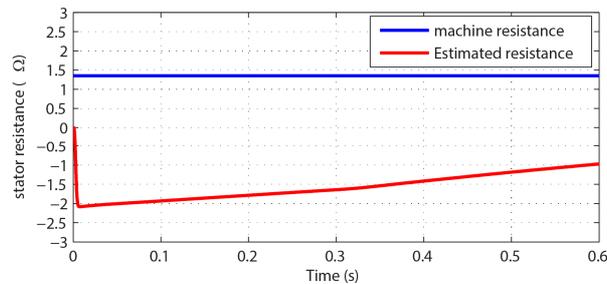


Fig. 15. Response of estimated stator resistance.

VI. CONCLUSION

In this paper, a comparative study between non-adaptive and adaptive backstepping control of permanent magnet synchronous motor using three level inverter is investigated. In the adaptive case, the parameters are estimated using adaptation laws. Results derived from simulation for different conditions such as variations in speed and load show the effectiveness of this strategy in rejection of disturbances, accuracy of tracking, and ability adapting parameter variations. Nevertheless, real test should confirm the simulation result.

Appendix

PARAMETERS OF THE MACHINE

Designation	Value
Frequency	50 Hz
Pole pairs (p)	2
Stator phase resistance (R_s)	1.35 Ω
d axis inductance (L_d)	7.66 mH
q axis inductance (L_q)	17 mH
Permanent magnet flux (ϕ_f)	0.158 Wb
Moment of inertia (J)	0.0035 kg.m ²
Damping coefficient (B)	0.001 Nm/rad/s

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