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Direct torque control of non-salient pole AFPMSMs with SVPWM inverter

Amir Yassin Hassan[1], Ahmed Gouda Rohieem[2], Saber Mohamed Saleh Salem[2]
[1]Department of Power Electronics and Energy Conversion, Electronics Research Institute, Cairo, Egypt
[2]Department of Electrical Engineering, Faculty of Engineering, Fayoum University, Fayoum, Egypt

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ABSTRACT

Axial flux motors use less material and thus are inherently less expensive. They can also deliver a high-power density, which is four times that of a radial flux motor. That makes studying the control methods for this motor necessary. The purpose of this study is to introduce a new dynamic and steady-state response control technique for axial flux permanent magnet synchronous motors (AFPMSMs). Dynamic equations describe the control characteristics of axial flux permanent magnet motors. The AFPMSM model and the space vector pulse width modulation (SVPWM) inverter were created using MATLAB Simulink. For the AFPMSM motor with an SVPWM inverter, direct torque control (DTC) is provided. The results of the proposed control technique are simulated and analyzed, and it is found to provide good performance. According to the results, the proposed control method reveals advantages in reducing the ripples and pulsating of the torque while enhancing speed dynamic and steady-state response.

Corresponding Author:

Amir Yassin Hassan
Department of Power Electronics and Energy Conversion, Electronics Research Institute
Joseph Tito St., El Nozha, P.O. Box: 12622, Cairo, Egypt
Email: amir@eri.sci.eg

NOMENCLATURE

T_e	Electromagnetic torque	T_l	Torque of load
P	Pole -pairs number	ω_r	Rotor angular velocity
ψ_{sa}	Field flux of the stator windings	B	Damping coefficient
i_{sa}	Stator current vector	J	Inertia moment for AFPMSM
$\mathcal{U}_{da}$, $\mathcal{U}_{qa}$	Stator voltage in d-q axis	ψ_{qa} , ψ_{da}	Flux in d-q axis
i_{da} , i_{qa}	Stator current in d-q axis	R_{sa}	Resistance of stator windings
L_{da}	D axis winding inductance	n	Number of phases
L_{qa}	Q axis winding inductance	ψ_f	Field flux of the rotor windings

1. INTRODUCTION

In the past two decades, permanent magnet machines have attracted the researcher's attention due to their high power to weight and good dynamic performance and are considered highly efficient motors, and can be used in many applications. Permanent magnet synchronous motors (PMSMs) are divided into two categories: Axial flux permanent magnet synchronous motor (AFPMSM) and radial flux permanent magnet synchronous motor (RFPMSM) [1]–[4]. Because of their high-power density and small size, AFPMSM can be used in a variety of applications, including electric vehicles (EVS) and bicycles. In terms of efficiency, dynamic response, and construction simplicity, AFPMSM performs better RFPMM [5]–[8].

The vector control including field-oriented control and direct torque control strategies are used in the AFPMSM control strategy. Vector control provides a better steady-state output for the motor, but it has a poor dynamic performance. Adjusting parameters is also needed, which will result in performance affection [1], [2], [9]–[12]. The conventional type of direct torque control (DTC) that uses a voltage source inverter (VSI) is non-complex, as it does not contain a current regulator and no PWM space voltage generator to provide good dynamic performance. However, conventional DTC has some drawbacks, such as a torque and flux ripple due to VSI, also using a hysteresis comparator that has a defined bandwidth and speed and load subject variation of the switching frequency [13], [14].

The first trial of space vector modulation DTC was performed on an induction motor; the SVPWM inverter is a suitable control solution for issues such as torque and flux ripple, as well as variable switching frequency on traditional DTC. Space vector pulse width modulation (SVPWM) inverter also controls solution for low voltage distortion and voltage frequency variation, as well as variable motor speed [15], [16]. DTC has several advantages that make it a good option for controlling AFPMSM, including better performance than field-oriented control, a simple structure, and good dynamics [17]–[23]. In this paper, the model dynamic equations of the AFPMSM are presented, as well as a control strategy for speed, torque, and flux based on SVPWM inverter DTC. Axial flux permanent magnet motor dynamic equations, direct torque control, space vector pulse width modulation, simulation, and experimental results, and conclusion are the sections of this paper.

