České vysoké učení v Praze
Fakulta elektrotechnická

Bakalářská práce

Simulation model of a Frequency Converter

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Studijní program: Elektrotechnika a informatika, strukturovaný, bakalářský

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Student: Mikuláš Jandák

Obor: Kybernetika a měření

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Zásady pro vypracování:

1. Seznamte se s funkcí frekvenčního měniče PowerFlex 7000 na základě dostupné technické dokumentace
2. Navrhněte a implementujte zjednodušený simulační model vnějšího chování měniče PowerFlex 7000 jako funkční blok v systému Simulink
3. Navrhněte možné použití bloku v jednoduchých simulovaných regulačních obvodech řízení momentu a rychlosti při použití asynchronního motoru.

Seznam odborné literatury: Dodá vedoucí práce

Vedoucí bakalářské práce: Doc. Ing. Petr Horáček, CSc.

Datum zadání bakalářské práce: zimní semestr 2006/07

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L.S.

Prof. Ing. Michael Šebek, DrSc.
vedoucí katedry

v zast.

Prof. Ing. Zbyněk Škvor, CSc.
děkan

V Praze, dne 5. 3. 2007

Prohlášení

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V Kolíně dne 15. 8. 2007 .... Mikoláš Jandák

Abstract

This bachelor thesis is intended to implement a simplified simulink model of the frequency converter PowerFlex7000 according to the given specification and to test this model in simple regulations with induction (asynchronous) machines of various power. The model should be tested in both speed and torque regulations.

Acknowledgment

I would like to thank Doc. Ing. Petr Horáček, CSc for supervising my thesis. Also, I am very grateful to my whole family and especially my parents for their patience and support throughout not only the period of my studies at CTU but also my life. Last but not least, I thank my cocker spaniel Daf for his mental support.

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1. Introduction

1.1. Historical overview of electric motors

The history of electrical motors goes back as far as 1820, when Hans Christian Oersted discovered the magnetic effect of an electric current. One year later, Michael Faraday discovered the electromagnetic rotation and built the first primitive DC motor. Faraday went on to discover electromagnetic induction in 1831, but it was not until 1883 that Tesla invented the induction (asynchronous) motor.

Currently, the main types of electric motors are still the same, DC, induction (asynchronous) and synchronous, all based on Oersted, Faraday and Tesla's theories developed and discovered more than a hundred years ago.

1.2. Development of control techniques of induction motors

Since its invention the induction motor has become the most widespread electrical motor in use today. This is due to the induction motors advantages over the rest of motors. The main advantage is that induction motors do not require an electrical connection between stationary and rotating parts of the motor. Therefore, they do not need any mechanical commutator (brushes), leading to the fact that they are maintenance free motors. Induction motors also have low weight and inertia, high efficiency and a high overload capability. Therefore, they are cheaper and more robust, and they do not tend to any failure at high speeds. Furthermore, the motor can work in explosive environments because no sparks are produced.

Taking into account all the advantages outlined above, induction motors must be considered the perfect electrical to mechanical energy converter. However, mechanical energy is more than often required at variable speeds, where the speed control system is not a trivial matter. The only effective way of producing an infinitely variable induction motor speed drive is to supply the induction motor with three phase voltages of variable frequency and variable amplitude. A variable frequency is required because the rotor speed depends on the speed of the rotating magnetic field provided by the stator. A variable voltage is required because the motor impedance reduces at low frequencies and consequently the current has to be limited by means of reducing the supply voltages. Before the days of power electronics, a limited speed control of induction motor was achieved by switching the three-stator windings from delta connection to star connection, allowing the voltage at the motor windings to be reduced. Induction motors are also available with more than three stator windings to allow a change of the number of pole pairs. However, a motor with several windings is more expensive because more than three connections to the motor are needed and only certain discrete speeds are available. Another alternative method of speed control can be realized by means of a wound rotor induction motor, where the rotor winding ends are brought out to slip rings. However, this method obviously removes most of the advantages of induction motors and it also introduces additional losses. By connecting resistors or reactances in series with the stator windings of the induction motors, poor performance is achieved. At that time the above described methods were the only ones available to control the speed of induction motors, whereas infinitely variable speed drives with good performances for DC motors already existed. These drives not only permitted the operation in four quadrants but also covered a wide power range. Moreover, they had a good efficiency, and with a suitable control even a good dynamic response. However, its main drawback was the compulsory requirement of brushes.

With the enormous advances made in semiconductor technology during the last 20 years, the required conditions for developing a proper induction motor drive are present. These conditions can be divided mainly in two groups:

1) The decreasing cost and improved performance in power electronic switching devices.
2) The possibility of implementing complex algorithms in the new microprocessors.

However, one precondition had to be made, which was the development of suitable methods to control the speed of induction motors, because in contrast to its mechanical simplicity their complexity regarding their mathematical structure (multivariable and non-linear) is not a trivial matter.

1.3. Overview of control techniques of induction motors

Historically, several general controllers have been developed:

1) Scalar controllers:

Despite the fact that "Voltage-Frequency" (V/f) is the simplest controller, it is the most widespread, being in the majority of the industrial applications. It is known as a scalar control and acts by imposing a constant relation between voltage and frequency. The structure is very simple and it is normally used without speed feedback. However, this controller doesn't achieve a good accuracy in both speed and torque responses, mainly due to the fact that the stator flux and the torque are not directly controlled. Even though, as long as the parameters are identified, the accuracy in the speed can be 2% (except in a very low speed), and the dynamic response can be approximately around 50ms.

