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Review Article:

The Required Voltage Compensation to Overcome the Effect of Changing Flux and Back-emf in Squirrel Cage Three Phase Induction Motor Drives

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Abstract

This paper demonstrates the design and development of decoupling method in vector control induction motor. Three-phase induction motor is one of the most electric devices which is widely used in industrial applications. One of the most problems at high power application is controlling the transient current to protect the motor from damage. Various control schemes have been used however vector control is the most promised one which is used nowadays for the control purposes. A motor model for 1.5kW three phase squirrel cage induction is chosen for the design. In vector control three phase current is represented with two phase which are d-axis and q-axis. At first, current control for each axis is designed, later decoupling between them is shown and described. Matlab Simulation is used to validate the design and to show the results.

1. Introduction

Most electric motors work through the interaction between the motor's magnetic field and electric current in a winding to produce force in the form of rotation of the shaft. Electric motors can be powered by direct current (DC) sources, such as batteries, motor vehicles or rectifiers, or by alternating current (AC) sources, such as a power grid, inverters or generators. General-purpose motors with standard dimensions and characteristics deliver convenient mechanical power for industrial use (Turan,2012).

Three phase induction motors are widely used in industrial for many purposes due to robust construction, reliability and high efficiency when controlled.

In general, two methods are used to start up induction motors and they are Direct on Line (DOL) method and control method which is mostly vector control. The use of asynchronous motors particularly squirrel-cage rotor has increased tremendously since the day of its invention. They are being used as actuators in many types of industrial processes, robotics, house appliances (generally single-phase) and other similar applications. The reason for its daily increasing popularity can be primarily attributed to its simplicity in design, robust construction and cost effectiveness, high efficiency, reliability and good self –starting capability (Boora,2013 -Shi,1999).

The induction motor is an important class of electric machines which finds wide applicability in industry and in its single phase form in several domestic applications. More than 85% of industrial motors in use today are in fact induction motors that is basically a constant speed motor with a shunt characteristic (Vithayathil,2006-Orost,2007).

This paper will look at modeling and decouple compensation of d-q current controller design of three phase induction machine. For this purpose, a three-phase induction motor 1.5 kW squirrel cage rotor type will be chosen and then for controllers' purposes, motor parameters will be calculated. This model describes the transient and the steady state behavior of the induction machine. The model is essential to evaluate and show asynchronous motor drives transient performances in MATLAB simulation. In addition, d-q axis model for the study of converting three phases to two phases dq axis has been described (Lee,1984). Moreover, based on Motor parameters current control loops designed. Current loop controllers are tested with different conditions and a voltage compensator will be designed and examined.

The purpose of this paper is to solve the issue of separating d, q current controller in transient operation while sudden change of speed occurs. These over currents appear at transient states where the controller is not fast enough to compensate for internal changes of the motor. To solve these problems controllers are improved with decoupling calculation. Main purpose of introducing decoupling technique in this system is to improve reliability of the application without losing output torque. However, eliminating flux linkage between d, q current axes, makes current controllers are independent which leads to remain the direct current controller constant while sudden change occur on quadrature current controller.

2. Specified Induction motor

2.1. Induction motor parameters

Firstly, calculating three phase induction motor parameters required for modelling the motor. All electrical and mechanical parameters of the induction motor have been tabulated and measured are shown in table 1.

2.2. Induction motor model

2.2.1. Three phase to alpha-beta model

Three phase voltage source which have been converted to $\alpha\beta$ coordinate and vice versa are the following equations (Clarke, 1951):

$$\begin{pmatrix} i\alpha \\ i\beta \end{pmatrix} = \begin{pmatrix} 3/2 & 0 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{pmatrix} * \begin{pmatrix} ia \\ ib \\ ic \end{pmatrix} \quad ...(1)$$

$$\begin{pmatrix} ia \\ ib \\ ic \end{pmatrix} = \begin{pmatrix} 2/3 & 0 \\ -1/3 & 1/\sqrt{3} \\ -1/3 & 1/\sqrt{3} \end{pmatrix} * \begin{pmatrix} i\alpha \\ i\beta \end{pmatrix} \quad ...(2)$$

Basing on equation (1 and 2) block diagram of conversion of three phase current to alpha beta and alpha beta to three phase can be represented as shown in figures (1 and 2).

2.2.2. Direct and Quadrature model.

The following set of equations are presented as a mathematical model of IMs (Shah,2012):

$$v_{sd=} R_s i_{sd} + \sigma L_s \frac{d}{dt} i_{sd} - w_e \sigma L_s i_{sq} + \frac{L_o}{L_r}\frac{d}{dt}\varphi_{rd} \quad (3)$$

$$v_{sq=} R_s i_{sq} + \sigma L_s \frac{d}{dt} i_{sq} + w_e \sigma L_s i_{sd} + w_e \frac{L_o}{L_r}\varphi_{rd} \quad (4)$$

Based on above equations the direct-quadrature current, torque, rotor and stator flux had been modeled as shown in figure 3.

3. Compensation term effect on Induction motor model

3.1. D-q Current loop controller

In order to design and build a model and simulate the effect of the compensating term on the controller, it is required to design a controller for each of current loop. In this section, a PI controller will be designed for each loop based on the parameters of the induction machine specified previously. Block diagram of a general PI controller is shown in figure 4.

The response of the dq current closed loop system needs around 0.007 second to reach steady state condition as shown in figure 6.

3.2. Examining Current loop controller

In order to use PI controller, the three phase induction machine need to be transformed to two phase with 90 degree phase shift (dq axis) (Lee,1984). The first part of the current is the Magnetizing current. Since there is no magnetic field within the rotor of the motor, it must be induced using electromagnetism. One of current axis is controlled in the stator to induce an electromagnetic field in the rotor. As the rotor is turned the magnetic field is rotated synchronously with the rotor to maintain a static orientation of the magnetic field relative to the rotor.

Second part of the current is the torque producing current. This current is controlled in the stator to produce another electromagnetic field within the stator itself that is oriented 90 degrees to the magnetic field simultaneously induced in the rotor as described above. As the torque produced increased the current increases and the torque applied to the rotor increases as well. The vector sum of these two currents in the stator that is solved by the drive in a Vector drive application, hence vector drive control.