2. AXIAL FLUX PERMANENT MAGNET MOTOR DYNAMIC EQUATIONS

Unless the stator of the AFPMSM differs from that of the non-salient PMSM, an axial flux permanent magnet motor can be modeled as a redial flux permanent magnet synchronous motor but with less air gab as shown in Figure 1. As a result, stator parameters such as inductance should be taken into account when measuring [18], [24]. The following are some assumptions in derivation:

- Neglected Saturation effect.
- Sinusoidal back-EMF.
- Losses caused by hysteresis, eddy currents, and stray are not taken into account.
- L_d is equal to L_q so, the AFPMSM does not have a non-salient pole effect.

The AFPMSM model in a-b-c is a differential equation of variable coefficients under the above assumptions and its equations are as follows [1], [9], [13], [19]–[24].

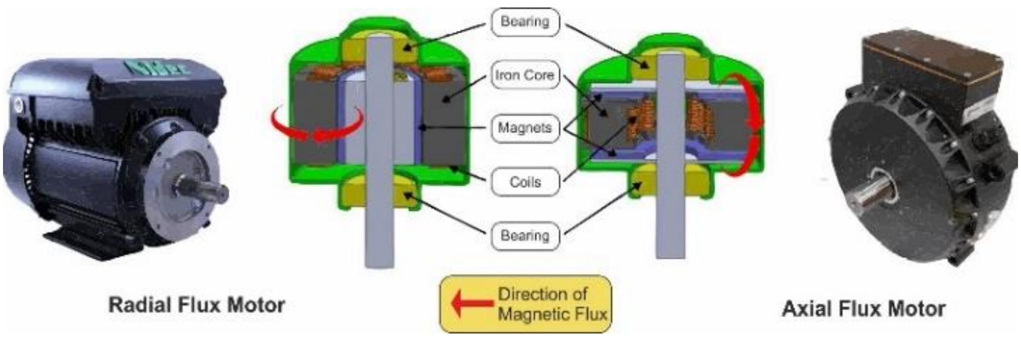

Figure 1. Axial flux motor vs radial flux

Motor torque equation:

$$T_e = P\, i_{sa}\psi_{sa} \tag{1}$$

Equation of motion for AFPMSM:

$$T_e - T_l - \mathrm{B}\omega_\mathrm{r} = \mathrm{J}\frac{d\omega_r}{dt} \tag{2}$$

For simple treatment with the (1) and (2), coordination transformation into a Direct-quadrature axis is used. The motor mathematical model will be as follow.
Direct-quadrature voltage equations:

$$\mathcal{U}_{da} = R_{sa}\, i_{da} + \frac{d\psi_{da}}{dt} - P\omega_r \psi_{qa} \tag{3}$$

$$\mathcal{U}_{qa} = R_{sa}\, i_{qa} + \frac{d\psi_{qa}}{dt} + P\omega_r \psi_{da} \tag{4}$$

Equations for the direct quadrature stator flux:

$$\psi_{da} = L_{da}\, i_{da} + \psi_f \tag{5}$$

$$\psi_{qa} = L_{qa}\, i_{qa} \tag{6}$$

Torque equation:

$$T_e = \frac{n}{2} P\, i_{qa}\left[\psi_f + \left(L_{da} - L_{qa}\right) i_{da}\right] \tag{7}$$

The torque equation will be in the form of:

$$T_e = \frac{n}{2} P\, i_{qa} \psi_f \tag{8}$$

By changing i_{qa}, the torque may be controlled for $L_{da} = L_{qa}$

3. DIRECT TORQUE CONTROL (DTC)

In the case of constant load torque, the concept of DTC can be understood using the equation of motion (2), which states that the rotor speed is solely determined by electromagnetic torque [9]. It is possible to express the electromagnetic torque as (9).

$$T_e = \frac{n}{2} \frac{P}{L_{da}} i_{qa}\, \psi_{sa}\, \psi_f \sin\delta + \frac{n}{4} \frac{L_{da} - L_{qa}}{L_{qa} L_{da}}\, \psi_{sa}{}^2 \sin 2\delta \tag{9}$$

Where δ is the torque angle.

According to the assumptions, the AFPMSM does not have a non-salient pole effect. So $L_d = L_q$ and the torque formula is:

$$T_e = \frac{n}{2} \frac{P}{L_{da}} i_{qa}\, \psi_{sa}\, \psi_f \sin\delta \tag{10}$$

This equation shows that a changing electromagnetic torque relies on a changing angle δ, DTC block diagram is shown in Figure 2.

