École Centrale de Nantes

Electric Vehicle Modelling and Simulation

Lab Report

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Date: 4/10/2021

1. Aims/Objectives

The aim of this lab is to enable us to acquire a better understanding of Induction motor modelling. Induction motor modelling is generated by two sub models-electrical model and mechanical model. With the construction of the corresponding models in Simulink, it is helpful for students to understand the equations on each model further. Besides, the analysis of simulation results is useful for engineering students to develop a better understanding of the influence of an added torque to the induction motor. The effects on currents and electromagnetic torques after adding a load to induction motor are also studied in this lab.

2. Induction Motor Modelling

The *d-q* frame is introduced to achieve a better dynamic performance in further field-oriented control. In practice, there are three commonly used reference frames of *d-q* frame. In this lab, synchronous reference frame is chosen to model induction motor (IM).

As shown in Figure 2.1, the mathematical model of IM is firstly transformed from the *a-b-c* frame to the stationary *α-β* frame, then to the synchronous *d-q* frame.

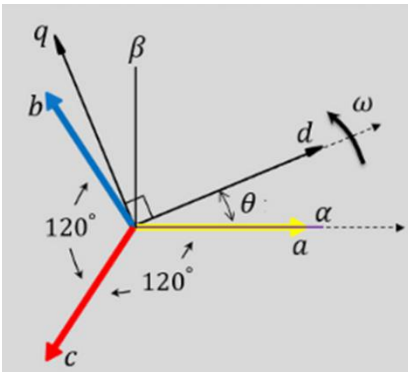


Fig. 2.1 transformation from the *a-b-c* frame to the *d-q* frame

Since the *α*-axis of the *α-β* frame is aligned with the *a*-axis of the *a-b-c* frame, the transformed variables in the *α-β* frame can be obtained as

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{2.1}$$

where *α*, *β*, *a*, *b*, *c* can be any variable on the corresponding axis, such as voltage, current and flux linkage.

Taking θ_e as the angle of the *d-q* frame with respect to the *α-β* frame, the variables in the *d-q* frame can be expressed as

$$\begin{bmatrix} d \\ q \end{bmatrix} = \begin{bmatrix} \cos(\theta_e) & \sin(\theta_e) \\ -\sin(\theta_e) & \cos(\theta_e) \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \tag{2.2}$$

where $\theta_e = \omega_e t$. ω_e is the rotating speed of the *d-q* frame.

In normal case, the rotor circuit of IM is shorted. Thus, after developing the two transformations (2.1) and (2.2), the stator circuit equations and the rotor circuit equations are given as

$$v_{ds} = r_s i_{ds} + \rho\lambda_{ds} - \omega_e \lambda_{qs} \tag{2.3}$$

$$v_{qs} = r_s i_{qs} + \rho\lambda_{qs} + \omega_e \lambda_{ds} \tag{2.4}$$

$$0 = r_r i_{dr} + \rho\lambda_{dr} - (\omega_e - \omega_r)\lambda_{qr} \tag{2.5}$$

$$0 = r_r i_{qr} + \rho\lambda_{qr} + (\omega_e - \omega_r)\lambda_{dr} \tag{2.6}$$

where ω_r is the rotor speed, λ_s is the stator flux linkage, λ_r is the rotor flux linkage, and ρ is differential operator. For the flux linkages of the stator and the rotor, they can be derived as

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \tag{2.7}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \tag{2.8}$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \tag{2.9}$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \tag{2.10}$$

where L_s is the stator inductance, and L_r is the rotor inductance, and L_m is the mutual inductance.

Furthermore, the electromagnetic torque T_e in the d-q frame can be represented as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \tag{2.11}$$

where P is the number of poles of the machine.

In addition, the mechanical model of IM can be expressed as

$$T_e = J\frac{d\omega_r}{dt} + B_m \omega_r + T_L \tag{2.12}$$

where B_m is coefficient of viscous friction.

3. Simulink Modelling

In order to study the role of *d-q* model, in this section, all the sub models built in section 2 will be developed in MATLAB/Simulink.

Firstly, three phase power supply of IM can be expressed as

$$\begin{cases} V_{as} = V_m \sin\left(\omega_e t\right) \\ V_{bs} = V_m \sin\left(\omega_e t - \dfrac{2\pi}{3}\right) \\ V_{cs} = V_m \sin\left(\omega_e t + \dfrac{2\pi}{3}\right) \end{cases} \tag{3.1}$$

where V_m is the amplitude of the three phase voltages. In Simulink the power supply is implemented as shown below.