The transformation is obtained by using (ab-dq) block to convert the output current and flux of the IM to dq values, and (dq-ab) block to convert the output of the controllers to ab values. Lamda is the rotor flux angle. One of the required parameter in both blocks (dq-ab and ab-dq) is known as Lamda which will be designed based on the below equations.

$$w_e(t) = \frac{d}{dt}\lambda(t) \quad ...(5)$$

$$\lambda = \int w_e dt = \int (w_r + w_{sl}) dt \quad ...(6)$$

$$w_{sl} = \frac{R_r}{L_r * imrd} * isq \quad ...(7)$$

$$w_{sl} = \frac{isq}{\tau_r * imrd} \quad ...(8)$$

Substituting equation 8 to the equation 6:

$$\lambda = \int (w_r + \frac{isq}{\tau_r * imrd})dt \quad ...(9)$$

While for batter result $I_{sq}{}^*$ has been used

As it can be seen from equations above, magnetization current (I_{mrd}) is needed and it can be found as shown below.

$$imrd = \frac{isd}{\tau_r s + 1} \quad ...(10)$$

Then, the lamda block can be redrawn as shown in figure 7.

In order to be able to show the overall model, a subsystem is designed for torque-speed conversion as shown in figure 8.

Finally, by placing Lamda block and PI controllers for direct and quadrature current (I_{sd} and I_{sq}), the current loop model can be designed as shown in figure 9.

3.2.1. Examine Current Loop Controller with Rated I_{sd} and Zero I_{sq} at No-Load and Full-Load Condition

In this part, with settling rated I_{sd} and zero I_{sq} at no-load condition, it is expected to see field (Ψrd) which is produced by I_{sd} and zero torque which is produced by I_{sq} and since the dq rotating frame is oriented on rotor flux, therefore Ψrq = 0 is expected. Since no-load is applied, therefore, speed will be also zero. Figures (10 and 11) show the simulation results using current loop model to observe whether the expectations will be obtained or not.

As it can be noticed from figures (10 and 11), since I_{sq} is zero and no load has been applied, the speed and torque are zero. The flux on d-axis is produced due to I_{sq} is rated and Ψrq = 0 as expected due to dq frame orientated on rotor flux. Next step, settling I_{sd} rated and I_{sq} zero at full-load condition, the simulation results are same as no-load with one difference which is the rotor rotates at reverse direction due to applying load torque and there is no torque produced by the motor to act against the load torque because of zero I_{sq}. Figure 12 shows the speed response of current loop with I_{sd} rated and I_{sq} zero at full load.

3.2.2. Examine Current Loop Controller with zero I_{sd} and Rated I_{sq} at No-Load and Full-Load Condition

In this section, zero I_{sd} and rated I_{sq} will be settled at no load and full load. The expectations are, firstly, Ψrq = 0 due to orientation and Ψrd = 0 since it is produced by I_{sd}. Secondly, zero speed and zero torque. Figures (13 and 14) show the responses at no-load.

As it can be seen from figures above, I_{sd} is produced at transient condition and very few Ψrd is also produced (0.027Wb) and it reduces to a very small value. These make the motor to produce a small amount of torque which leads to rotate the rotor at no load. However, once the rated load is applied the rotor will rotate in reverse direction and the motor torque will be zero as shown in figure 15, while the load has been applied at 0.9 second.

3.2.3. Examine Current Loop Controller with Rated I_{sd} and Rated I_{sq} at No-Load and Full-Load Condition

In this section, rated I_{sd} and rated I_{sq} will be settled at no load and full load. The expectations are, at first, Ψrq = 0 due to orientation of dq-axis on rotor flux and Ψrd will be produced since I_{sd} is applied. Secondly, at no-load case, torque is produced by I_{sd} and speed goes to infinity since there is no speed controller to limit its increasing. Once a full load is applied, the slop of speed will change. Figures (16, 17 and 18) show the system response at rated I_{sd} and rated I_{sq}.

3.2.4. Voltage Compensation

In general, when the load changes the PI controller supplies a desired value of voltage to increase or decrease the current and this variation will affect the flux and back-emf. In order to overcome these changes, a voltage compensator is used which will be supplied by the PI controller only to change the current. This means the system is decoupled that is why the compensation term is also called "decoupling term". The voltage compensation term has been designed as shown in below equations.

$$v_{sd=} R_s i_{sd} + \sigma L_s \frac{d}{dt} i_{sd} - w_e \sigma L_s i_{sq} + \frac{L_o}{L_r}\frac{d}{dt}\varphi_{rd} \quad (11)$$

$$v_{sq=} R_s i_{sq} + \sigma L_s \frac{d}{dt} i_{sq} + w_e \sigma L_s i_{sd} + w_e \frac{L_o}{L_r}\varphi_{rd} \quad (12)$$

Since electrical speed (We) is needed in the equations, it can be easily obtained from lamda subsystem as shown in figure 19.

Now, the responses of the above system will be tested to figure out the difference between I_{sd-q} with and without Voltage compensator term.

As it can be noticed from figure 22, without compensation term, in a transient condition I_{sd} has reached around 3.6 Ampere and it required 9 ms to reach steady state condition (figure 22-A) while with voltage compensation term the overshoot of the I_{sd} is very small and I_{sd} needed less time to reach steady state value (figure 22-B). The reason behind this is, I_{sq} affects the I_{sq} when there is no voltage compensation term, the high overshoot occurs due to

$$\left(\frac{Lo}{Lr} * \frac{d}{dt}\Psi rd\right)$$

back-emf term and the long duration occurs because of ($- We{*}\sigma{*}Ls{*}Isq$).

However, when the voltage compensation term is used, I_{sq} will not affect I_{sd} and the two terms will be decoupled as shown in figure 23. This is the reason for taking less time to reach steady state and producing less overshoot.

3.2.5. Controllability and Observability of dq Current Loop Controller.

The dq current closed loop block diagram as described in previous section is shown in figure 24.