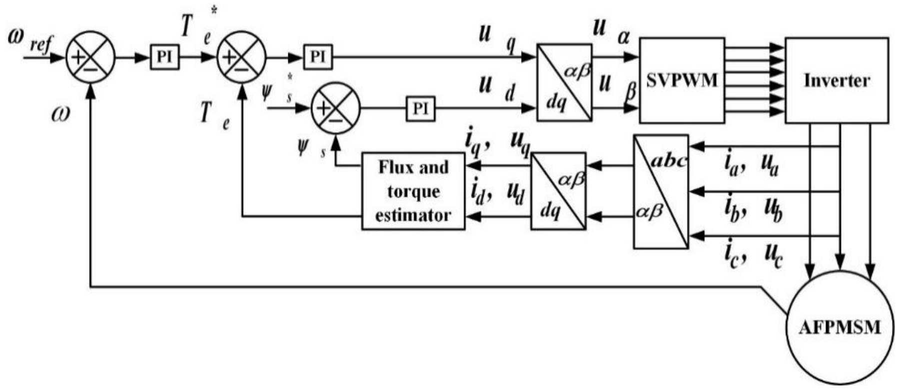

Figure 2. DTC-SVPWM inverter control block diagram

3.1. Flux and torque estimation equations

The torque estimation equation is (10), which shows that in the case of stator flux constant, the torque depends on load angle δ and is considered to be a step depending on the voltage vector. The maximum torque is achieved when δ is equal to π/2. The load angle is controlled within the range of -π/2- π/2. In another way, the flux of stator must be controlled to have the amplitude constant and the motor speed is controlled to obtain the maximum change in actual torque. Flux estimation (5) and (6), the AFPMSM stator flux given by:

$$\psi_{sa} = \sqrt{(\psi_{qa})^2 + (\psi_{da})^2} \quad (11)$$

3.2. PI controller

A PI controller with two variable gains, the first of which is integral gain and the second of which is the proportional gain, can be used to control speed, stator flux, and torque. The PI controllers receive the speed, flux, torque error as input. The reference generator torque and Stator voltages in the d-q axis are then outputs of the PI controller [25].

$$\mathrm{T}_e^* = k_p e + k_i \int e\, dt \quad (12)$$

$$e_\omega = \omega_{ref} - \omega \quad (13)$$

$$U_d = k_p e + k_i \int e\, dt \quad (14)$$

$$e_\psi = \psi_s^* - \psi_s \quad (15)$$

$$U_q = k_p e + k_i \int e\, dt \quad (16)$$

$$e_\mathrm{T} = \mathrm{T}_e^* - \mathrm{T}_e \quad (17)$$

In this study the constant values of PI controllers as follows: for speed $K_P = 20,\ K_i = 45$, for flux $K_P = 1,\ K_i = 75$, while for torque $K_P = 150,\ K_i = 100$.

4. SPACE VECTOR PULSE WIDTH MODULATION (SVPWM) INVERTER

Since it has a higher DC voltage utilization rate and lower output waveform distortion, the SVPWM inverter is considered the best technique for controlling inverters [24], [26]–[28]. Based on the space vector principle, the SVPWM inverter model in MATLAB will include a switching time calculation model, PWM waveform generation, and sector selection [24], [26], [29].

4.1. The reference voltage and angle

The reference voltage and angle equations:

$$\begin{vmatrix} V_d \\ V_q \end{vmatrix} = \frac{2}{3} \begin{vmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{vmatrix} \begin{vmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{vmatrix} \quad (18)$$

$$V_{ref} = \sqrt{V_d^2 + V_q^2} \quad (19)$$

$$\alpha = tan^{-1}\left(\frac{V_q}{V_d}\right) \quad (20)$$

4.2. Conversion time in any sector

$T_s = \frac{1}{f}$, f is the fixed clock frequency

$$T_1 = \frac{\sqrt{3} T_s V_{ref}}{V_{dc}} \sin\left(\frac{\gamma}{3}\pi - \alpha\right) \quad (21)$$

$$T_2 = \frac{\sqrt{3}T_s V_{ref}}{V_{dc}} \sin\left(\alpha - \frac{\gamma-1}{3}\pi\right) \quad (22)$$

$$T_0 = T_f - T_1 - T_2 \quad (23)$$

where γ is the sector from 1 – 6, $0 \leq \alpha \leq 60^o$.