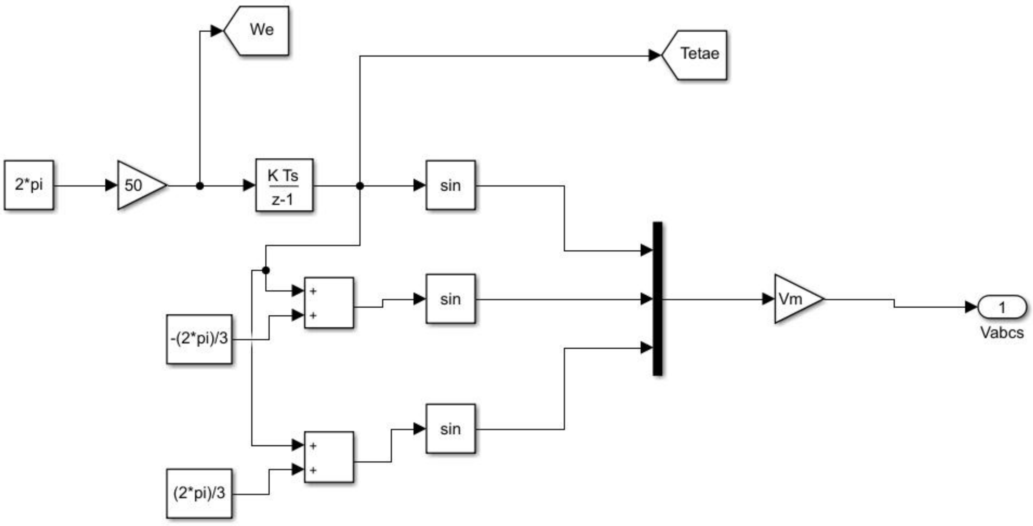


Fig. 3.1 the block diagram of power supply

According to the transformations (2.1) and (2.2), the stator voltage components in *d-q* frame are obtained, as shown in Figure 3.2.

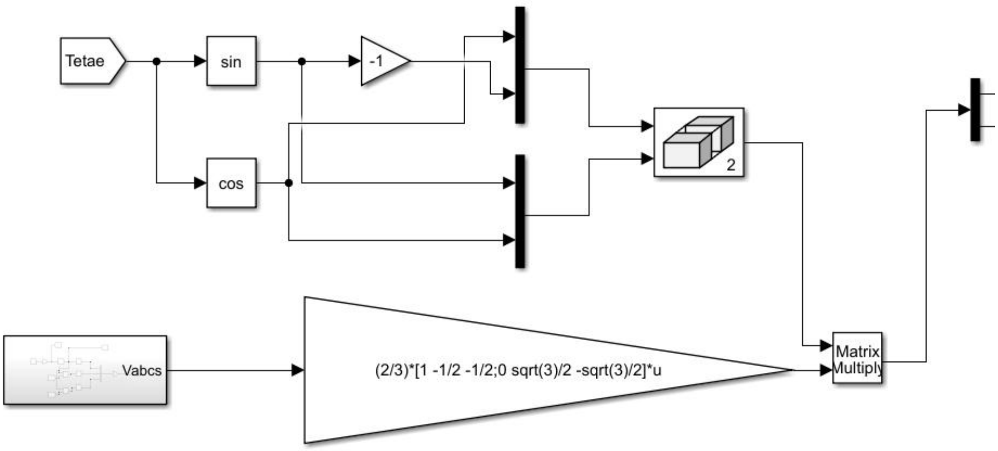
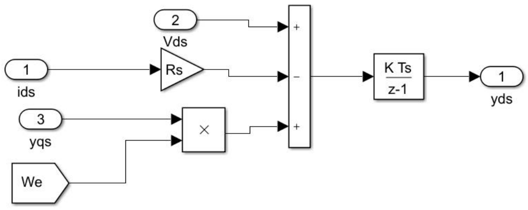


Fig. 3.2 the block diagram of equation (2.1) and (2.2)