Closed Loop transfer function of dq current loop controller is

$$\frac{Isdq(s)}{Isdq*(s)} = \frac{20.3kp(s+a)}{s^2+(20.3kp+83.2)s+20.3kpa} \quad \ldots (13)$$

Now, by substituting kp = 82.5656 = 942.15 the closed loop can be obtained.

$$\frac{Isdq(s)}{Isdq*(s)} = \frac{1676\, s+1579120}{s^2+1759\, s+1579120} \quad \ldots (14)$$

Then the state equation is

$$\begin{bmatrix} x'1 \\ x'2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1579120 & -1759 \end{bmatrix} \begin{bmatrix} x1 \\ x2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} * u \qquad \ldots (15)$$

The output equation is

$$y = [1579120 \quad 1676\ ] \begin{bmatrix} x1 \\ x2 \end{bmatrix} \qquad \ldots (16)$$

$$A = \begin{bmatrix} 0 & 1 \\ -1579120 & -1759 \end{bmatrix},\ B = \begin{bmatrix} 0 \\ 1 \end{bmatrix},$$

$$C = [1579120 \quad 1676\ ]$$

$$transpose\ of\ A\ is \begin{bmatrix} 0 & -1579120 \\ 1 & -1759 \end{bmatrix},$$

$$and\ transpose\ of\ C\ is \begin{bmatrix} 1579120 \\ 1676 \end{bmatrix}$$

Then the Controllability of dq current loop controller can be found by this formula

$$M = [B: A * B\ ] \qquad \ldots (17)$$

$$A * B = \begin{bmatrix} 0 & 1 \\ -1579120 & -1759 \end{bmatrix} * \begin{bmatrix} 0 \\ 1 \end{bmatrix} \Rightarrow A * B = \begin{bmatrix} 1 \\ -1759 \end{bmatrix}$$

$$So, \quad M = \begin{bmatrix} 0 & 1 \\ 1 & -1759 \end{bmatrix}$$

M matrix is non-singular since it has a non-zero determination (Det=-1). Also, the two row and column vectors can be seen to be linearity independent, so it's a rank 2 and therefore the system is controllable. Also, the Observability of dq-current loop controller can be found by this formula

$$N = [Ct: At * Ct\ ] \qquad \ldots (18)$$

$$At * Ct = \begin{bmatrix} 0 & -15791201 \\ 1 & -1759 \end{bmatrix} * \begin{bmatrix} 1579120 \\ 1676 \end{bmatrix} \Rightarrow$$

$$At * Ct = \begin{bmatrix} -2.6 * 10^9 \\ -1.4 * 10^6 \end{bmatrix}$$

$$So, \quad N = \begin{bmatrix} 1579120 & -2.6 * 10\text{^}9 \\ 1676 & -1.4 * 10\text{^}6 \end{bmatrix}$$

N matrix is non-singular since it has a non-zero determination (Det=2.2*10^12). Also, the two row and column vectors can be seen to be linearity independent, so it's a rank 2 and therefore the system is observable.

Conclusion

In this study, a vector control was addressed and designed where at first parameters of the induction motor were calculated and based on motor parameters current loop designed and modeled. In simulation it was found that the system requires almost 5 milliseconds to reach steady state value and that match the theoretical design. After that, a voltage compensator was designed to decouple the d-axis and q-axis to overcome the change in flux and back induced emf during the sudden change in load. In conclusion voltage compensator term which is also called feed forward, provides less sensitivity to wrong controller and helps to reduce the dependence of the system on the feedback. Also, by using voltage compensation term the speed value when I_{sd}= o I_{sq}=2.904 is so decreased as compared to without compensation term.

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معوض الجهد المطلوب للتغلب على تاثير تغيير التدفق والجهد الخلفي في المحركات الحثية ثلاثية الطور من نوع القفص السنجابي

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المستخلص

هذا البحث يثبت امكانية تصميم وتطور السيطرة على ماكنة الحث بطريقة التحكم الشعاعي. ان مكائن الحث ثلاثية الاطوار تعتبر من اكثر المكائن استعمالا في المعامل والمصانع. من اكبر المشاكل ضمن تطبيقات مكائن الضغط العالية هي عملية التحكم للتيار العابر لحماية الماكنة. هناك عدة طرائق تحكم ولكن تعتبر طريقة التحكم الشعاعي من انجحها. لاجراء عملية تصميم المتحكم لقد تم استخدام ماكنة حث بقدرة 1.5 كيلو واط. ضمن طريقة التحكم الشعاعي يتم استخدام عملية تحويل تيار ثلاثي الاطوار الى بعدين ضمن المحاور (d) و (q). في البداية قد تم تصميم متحكم لكل محور على حدا ولاحقا سوف تم توضيح عملية دمجهما. لقد تم استخدام برنامج النمذجة ماتلاب لاثبات التصميم و لتحليل وعرض النتائج.

الكلمات المفتاحية : المحرك الحثي ، مانعه للتقارن ، تحويل ثلاثي الاطوار.

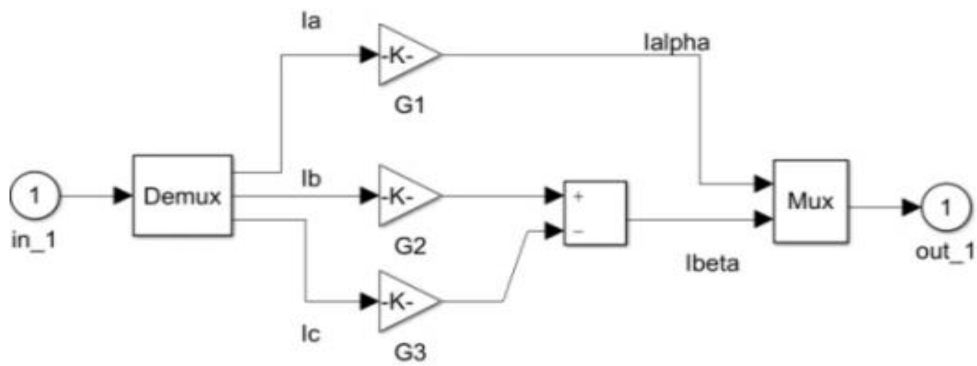


Fig. 1: Block diagram of three phase to alpha beta model. (Source: Researcher)

