A STUDY OF PID DIRECT TORQUE CONTROL FOR THREE-PHASE ASYNCHRONOUS MOTOR

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Abstract: Three-phase asynchronous motors (are aslo called induction motors) are rugged, robust, and an integral part of many applications for most industries worldwide. The general type of the three-phase asynchronous motor, mostly used in industry, is the squirrel cage. The method introduced into this paper is called direct torque control (DTC), which utilizes the characteristic of a motor to produce a quick and robust response in inverters. The entire motor system is analyzed and simulated by Matlab and Simulink toolbox, where the PID direct torque controlled to approach is applied. Our main contributes to this paper is to compare the performance of induction motor, including three scenarios: without load, negative load and positive load by using PID direct torque control method. The simulation results show the effective of proposed control of induction motor with three scenarios.
Keywords Three-phase asynchronous motor, Induction motor, PID-DTC controller, Simulation

1. Introduction

Nowadays, three-phase asynchronous motors are being widely applied in the communication system of modern technological lines because it has many priority points compared to DC motors. Many of which are the following priorities: [1],[2]

- Compact design
- Rugged construction
- Reliable, easy, and high-efficiency operation
- Low maintenance cost
- Simple control gear for starting and speed control

However, because of the multi-parameters nonlinear structure, it is difficult to control the three-phase asynchronous motor. In the past few years, with the strong development of science and technology, computer electronics technology, computer science, power semiconductor technology, and control engineering has created a fundamental change in the direction of industrial automation solutions, many modern and effective control methods have been proposed for asynchronous motor control. In particular, the vector control method and direct torque control are reliable and efficient methods to control asynchronous motor systems so that it can gradually replace the DC motor.

Meanwhile, since its first introduction in 1984, according to [12], the principle of direct torque control (DTC) has been widely applied to three-phase asynchronous motor drives, also commonly called induction motor inverters. Despite its simplicity, DTC is not only capable of producing rapid torque and flux control but also robust to the variation of the motor's parameters and perturbations. However, some unusual spots on torque, flux, and current pulsations occur when the motor is in its steady-state operation and are reflected in the built-in observer, which estimates the speed of the motor, and also in the increased acoustical noise [3].

Asynchronous motor control is a topic that has been interested by many researchers. Some notable projects can be mentioned as follows:

- Field-Oriented Control (FOC) [4]
- Direct Torque Control (DTC) [3]
- Passive based control (PBC) [5]
- Input-Output feedback linearization control [6]
- Control using fuzzy logic and neural networks [7]
- Internal Model Control (IMC) [8]
- Sliding mode control of induction motor fed with three-level NPC inverter [9]

The paper consists of 4 sections. Part 1 introduces the model and main points of this article. Part 2 presents the mathematical equations of the induction motor. Part 3 shows PID DTC control scheme and simulation results of this method. Finally, the conclusion is mentioned in part 4.

2. Mathematical Model of a Three-Phase Asynchronous Motor

2.1. A Model of Three-Phase Asynchronous Motor in Stator Coordinate ($\alpha\beta$) [9]

The dynamic model of the motor in the $\alpha\beta$ coordinate is analyzed as follows:

$$\begin{aligned}
&\frac{di_{sa}}{dt} = -\gamma i_{s\alpha} + \frac{K}{T_r}\psi_{r\alpha} + K\omega\psi_{r\beta} + \alpha u_{s\alpha}\\
&\frac{di_{sb}}{dt} = -\gamma i_{s\beta} + \frac{K}{T_r}\psi_{r\beta} + K\omega\psi_{r\alpha} + \alpha u_{s\beta}\\
&\frac{d\psi_{r\alpha}}{dt} = \frac{L_m}{T_r} i_{s\alpha} - \frac{1}{T_r}\psi_{r\alpha} - \omega\psi_{r\beta}\\
&\frac{d\psi_{r\beta}}{dt} = \frac{L_m}{T_r} i_{s\beta} - \frac{1}{T_r}\psi_{r\beta} + \omega\psi_{r\alpha}\\
&T_e = \mu(\omega\psi_{r\alpha} i_{s\beta} - \omega\psi_{r\beta} i_{s\alpha})\\
&\frac{d\omega}{dt} = \frac{p}{J}(T_e - T_L)
\end{aligned} \tag{1}$$

Where: $i_{s\alpha}, i_{s\beta}$: stator currents (A); $u_{s\alpha}, u_{s\beta}$: stator voltages (V); $\psi_{r\alpha}, \psi_{r\beta}$: rotor fluxs (Wb); ω: rotor speed (rad/s); T_e: motor torque (Nm); T_L: load torque (Nm); $\gamma = \left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}\right)$; $K = \frac{1-\sigma}{\sigma L_m}$; $T_r = \frac{L_r}{R_r}$; $T_s = \frac{L_s}{R_s}$; $\mu = \frac{3}{2}\frac{pL_m}{L_r}$; $\sigma = 1 - \frac{L_m^2}{L_s L_r}$; $\alpha = \frac{1}{\sigma L_s}$ are constants, R_s - stator resistance, R_r – rotor resistance, L_s - inductance coefficient, p is the number of poles, J is moment of inertia of the rotor.