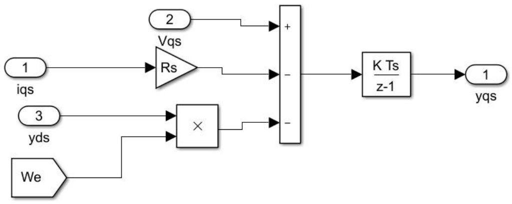
For equations (2.3)~(2.6) and (2.12), there are some derivative terms in the equations, it is wise to put all these terms alone to one side and then integrate on both sides. Taking equation (2.3) as an example, it can be rewritten as

$$\lambda_{ds} = \int V_{ds} - r_s i_{ds} + \omega_e \lambda_{qs} \tag{3.3}$$

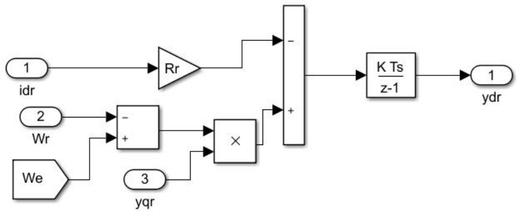
in this way, the corresponding block diagrams of equation (2.3) ~ (2.6) in Simulink can be constructed as below:



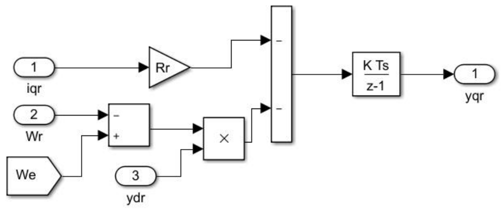
(a) equation (2.3)



(b) equation (2.4)



(c) equation (2.5)



(d) equation (2.6)

Fig. 3.3

Similarly, equation (2.12) can be rewritten as

$$\omega_r = \frac{1}{J} \int \left(T_e - T_L - B_m \omega_r \right) \tag{3.4}$$

its block diagram is showed as Figure 3.4.

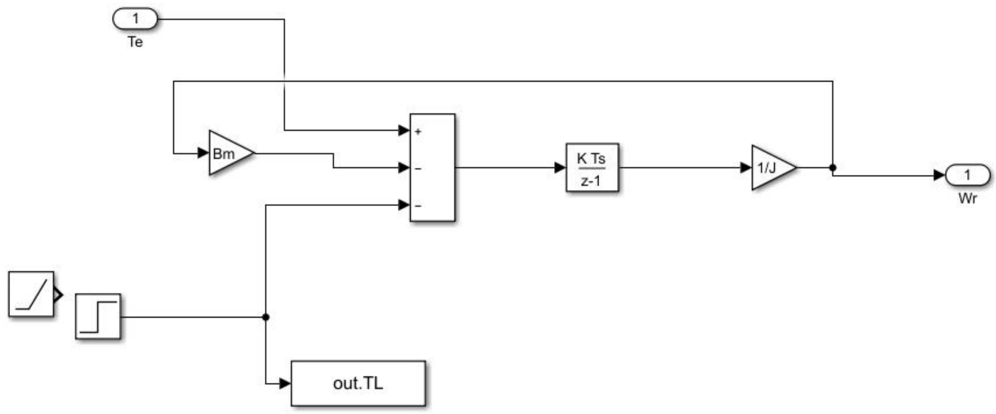
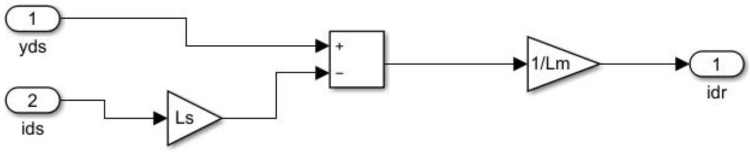
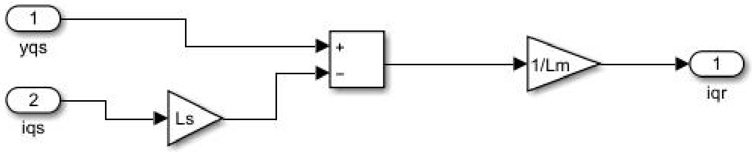


Fig. 3.4 the block diagram of equation (2.12)

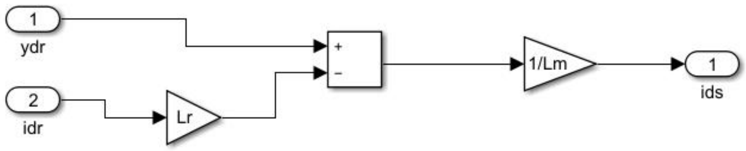
Equations (2.7) to (2.10) can be easily developed in Simulink as shown in Figure 3.5. Besides, the block diagram of equation (2.11) is built as shown in Figure 3.6. Finally, the overall structure of the model is shown in Figure 3.7.