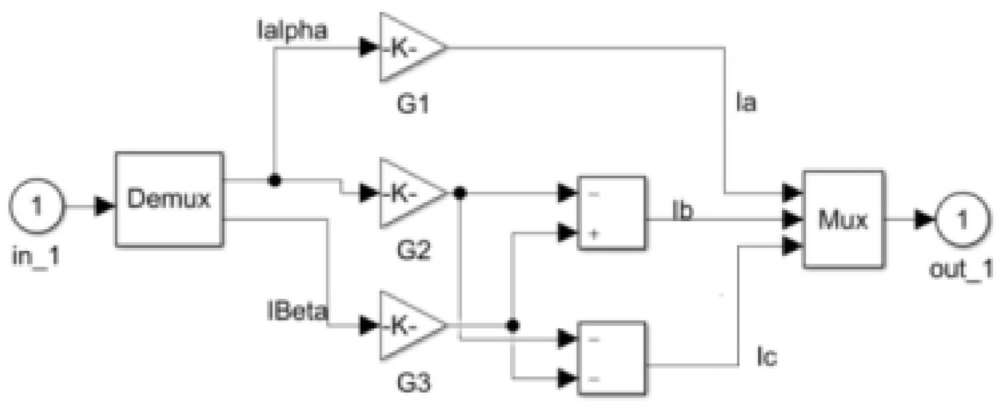


Fig. 2: Block diagram of alpha beta to three phase model. (Source: Researcher)

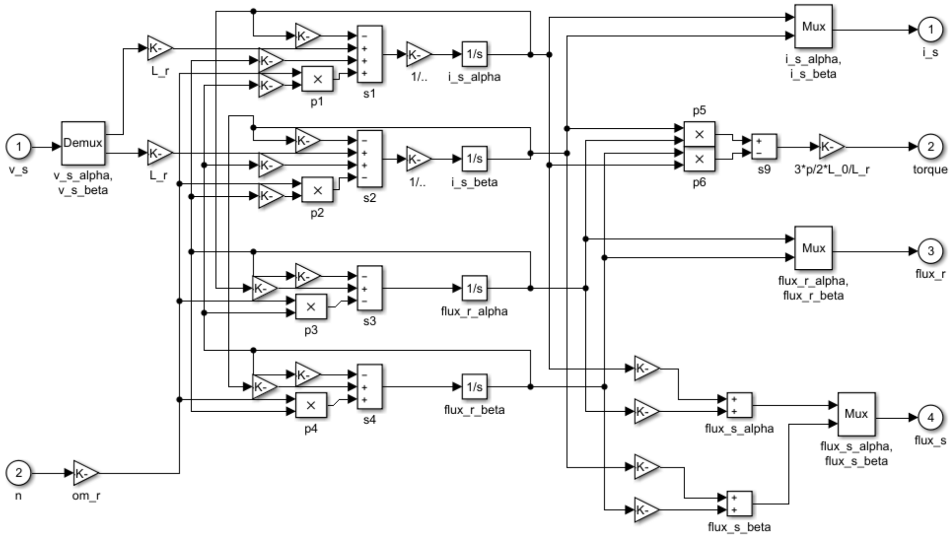


Fig. 1: Simulink model of the Induction motor. (Source: Researcher)

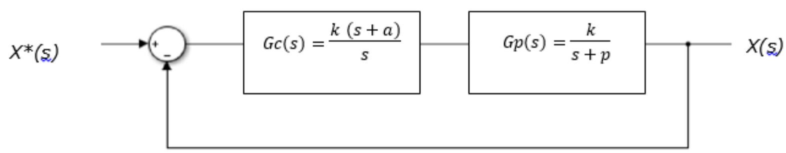


Fig. 2: PI Controller Block diagram. (Source: Researcher)

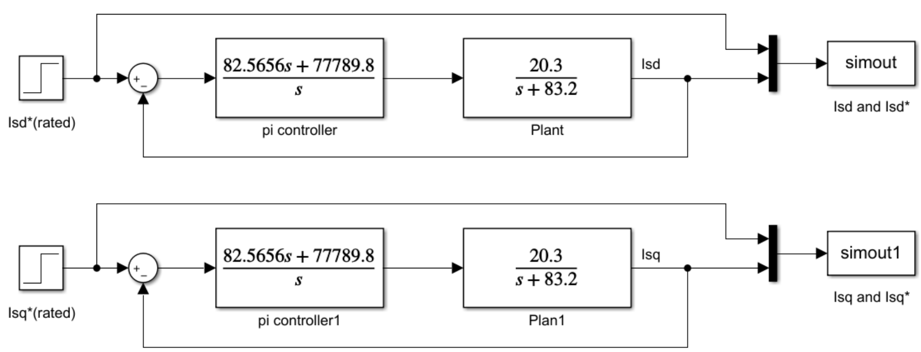


Fig. 3: pi controller for dq Current loop. (Source: Researcher)

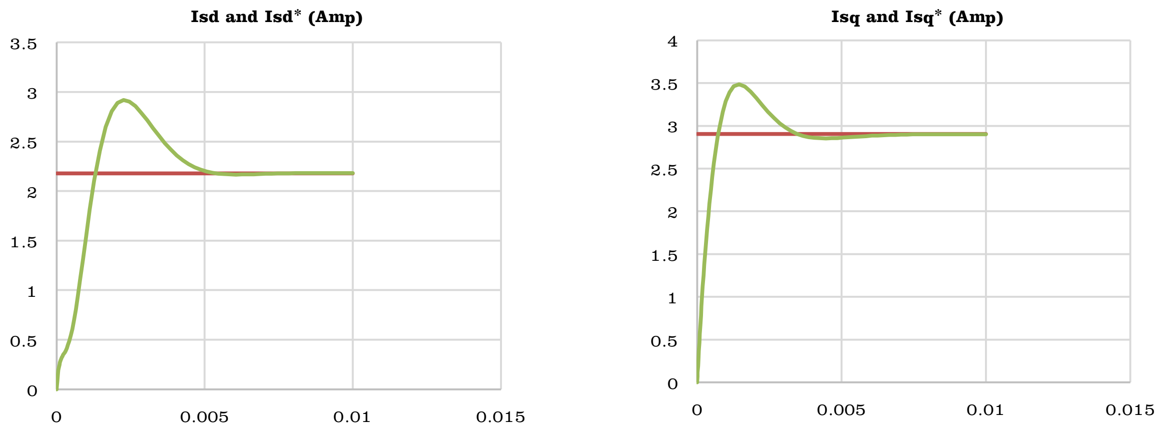


Fig. 6: Closed loop d-q Current Response. (Source: Researcher)