2.2. A Model of Three-Phase Asynchronous Motor in Rotor Coordinate (dq) [10]

The dynamic model of the motor in the dq coordinate is analyzed as follows:

$$\begin{aligned}
&\frac{di_{sd}}{dt} = -\left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_s}\right) i_{sd} + \omega_s i_{sq} +\\
&+ \frac{1-\sigma}{\sigma T_r}\psi'_{rd} + \frac{1-\sigma}{\sigma}\omega\psi'_{rq} + \frac{1}{\sigma L_s}u_{sd}\\
&\frac{di_{sq}}{dt} = -\left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}\right) i_{sq} - \omega_s i_{sd} +\\
&+ \frac{1-\sigma}{\sigma T_r}\psi'_{rq} - \frac{1-\sigma}{\sigma}\omega\psi'_{rd} + \frac{1}{\sigma L_s}u_{sq}\\
&\frac{d\psi'_{rd}}{dt} = \frac{1}{T_r} i_{sd} - \frac{1}{T_r}\psi'_{rd} + (\omega_s - \omega)\psi'_{rq}\\
&\frac{d\psi'_{rq}}{dt} = \frac{1}{T_r} i_{sq} - \frac{1}{T_r}\psi'_{rq} - (\omega_s - \omega)\psi'_{rd}\\
&with\left(\psi'_{rd} = \psi_{rd}/L_m ; \psi'_{rq} = \psi_{rq}/L_m\right)
\end{aligned} \tag{2}$$

2.3. Coordinate System Transformation

2.3.1. Conversion of abc Coordinate to $\alpha\beta$ Coordinate and Vice Versa

Conversion of abc coordinate to $\alpha\beta$ coordinate:

$$\begin{cases} u_{s\alpha} = \frac{2}{3}\left(u_a - 0.5u_b - 0.5u_c\right)\\ u_{s\beta} = -\frac{2}{3}\left(-\frac{\sqrt{3}}{2}u_b + \frac{\sqrt{3}}{2}u_c\right)\end{cases} \tag{3}$$

Conversion of $\alpha\beta$ coordinate to abc coordinate:

$$\begin{cases} u_{sa} = u_{s\alpha}\\ u_{sb} = -\frac{1}{2}u_{s\alpha} + \frac{\sqrt{3}}{2}u_{s\beta}\\ u_{sc} = -\frac{1}{2}u_{s\alpha} - \frac{\sqrt{3}}{2}u_{s\beta}\end{cases} \tag{4}$$

2.3.2. Conversion of abc coordinate to dq coordinate and vice versa

Conversion of abc coordinate to dq coordinate as follows

$$\begin{cases} u_{sd} = \frac{2}{3}\left[u_a \cos\vartheta_s + u_b \cos\left(\vartheta_s - \frac{2\pi}{3}\right) + u_c \cos\left(\vartheta_s - \frac{4\pi}{3}\right)\right] \\ u_{sq} = -\frac{2}{3}\left[u_a \sin\vartheta_s + u_b \sin\left(\vartheta_s - \frac{2\pi}{3}\right) + u_c \sin\left(\vartheta_s - \frac{4\pi}{3}\right)\right] \end{cases} \quad (5)$$

Conversion of dq coordinate to abc coordinate:

$$\begin{cases} u_a = \cos\vartheta_s - \sin\vartheta_s \\ u_b = u_{sd}\cos\left(\vartheta_s - \frac{2\pi}{3}\right) - u_{sq}\sin\left(\vartheta_s - \frac{2\pi}{3}\right) \\ u_c = u_{sd}\cos\left(\vartheta_s - \frac{4\pi}{3}\right) - u_{sq}\sin\left(\vartheta_s - \frac{4\pi}{3}\right) \end{cases} \quad (6)$$

2.3.3. Conversion of $\alpha\beta$ Coordinate to dq Coordinate and Vice Versa

Conversion of $\alpha\beta$ coordinate to dq coordinate:

$$\begin{cases} u_{sd} = u_{s\alpha}\cos\vartheta_s + u_{s\beta}\sin\vartheta_s \\ u_{sq} = -u_{s\alpha}\sin\vartheta_s - u_{s\beta}\cos\vartheta_s \end{cases} \quad (7)$$

Conversion of dq coordinate to αβ coordinate:

$$u_{s\alpha} = u_{sd}\cos\vartheta_s - u_{sq}\sin\vartheta_s \quad (8)$$
$$u_{s\beta} = u_{sd}\sin\vartheta_s + u_{sq}\cos\vartheta_s$$