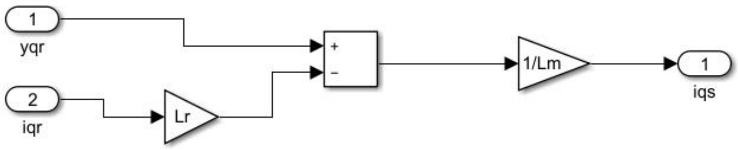
(a) the block diagram of equation (2.7)



(b) the block diagram of equation (2.8)



(c) the block diagram of equation (2.9)



(d) the block diagram of equation (2.10)

Fig. 3.5

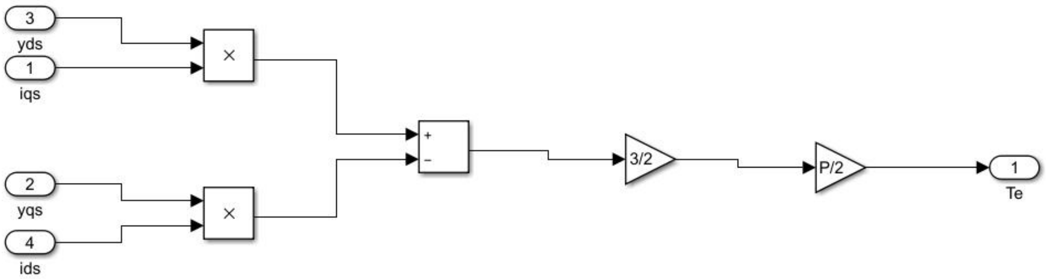


Fig. 3.6 the block diagram of equation (2.11)