5. SIMULATION AND EXPERIMENTAL RESULTS

In the case of switching frequency of pulse width 20000 Hz and 250-volt DC voltage and 300-rpm reference speed are used, the simulation time is 0.7 sec. To improve system efficiency, reference flux values based on permanent magnet flux and load torque must be calculated, while keeping changes in reference flux due to torque conditions to a minimum. The following formula can be used to calculate the reference flux value: [2], [30]. The motor reference flux is calculated using (24) (0.196 Wb).

$$\left|\psi_s^*\right| = \sqrt{\psi_f^2 + \left(\frac{2}{3}\frac{T_e^* L_s}{p\psi_f}\right)^2} \quad (24)$$

5.1. At no-load

The motor starts with no load at 300 rpm reference speed. By monitoring the dynamic and steady-state response from the simulation results in Figures 3, 4, 5 and 6, the speed of the motor during starting is accelerated fast and it reaches the reference speed within 0.045 sec. The system achieves reference speed without any overshoot, the rise time is about 0.045 sec, and the steady-state error is equal to 0.03%.

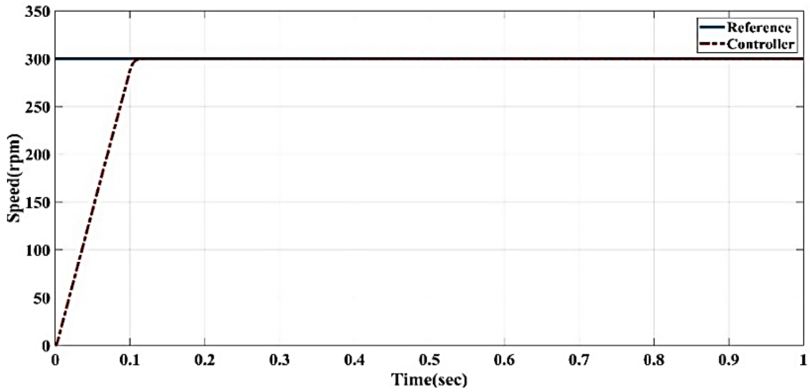

Figure 3. Motor speed (rpm) dynamic and steady-state response at no load

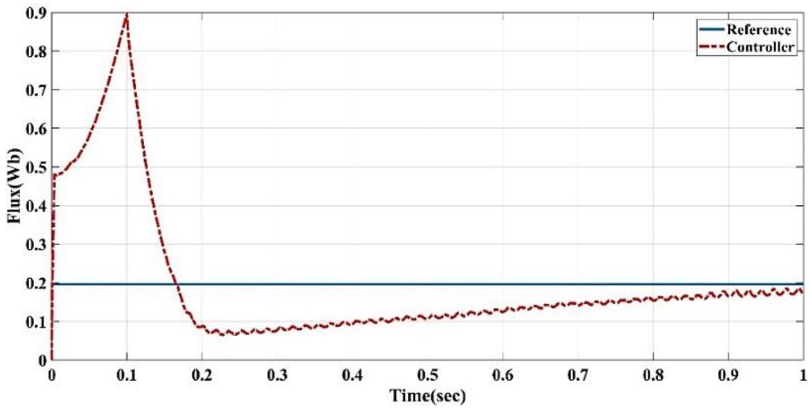

Figure 4. Flux dynamic and steady-state response of the motor at no load

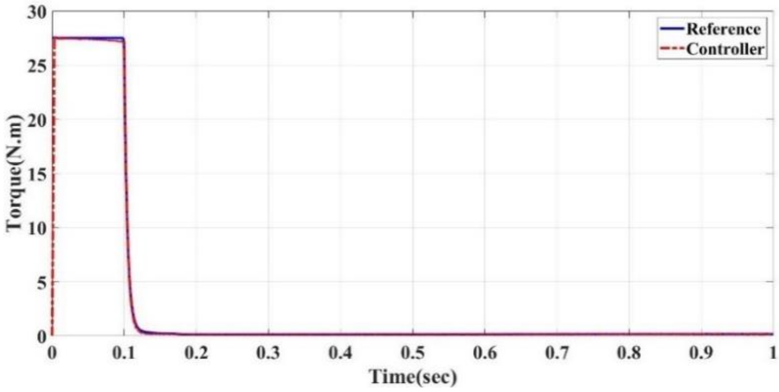

Figure 5. Motor torque dynamic and steady-state response at no load

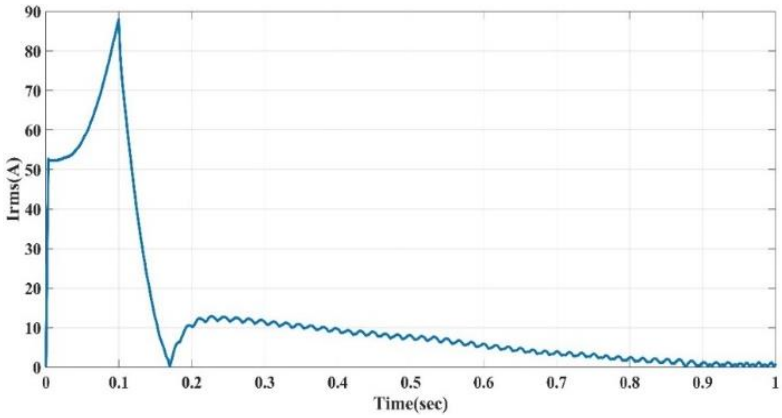

Figure 6. Motor reconfigurable manufacturing system (RMS) current under no load

5.2. In case of full load condition

In the case of full load condition and at t=0.15 sec, the load torque is applied (11 N.M) to the motor. The speed response fluctuates but with a low change in value that equals 1.5 rpm and the steady-state error is equal to 0.23% and the 3-phase current I_{abc} is sinusoidal as illustrated in Figures 7, 8, 9 and 10. It is obvious from the Figures that the control response in case of full load condition is very good for speed, torque and flux.