2.4. The Parameters of Induction Motor

Table 1. The parameters of induction motor

Parameters	Value
R_s : stator resistance	3 (Ω)
R_r : rotor resistance	4 (Ω)
L_s : stator inductance	0.0758 (H)
L_r : rotor inductance	0.0758 (H)
L_m : mutual inductance	0.07452 (H)
J_m : moment of inertia	0.004 (kg.m^2)
p : the couple of poles	2
T_L : load torque	0 (initial) (Nm)

3. Direct-Torque Control

3.1. Direct-Torque Control of Induction Motor

Direct Torque Control (DTC), was first introduced in 1984 and emerged in the rest 80s to the present. All in all, the studied method keeps the flux of the stator in vector space on a desired pre-defined track and controls the amplitude of the torque by altering the speed of the flux produced in the motor's stator along the track. Thus, the characteristic of the motor is reformed by the stator flux instead of the stator current as in FOC [11].

The effects of DTC on the induction motor system are characterized as follows [12]:

- Flux and Torque can be changed rapidly with accuracy when changing the references.
- Power losses during the transitivity of transistors are minimized because they are only switched to maintain the torque and flux within their hysteresis bands.
- No overshoot in the step response.
- There is no need for dynamic coordinate transforms because all calculations are processed in the stationary coordinate system.
- The switch control signal is directly controlled by the hysteresis control, so the separated modulator is redundant.
- There are no PI controllers as in FOC [11]. Therefore, reducing the human efforts or micro-processing resources for tuning.

3.2. Simulation Results

The simulation program for three-phase asynchronous motor is shown from Figure 2a to Figure 2d. The simulation is performed in MATLAB/Simulink environment.

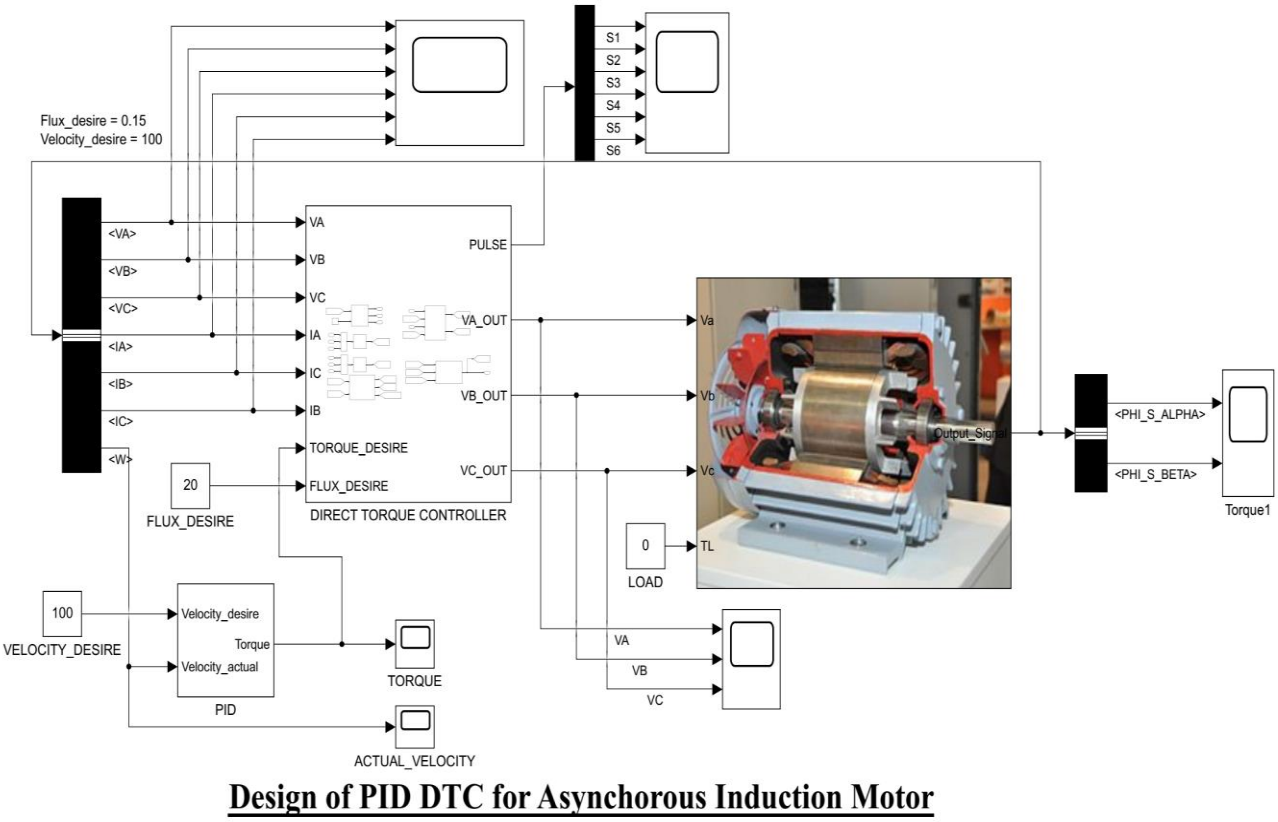

Fig. 2a. Simulation program to control three-phase asynchronous motor with PID-DTC