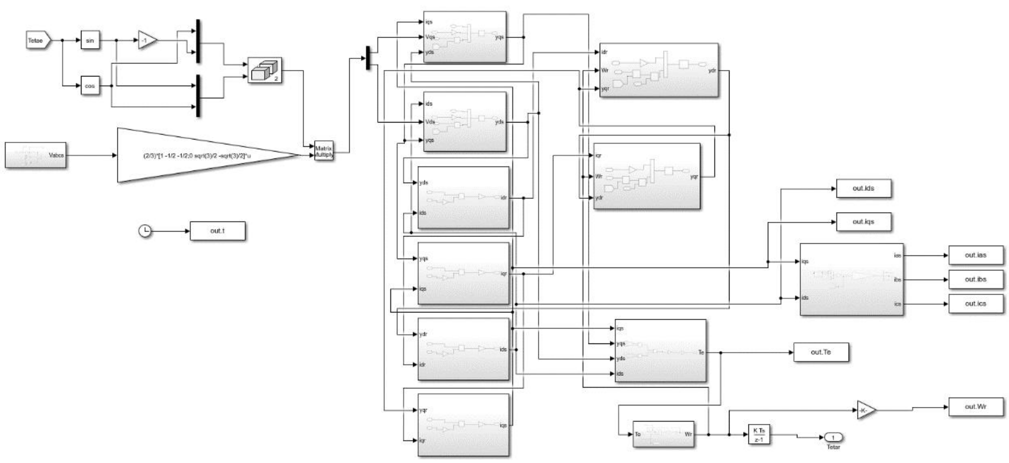


Fig. 3.7 the overall structure of the model in Simulink

4. Simulation results and analysis

4.1 Load torque and electromagnetic torque

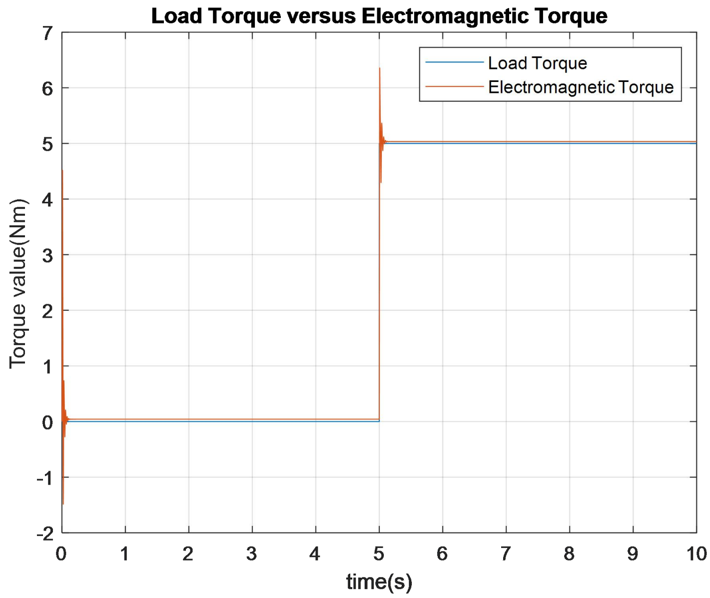


Fig. 4.1

From the graph it can be observed that the Electromagnetic Torque has a fluctuation at $t = 0$. Then it levels out to 0 until a load torque is added to the induction machine. The load torque value stays at 0 until it is set to 5N·m when $t = 5$s. From the Electromagnetic response it can be seen that its value starts to vary at $t = 5$s. And after the transient state its value reaches slightly more than 5 N·m, because of the viscous friction according to equation (2.12). In all, it is clear that the Electromagnetic torque and the added load torque have a similar shape.

4.2 Rotor speed

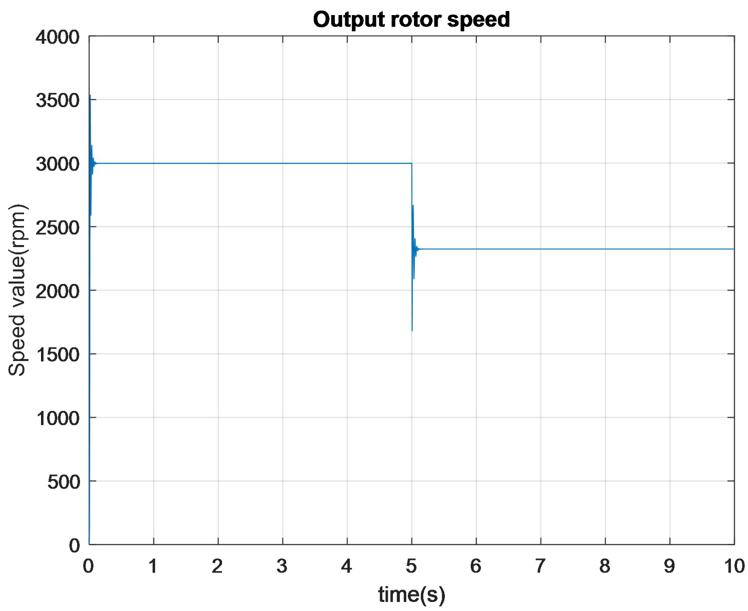


Fig. 4.2

Since the frequency is set to 50 Hz, by ω_r=2πf the motor speed can be calculated. Further transformed in rpm unit, the expected motor speed is 3000rpm. The output rotor speed response shows that the motor speed stays at 3000rpm which accords with the theoretical value. After the load torque is added to the induction machine, it is obvious that the rotor speed experience a considerable reduction. This process can be well explained by the torque-speed characteristic as shown below, IM in this case is in the red region.