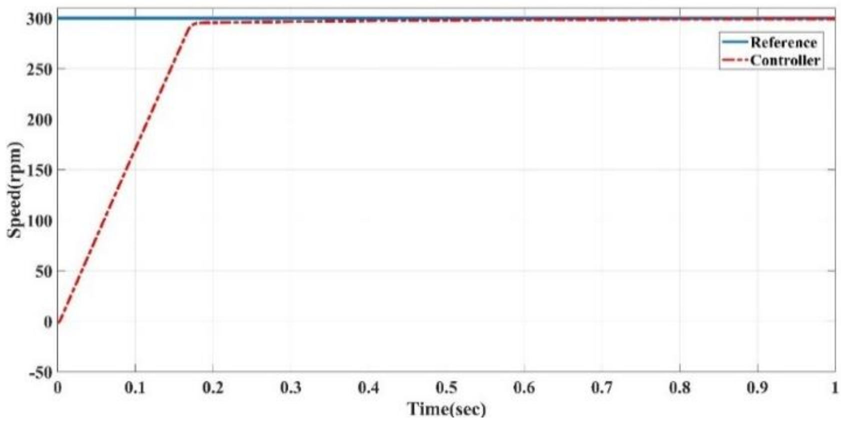

Figure 7. Motor speed dynamic and steady-state response under full load

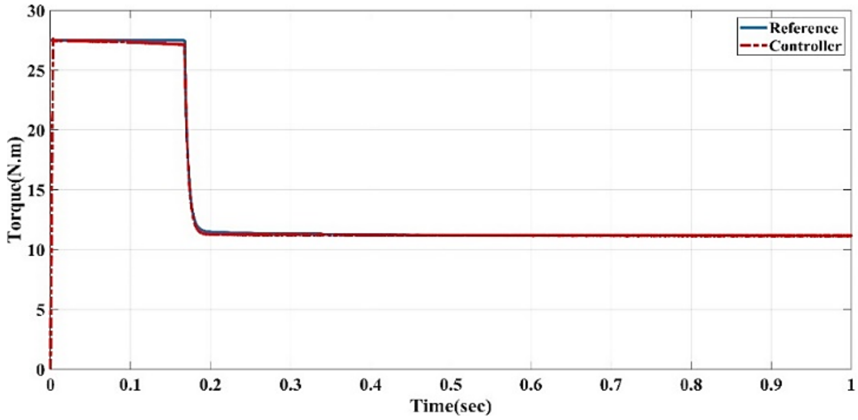

Figure 8. Motor Torque dynamic and steady-state response under motor full load

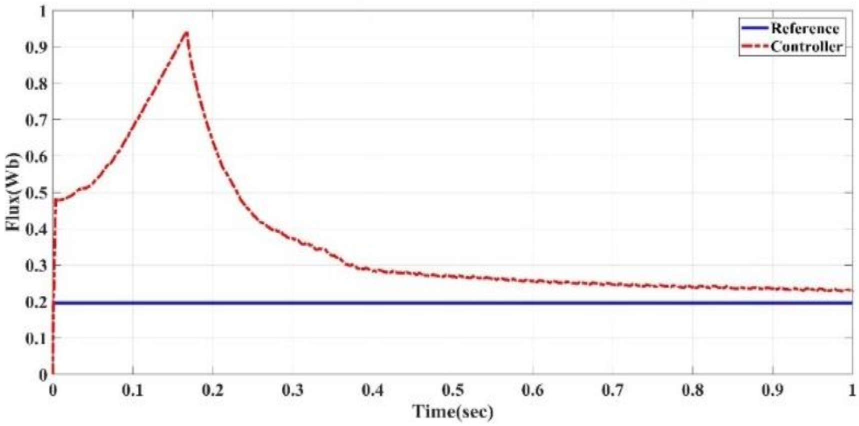

Figure 9. Flux dynamic and steady-state response under motor full load

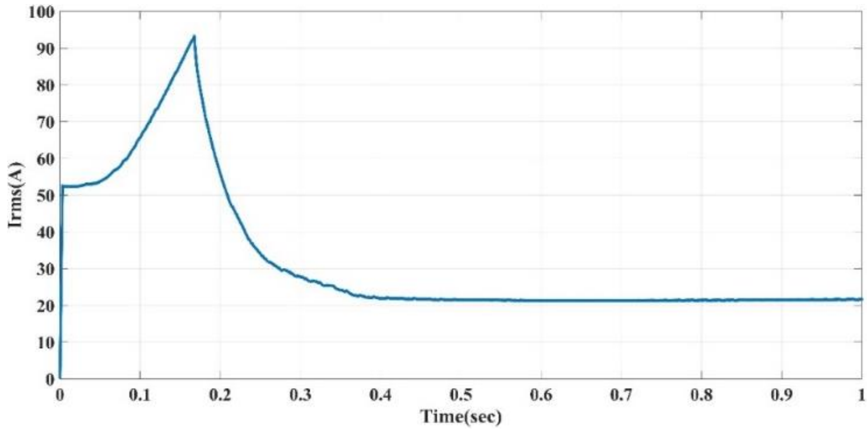

Figure 10. Motor RMS current under full load

5.3. Variable reference speed under full load torque

If the reference speed is varied during full load, at times 0 sec, 0.5 sec, 1 sec, 1.5 sec, the reference speed is set to 25, 50, 75, & 100% of the nominal speed, the drive system obtains the required reference speed values with a steady-state error equal to 0.266 %. The speed responses under-speed