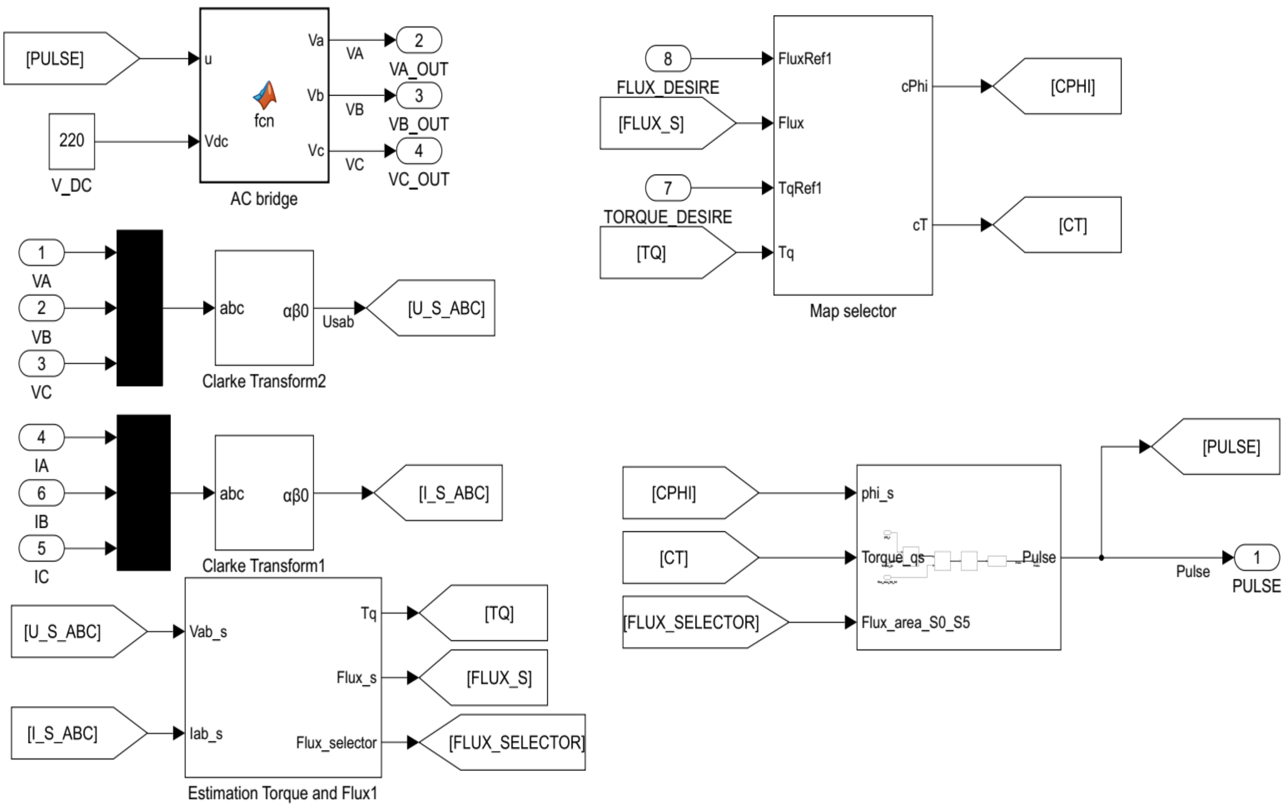

Fig. 2b. Direct Torque Controller block

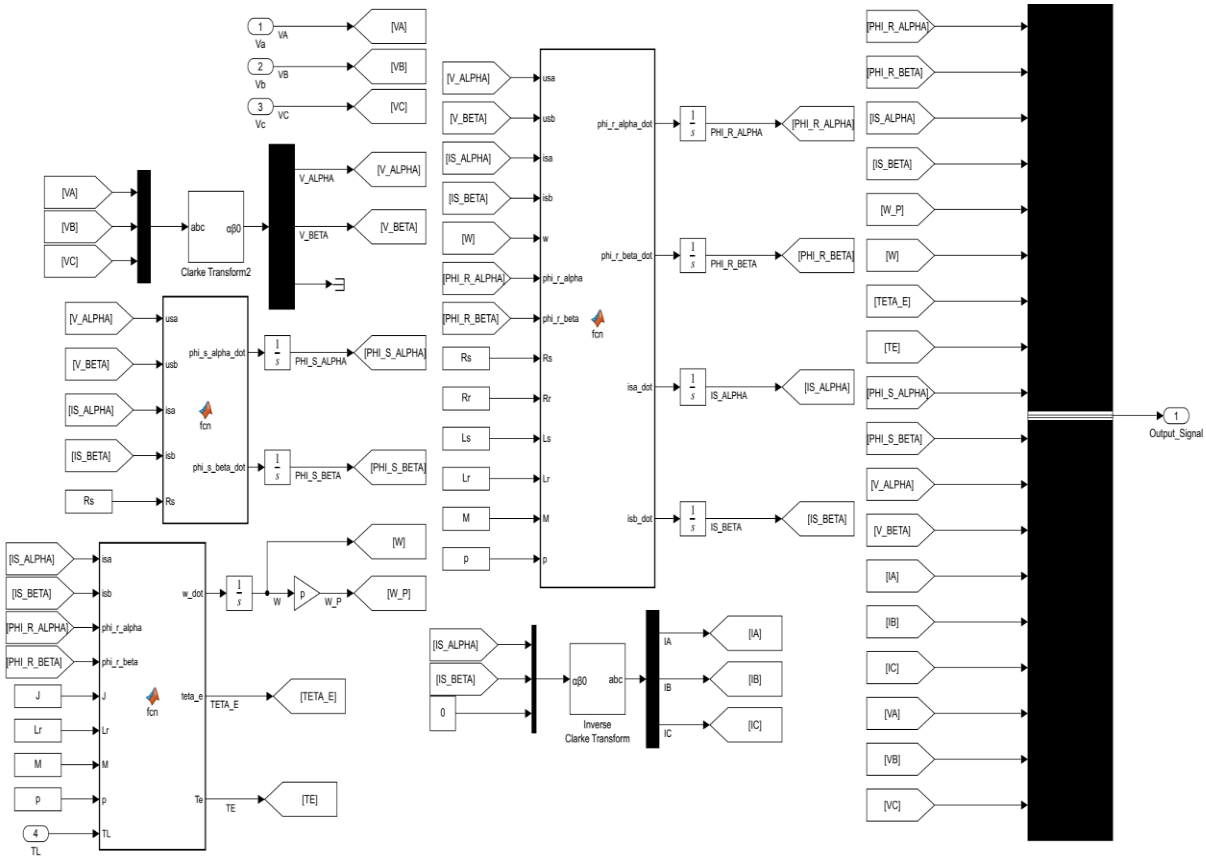

Fig. 2c. Three-phase asynchronous motor block

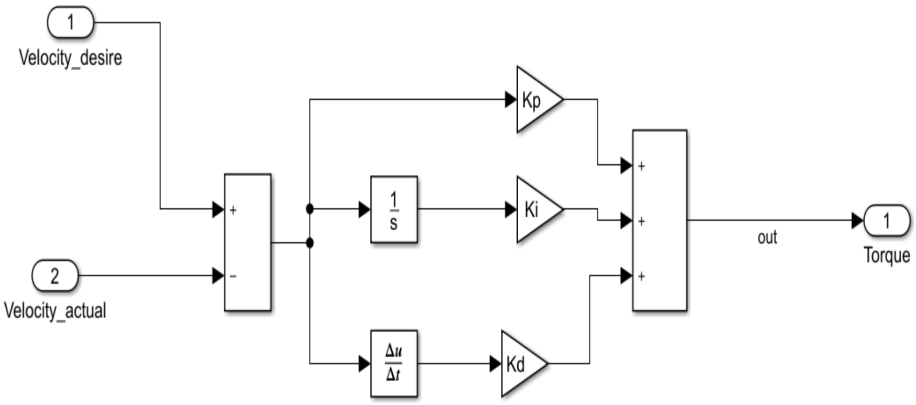

Fig. 2d. PID controller

Table 2. The parameter of PID controller

Parameters	Value
K_p	8
K_i	3
K_d	0

3.2.1. Scenario 1: No load and Motor speed is 100 (rpm): $T_L = 0$ and $w_d = 100$

In this subsection, the results of first senario are presented from Figure 3 to Figure 7.