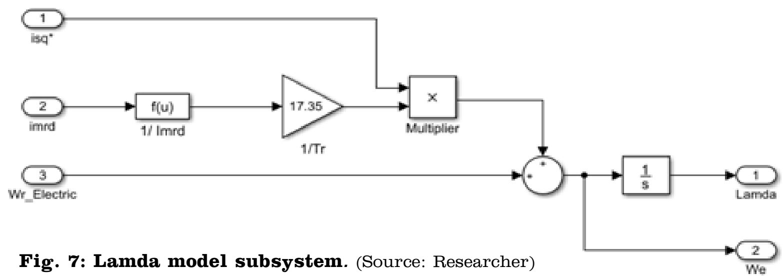


Fig. 7: Lamda model subsystem. (Source: Researcher)

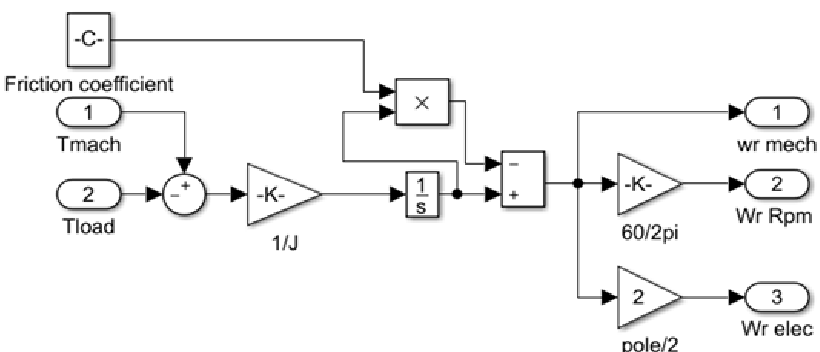


Fig. 8: Torque speed subsystem. (Source: Researcher)

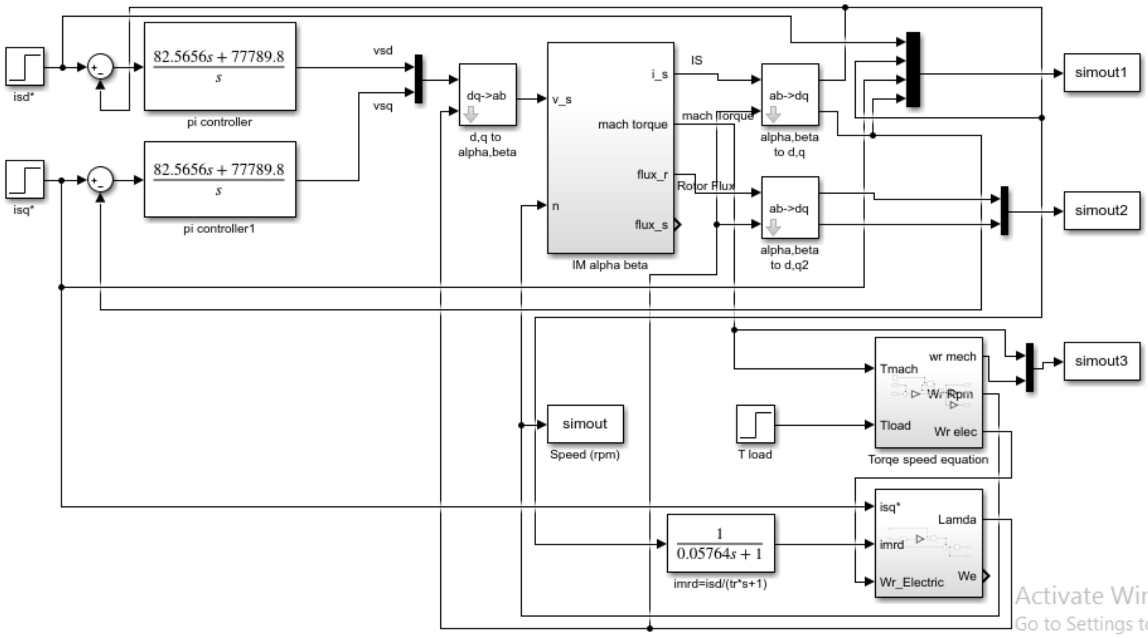


Fig. 9: current Loop Model. (Source: Researcher)

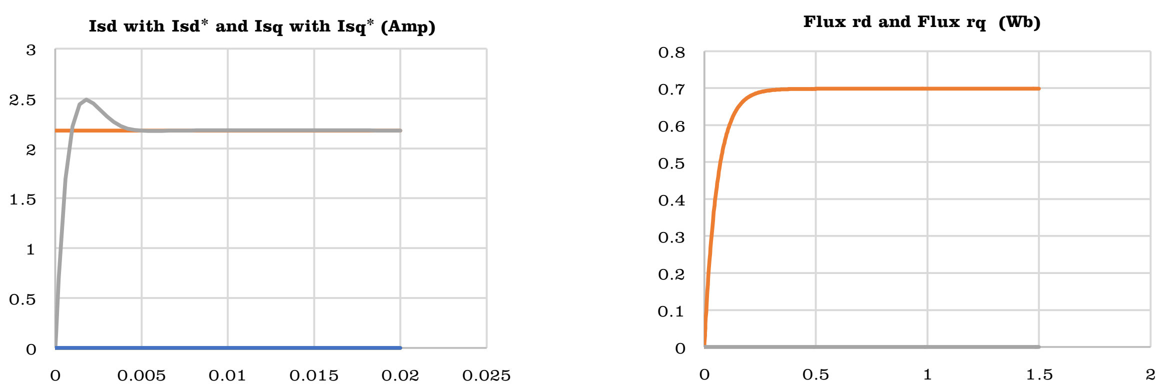


Fig. 10: Isdq and Fluxdq responses. (Source: Researcher)