variation is shown in Figure 11. The control response for speed with respect to reference is very good in case of variable reference speed under full load torque.

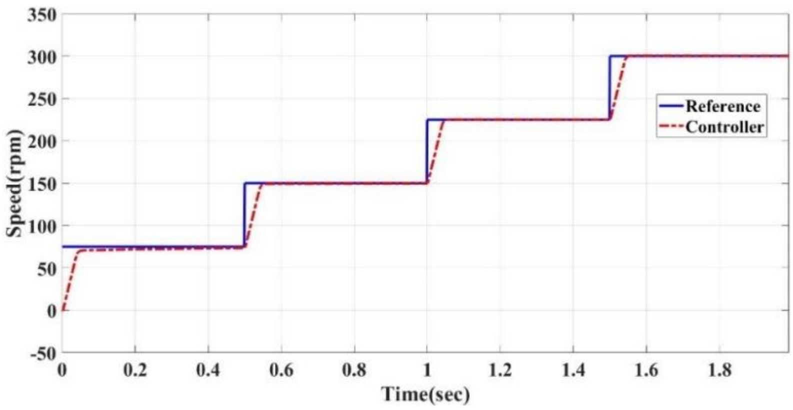

Figure 11. Motor speed dynamic and steady-state response under variable speeds under full load

5.4. Variable load torque under reference speed

Considering a changeable reference load torque at maximum speed, at times 0 sec, 0.5 sec, 1 sec, and 1.5 sec, the reference load torque is set to 25, 50, 75, & 100% of the nominal torque, the drive system achieves the predetermined reference speed values with a steady-state error equal to 0.264 %. Then, torque responses under load torque variation are shown in Figure 12. The parameters of the motor used in the simulation are listed in Table 1.