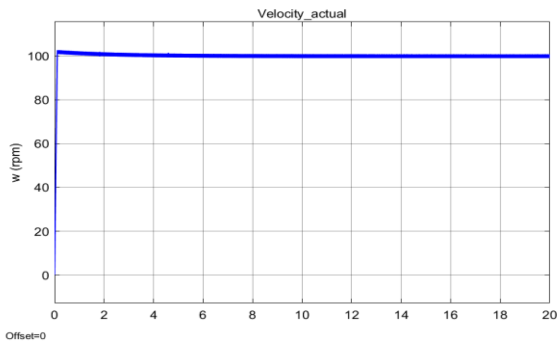

Fig. 3. Motor speed $w_d = 100$ (rpm) without load

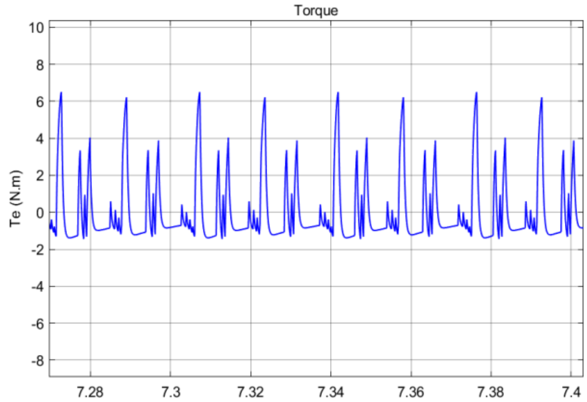

Fig. 4. Torque of motor (Nm) without load

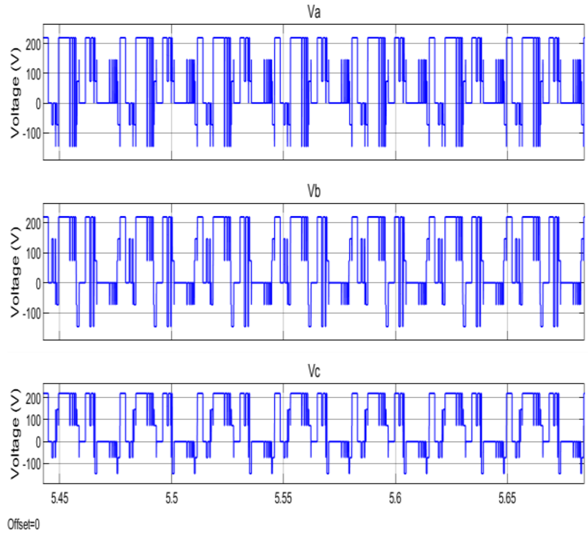

Fig. 5. Signal voltage of 3 phases a, b, c without load (V)

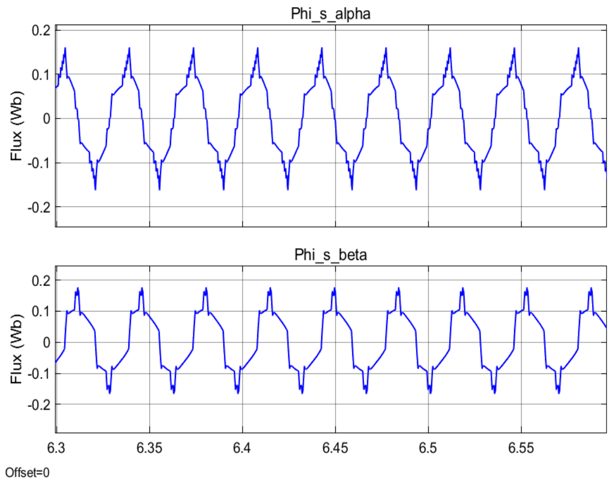

Fig. 6. Rotor Fluxs without load (Wb)

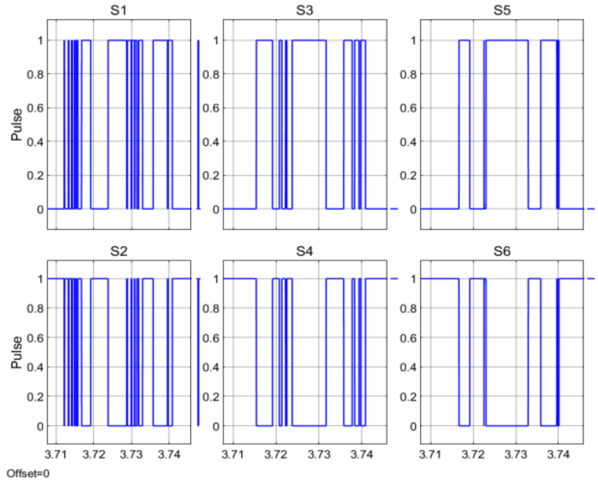

Fig. 7. Pulse of S_0 – S_6 areas without load

3.2.2. Scenario 2: Positive Load and Motor speed is 100 (rpm): $T_L = 2$ and $w_d = 100$

In this subsection, the results of sencond senario are shown from Figure 8 to Figure 12.