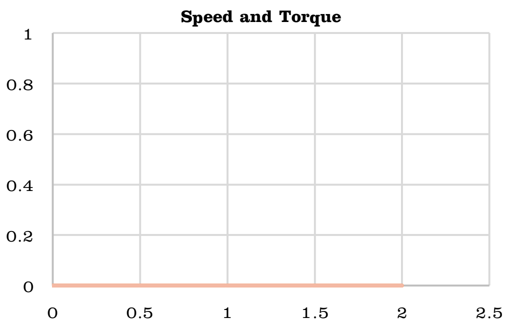


Fig. 11: speed and Torque response at no Load. (Source: Researcher)

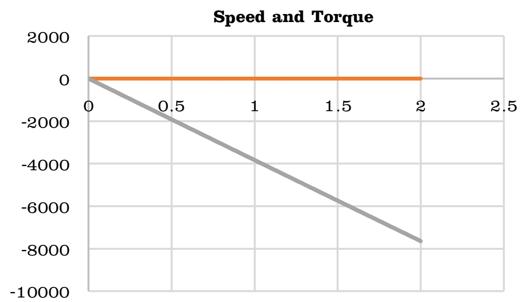


Fig. 12: speed and Torque Response at full load. (Source: Researcher)

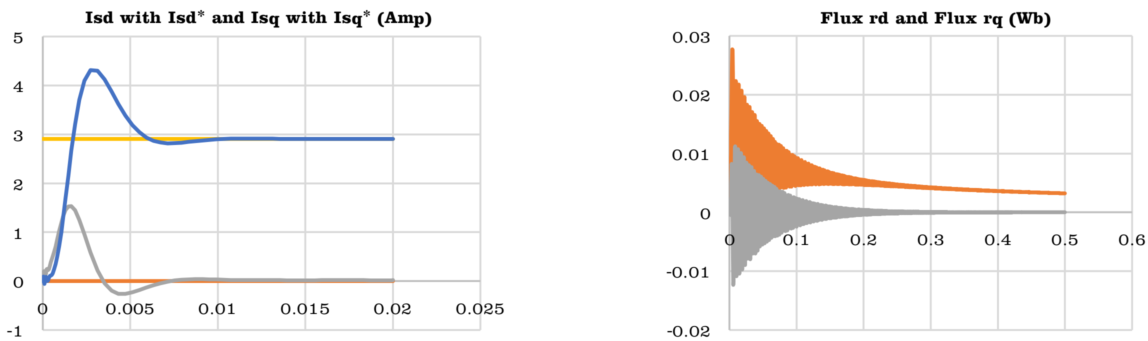


Fig. 13: Isdq and Ψrdq responses. (Source: Researcher)

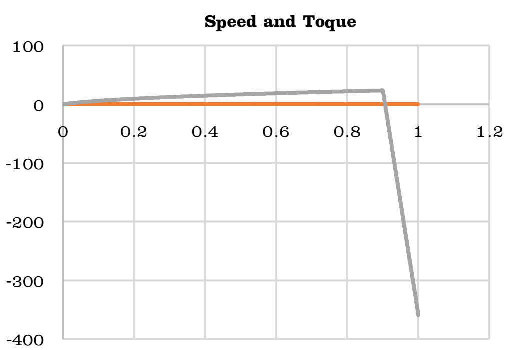


Fig. 14: Speed and Torque response. (Source: Researcher)

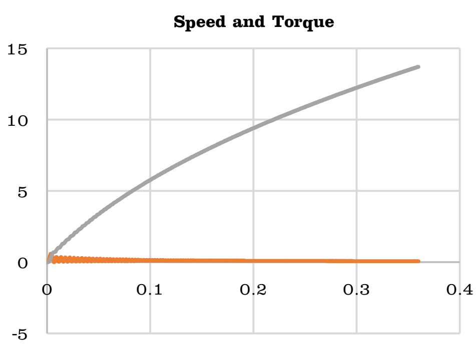


Fig. 15: Speed and Torque response (rated load applied at 0.9 second) (Source: Researcher)

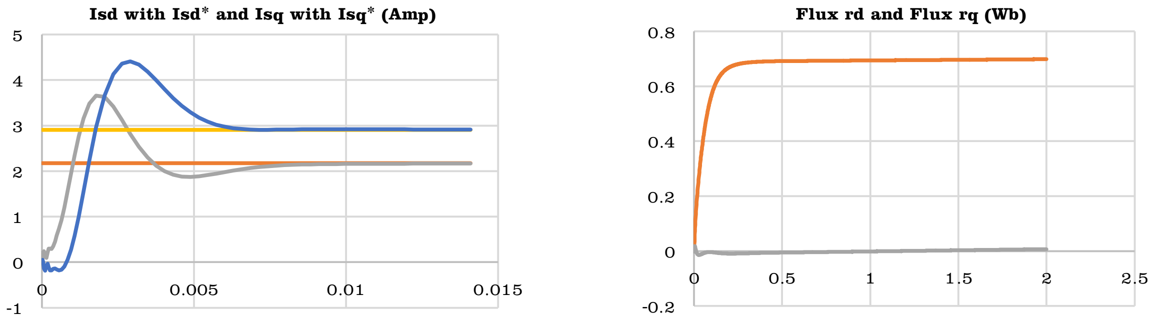


Fig. 16: Isdq and Ψrdq responses. (Source: Researcher)