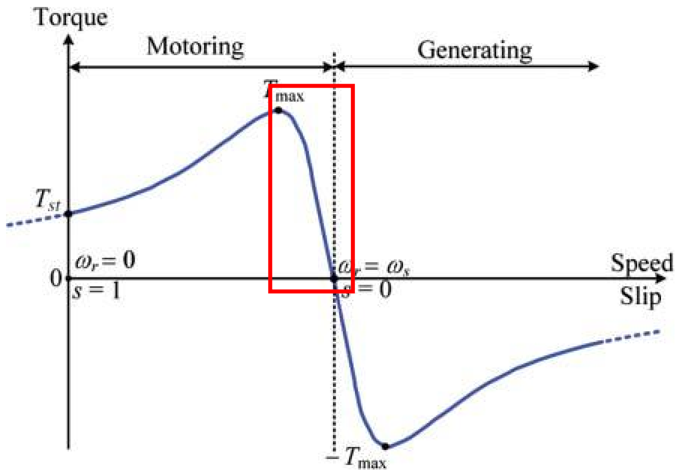


Fig. 4.3 torque-speed characteristic of induction machine

4.3 Current analysis

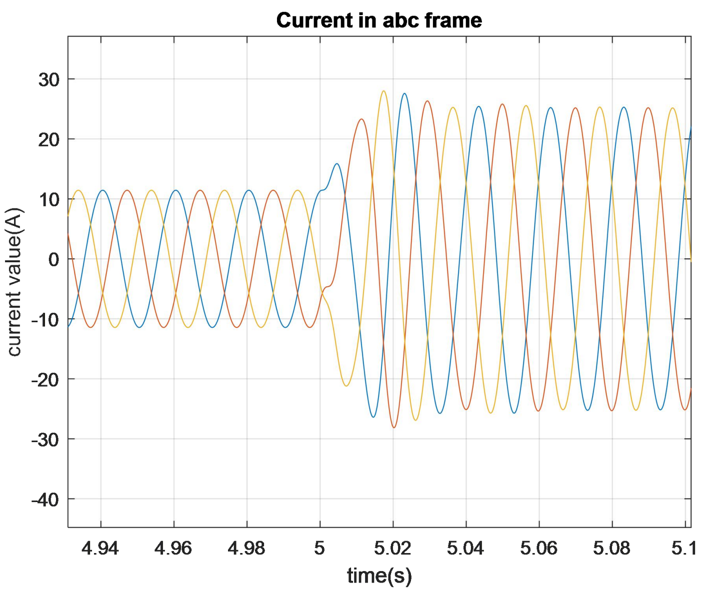


Fig. 4.4 stator current in *a-b-c* frame

The graph above shows that the current in *a-b-c* frame respectively. It can be observed from the graph that the phase shift between i_a, i_b and i_c is 120 degree. Besides, the current shape is sinusoidal wave.

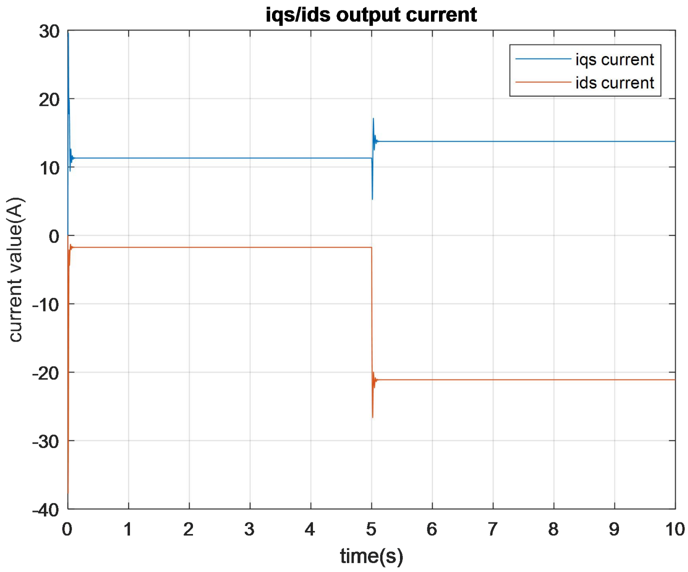


Fig. 4.5 stator current in *d-q* frame

From the graph shown above, it can be observed that the current in *d-q* frame has a constant result. Compared with current in *a-b-c* frame, it is easier to observe in *d-q* frame because they are constant which also shows there is no dependence on frequency. Besides, at t = 5s, with a load torque added to the system, the current value increases.

5. Conclusion

The simulation results show that the added load torque affects the output rotor speed, current value and electromagnetic torque. After introducing a load torque, the current increases while the electromagnetic torque increase and its value is in the same level with (slightly bigger than) the load torque. In addition, the added torque value causes a decrease on the output rotor speed. From the simulation results it also indicates the comparison between using *d-q* frame on current and using *a-b-c* frame on current. It is obvious that by applying a *d-q* frame, the current value in the induction motor becomes a constant, which is easier for analysis and it also shows that it is independent of the frequency of power supply. In all, the structure of an induction motor and its models are constructed and studied in this lab. Besides, the induction motor's response to an added load torque is also analyzed.

6. References

[1] Bellure, A., & Aspalli, M. S. (2015). Dynamic dq model of Induction Motor using Simulink. International Journal of Engineering Trends and Technology (IJETT), 24(5), 252-257.

[2] Chau, K. T. (2015). Electric vehicle machines and drives: design, analysis and application. John Wiley & Sons.