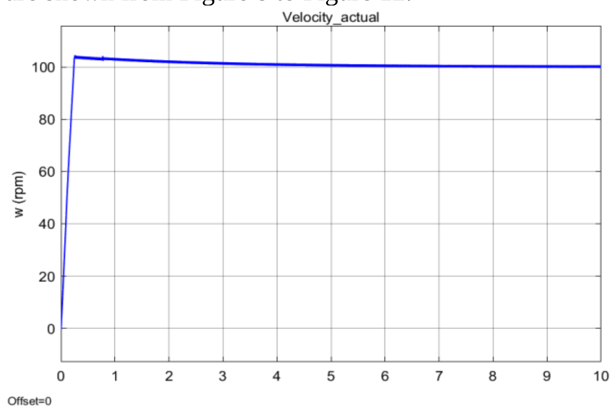

Fig. 8. Motor speed $w_d = 100$ (rpm) with positive load

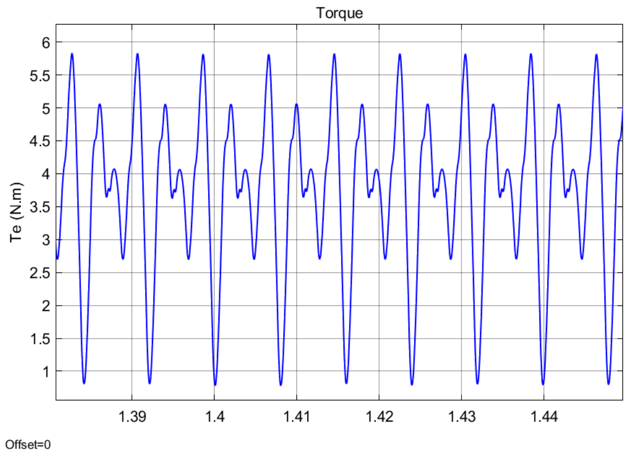

Fig. 9. Torque of motor (Nm) with positive load

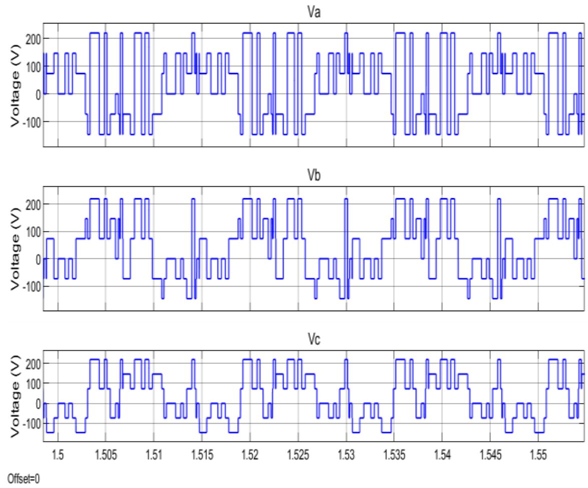

Fig. 10. Signal voltage of 3 phases a, b, c with positive load (V)

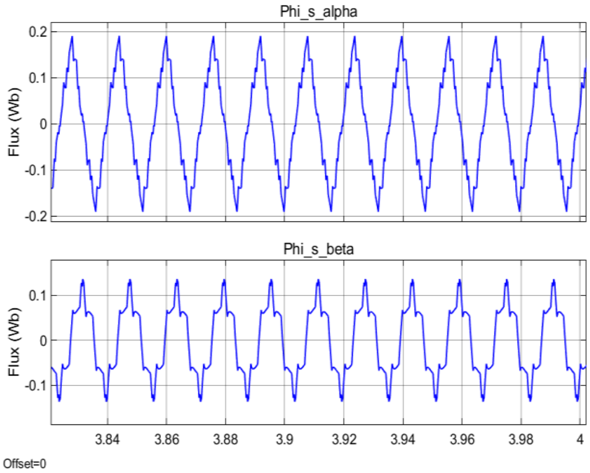

Fig. 11. Rotor fluxs with positive load (Wb)

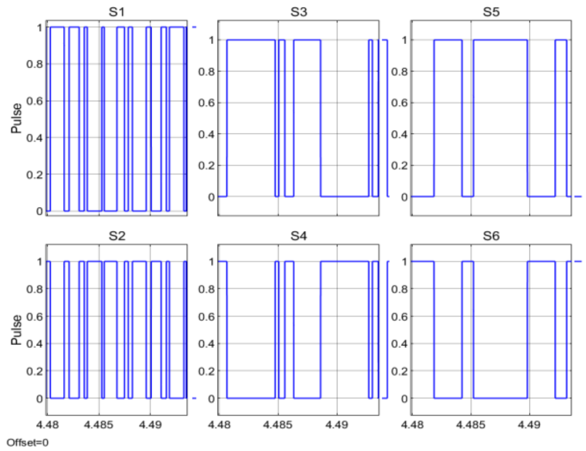

Fig. 12. Pulse of $S_0 - S_6$ areas with positive load

3.2.3. Scenario 3: Negative Load and Motor speed is 100 (rpm): $T_L = -2$ và $w_d = 50$

Finally, the simulation results of the third senario are shown from Figure 13 to Figure 17.