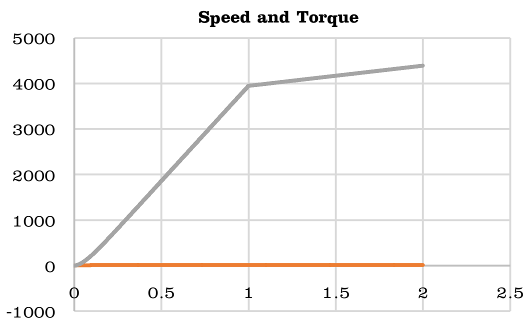


Fig. 17: Speed and Torque at no load and full load (load applied after 1sec). (Source: Researcher)

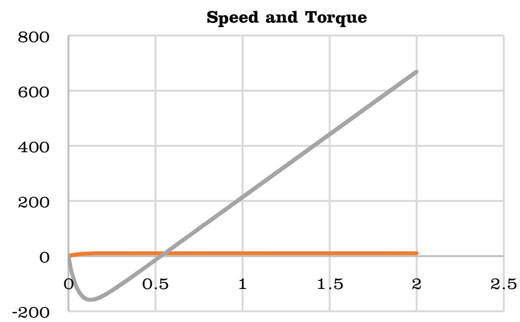


Fig. 18: Speed and Torque at full load (load applied at zero) (Source: Researcher)

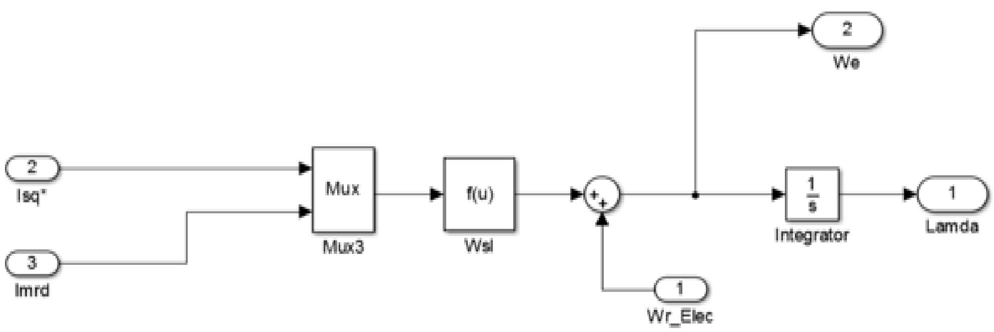


Fig. 19: Lamda subsystem shows (We) in it. (Source: Researcher)

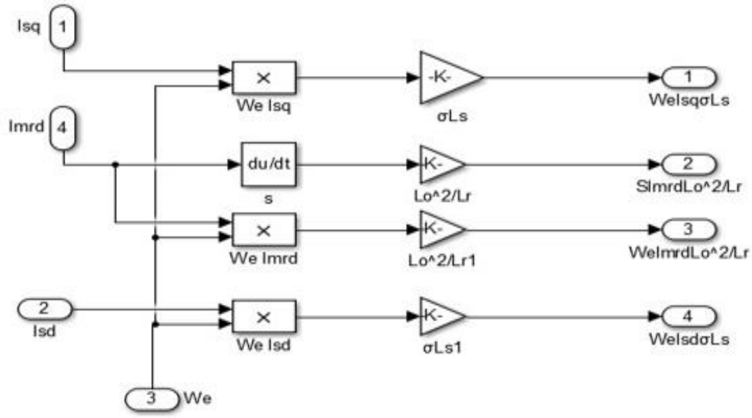


Fig. 20: Voltage Compensation term Subsystem. (Source: Researcher)

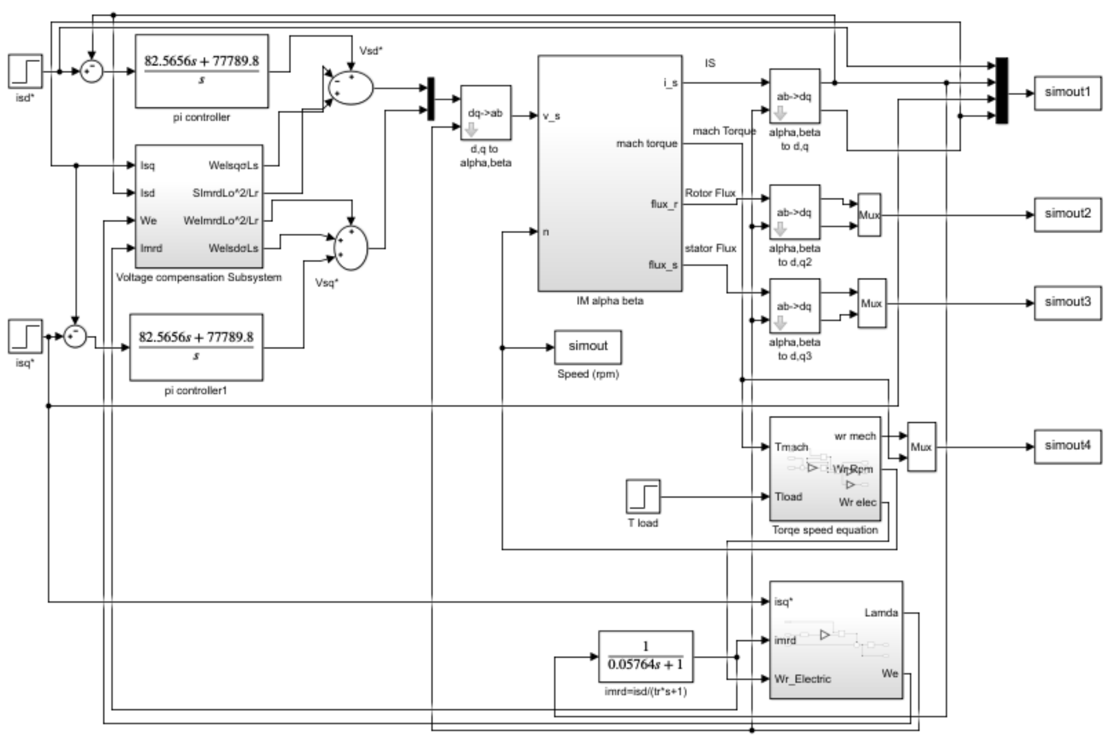
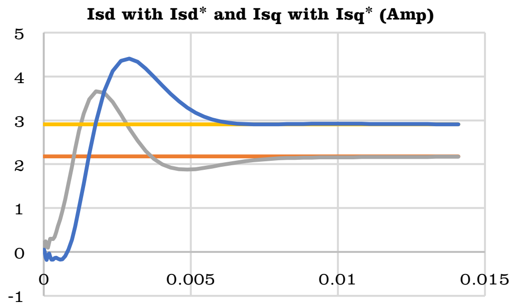
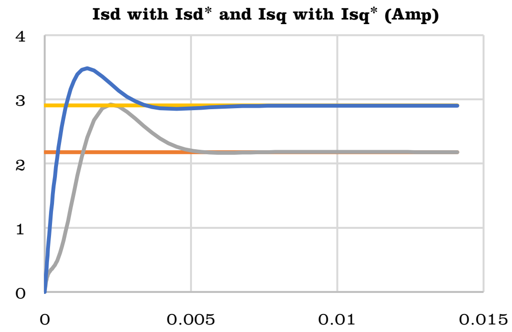