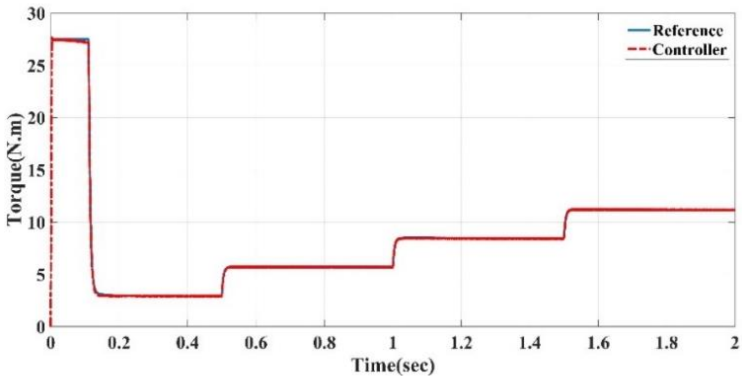

Figure 12. Motor torque dynamic and steady-state response under variable load torque under reference speed

Table 1. Lists the specs for axial flux motors

Parameter	Value	Parameter	Value
Number of pole pairs	2	Damping coefficient B	0.005
Stator resistance R_{sa} (Ohm)	0.2	Inertia moment J	0.089
Stator inductance L_{sa} (mH)	8.5	Rated speed (Rpm)	300
Rotor magnetic flux ψ_f (Wb)	0.175	Rated torque N.M	11
VDC dc-voltage (volt)	250		

6. CONCLUSION

In this study, PI-DTC is used to control the axial flux motor's speed, torque, and flux. The simulation results show that DTC is a more accurate and excellent dynamic response. The novelty of this paper is the application of DTC with SVPWM inverter for AFPMSM, and the model results appear low torque rippled with high dynamic and steady-state response. According to the results, the control parameters are extremely manageable with this approach, and the dynamic response to the suggested method has a minimal overshoot (0.1%), a modest steady-state error (0.23%), and a short rising time (0.049 sec).

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BIOGRAPHIES OF AUTHORS

Amir Yassin Hassan received his B.Sc. with excellent grade with honor degree in Electrical Engineering from Fayoum University, Egypt, in June 2010. In 2011 he joined the Electronics Research Institute (ERI) as a Researcher Assistant at Power Electronics and energy conversion department. A. Yassin obtained his M.Sc. from Fayoum University at 2014 and he became an Assistant Researcher in ERI. He received his Ph.D. in Electric Drives from Ain Shams University in January 2019 and he became a Researcher in ERI. He was honored as "The Best Assistant Researcher" at ERI for years 2015, 2016, 2017 and 2018 respectively also he is awarded as the winner in "Engineering Innovation Competition 2015" at Egyptian Engineers Syndicate. His major interests are: Electrical Drives Control, Modeling and Simulation of Electrical Systems, Artificial Intelligence, Thermal Modelling and Electrical/Hybrid Vehicles Modeling, Simulation, and Control. He can be contacted at email: amir@eri.sci.eg.

Ahmed Gouda Rohieem received the B.Sc. degree in power and machine engineering, in 2010 from Cairo University, Cairo, Egypt, and in progress, the M.Sc. degree in electric power engineering, at Fayoum University. He is currently a maintenance supervisor in Natural Gas Vehicles Company (Car gas) in Egypt. His research interests include electric machines and drives, automation control engineering and design, signal processing, and machine learning. He can be contacted at email: ahmedgouda_18@hotmail.com.

Saber Mohamed Saleh Salem received the M.Sc. and Ph.D. degrees in digital protection from Cairo University, Cairo, Egypt, in 2005 and 2009. In 2013 and 2018, he became an Assistant Professor and Associate Professor with Fayoum University, Fayoum, Egypt, while continuing his research. He was active in the field of engineering consultancy at the Engineering Research and Consulting Center at the Faculty of Engineering, Fayoum University. He also has contributions as director of the Disaster and Crisis Management Center at the Faculty of Engineering, Fayoum University. His research interests include digital protection, renewable energy, electronic control of electric machines, and digital signal processing. He can be contacted at email: sms08@fayoum.edu.eg.