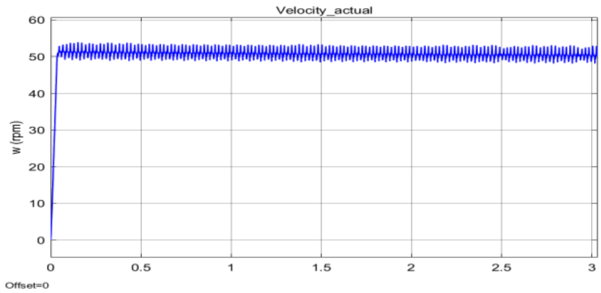

Fig. 13. Motor speed $w_d = 50$ (rpm) with negative load

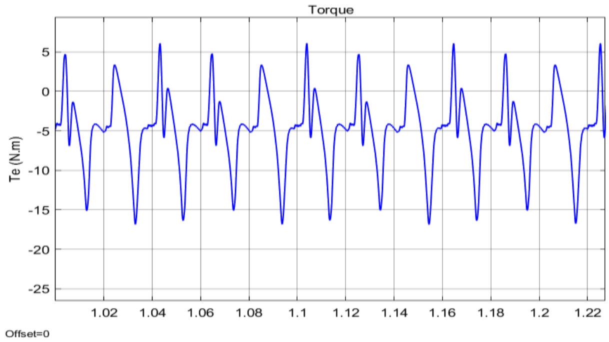

Fig. 14. Torque of motor (Nm) with negative load

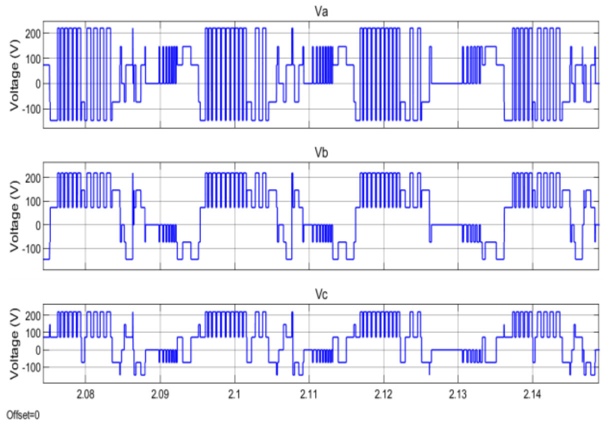

Fig. 15. Signal voltage of 3 phases a, b, c with negative load (V)

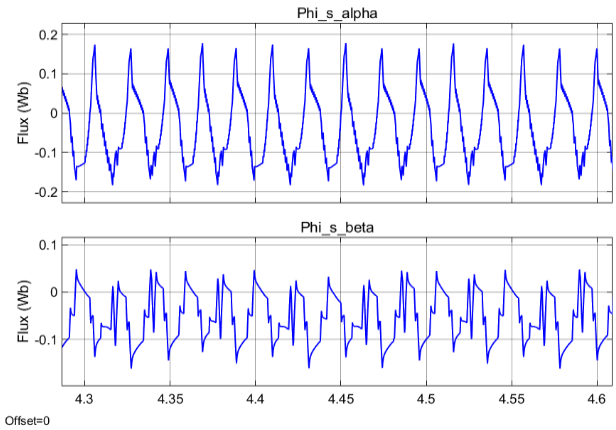

Fig. 16. Rotor fluxs with negative load (Wb)

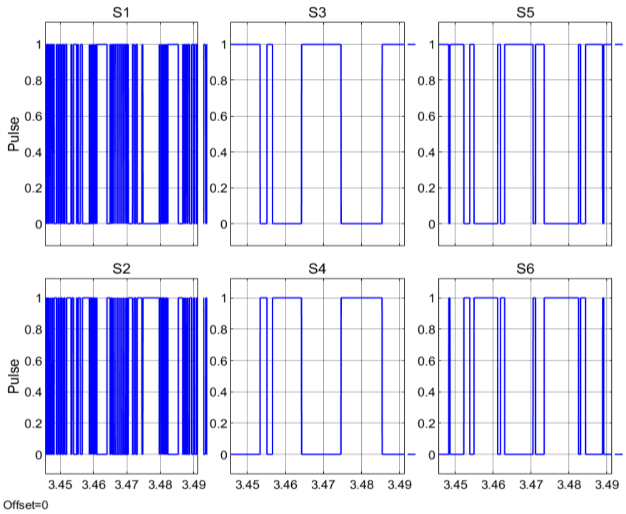

Fig. 17. Pulse of $S_0 - S_6$ areas with negative load

3.2.4. Comments

The simulation results with 3 different scenarios, including load torque and speed input, the PID -DTC controller gives the expected speed output response with the input that calculated from the controller by deisigning of the authors. The pros and cons are listed below:

Pros:

- Easily to design simulation model of the controller.
- Does not require too much mathematical theory as well as physics and analysis into the kinematic equation of the 3-phase asynchronous motor.

Cons:

- Output is the speed and torque of the motor, has large or small fluctuations depending on the control position.
- Output uses Space Vector Modulation to provide control signal to the inverter circuit making the control output intermittent and smooth, which in fact causes rapid heating of the motor, causing damage to the coil in the stator.

4. Conclusion

In this study, the authors successfully built a three-phase asynchronous motor system on MATLAB/Simulink software and applied the PID-DTC control algorithm to the system through a number of cases. In general, the PID-DTC controller gives good quality output response. The simulation results have tested the feasibility and accuracy of the control method. The authors also propose to build a realistic model to evaluate control quality in the following studies. At the same time, developing research field-oriented control method for three-phase asynchronous motor to compare with the PID-DTC algorithm.

5. References

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