Fig. 21: Current Loop Model with Compensation term. (Source: Researcher)

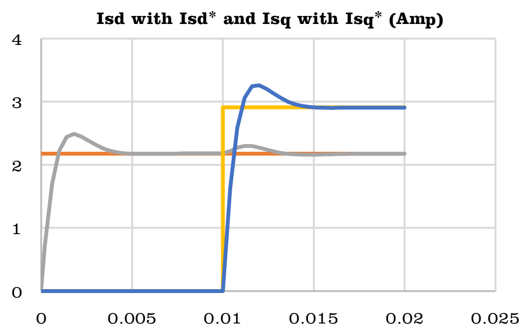


B- With Voltage Compensation term.

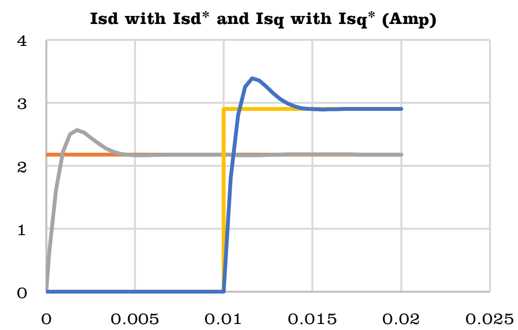


A- Without Voltage compensation term.

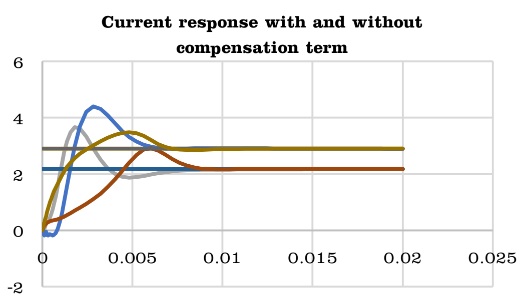
Fig. 22: Isdq responses with and without Voltage Compensation. (Source: Researcher)



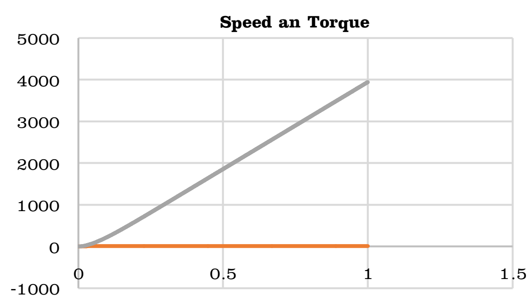
B- With Voltage Compensation term.



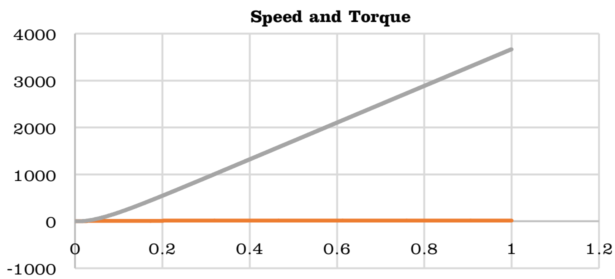
A- Without Voltage compensation term.



C- Current responses with and without Voltage Compensator.



D- Without Voltage compensation term.



E- With Voltage compensation term.

Fig. 23: Isdq and Speed Torque responses with and without Voltage Compensation. (Source: Researcher)

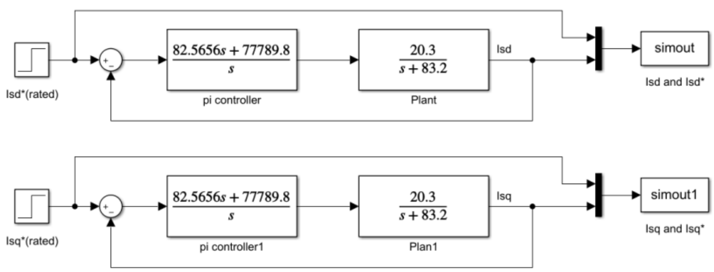


Fig. 24: dq current closed loop controller. (Source: Researcher)

Table 1: Squirrel-Cage Induction Motor Parameters. (Source: Researcher)

Motor parameter	Value
Rated Mechanical power	1.5kW (2HP)
Line-to-Line Voltage (V_{L-L})	380 V
Frequency (f)	50 Hz
Connection Type	star connection
Rated Speed (N)	1380 rpm
Line-to-Line Rated Current	3.63 Amp
Full-Load Power Factor	0.8 Lag
Line-to-Line Starting Current	15 Amp
Stator Resistor	4.1 Ωmeasured by ohmmeter
Moment of inertia (j)	0.0026kg.m^2
Rotor Leakage Inductance Lr	0.348365 H
Stator Leakage Inductance Ls	0.339445 H
Magnetizing Inductance Lm or Lo	0.32063 H
Rotor Resistance Rr	6.04 Ω
Friction Coefficient D	0.0084Nm/rad/second