2) Vector Controllers:

In these types of controllers, there are control loops for controlling both the torque and the flux. The most widespread controllers of this type are the ones that use vector transform such as Park transform. Its accuracy can reach values such as 0.5% regarding the speed and 2% regarding the torque, even when at standstill. The main disadvantages are the huge computational capability required and the compulsory good identification of the motor parameters.

3) Field Acceleration method:

This method is based on maintaining the amplitude and the phase of the stator current constant, whilst avoiding electromagnetic transients. Therefore, the equations used can be simplified saving the vector transformation, which occurs in vector controllers. This technique has achieved some computational reduction, thus overcoming the main problem with vector controllers and allowing this method to become an important alternative to vector controllers. Nonetheless, identifying parameters is still an issue and as the previous control technique Field Acceleration method also hugely depends on knowing parameters of the stator and rotor windings.

4) Direct Torque Control:

DTC has emerged over the last decade to become one possible alternative to the well-known Vector Control of Induction Machines. Its main characteristic is the good performance, obtaining results as good as the classical vector control but with several advantages based on its simpler structure and control diagram. DTC is said to be one of the future ways of controlling the induction machine in four quadrants. In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state. This method still requires further research in order to improve the motor's performance, as well as achieve a better behavior regarding environmental compatibility (Electro Magnetic Interference and energy), that is desired nowadays for all industrial applications.

1.4. Structure of this bachelor thesis

The work presented in this thesis is organized in five main parts. These four parts are structured as follows:

Part 1 is entitled “Introduction." and it gives overview of main control techniques used both in the past and nowadays.

Part 2 is entitled “Functional description of the drive." and it sums up the most significant parts of the frequency converter PowerFlex7000.

Part 3 is entitled “Vector control.". It is devoted to introduce control approach implemented in PowerFlex7000 and shows similarities and differences not only between scalar and vector control but also between controlling AC and DC motors. It also gives short overview of mathematical model of the induction machine and transformations which support Vector control.

Part 3 is entitled “Implementation in Simulink". It describes the structure and main blocks of the model of Powerflex7000 in Simulink and it points out the differences between the frequency converter and its model.

Part 4 is Appendix which shows simulation results. This part also includes comments and with help of figures describes problems with which I had to deal and tries to come up with possible solutions. This part also tries to show advantages of Vector control.

Last part, which is Conclusion, summarizes things which have been accomplished and things which have not been solved.

1.5. Aims of this bachelor thesis

The main aim is to design Simulink model of PowerFlex7000 with emphasis on external behavior. Nonetheless, this work should also emphasize the properties of vector control and show advantages over scalar (V/Hz) control. This work is also supposed to be used in the following application regarding digging wheel excavator SchRs 1320/4x30 which includes two frequency converters Powerflex7000 and two motors Siemens ARNRY-6 (1000kW, 6000V, 118A, and 1000rpm).

1.6. Symbols

In this thesis I will use following notation:

$\overline{x}$	complex number
L_s	stator inductance
L_{sl}	stator leakage inductance
L_r	rotor inductance
L_{rl}	rotor leakage inductance
L_m	magnetizing (mutual) inductance
ψ_s	stator flux
ψ_r	rotor flux
ψ_m	magnetizing flux
i_s	stator current
i_r	rotor current
i_m	magnetizing current
ω_m	mechanical angular velocity
i_a, i_b, i_c	stator current – phase a,b,c
u_a, u_b, u_c	stator voltage – phase a,b,c
$\psi_{sa}, \psi_{sb}, \psi_{sc}$	stator flux – phase a,b,c
$\psi_{ra}, \psi_{rb}, \psi_{rc}$	rotor flux – phase a,b,c
s	slip
T_e	electromagnetic torque
T_l	load torque
d,*q*	indexes referring to *d*,*q* coordinate system

2. Functional description of the drive

2.1. General description

The PowerFlex7000, which is shown in Figure 1, is an adjustable speed ac drive in which motor speed control is achieved through control of the motor torque. The motor speed is calculated or measured and the torque is adjusted as required to make the speed equal to the speed command. The parameters of the motor and the load determine the stator frequency and the drive synchronizes itself to the motor. The methods of control implemented in PowerFlex7000 are known as sensorless direct rotor flux oriented vector control and full vector control. The term rotor flux vector control indicates that the position of the stator current vector is controlled relatively to the motor flux vector. Direct vector control means that the motor flux is measured, in contrast to the indirect vector control in which the motor flux is predicted. This method of control is used without tachometer feedback for applications requiring continuous operation above 6 Hertz and less than 100% breakaway torque. Full vector control can also be achieved with tachometer feedback which enables motor to operate continually down to 0.2 Hertz with up to 150% breakaway torque. In both control methods, the stator current (I_s) is split into flux producing component (I_{sd}) and an orthogonal torque producing component (I_{sq}) which are controlled independently. The aim of vector control is to allow a complex ac motor to be controlled as if it was a simple dc motor with independent, decoupled field and armature currents. This allows the motor torque to be changed quickly without affecting the flux. Vector control offers superior performance over volts/hertz type drives. The speed bandwidth range is 1-15 radians per second, while the torque bandwidth range is 20-100 radians per second. The PowerFlex7000 drive can be used with either induction (asynchronous) or synchronous motors. PowerFlex7000 consists of the following parts:

1) Speed control block
2) Flux control block
3) Current control block
4) Line converter feedback block
5) Machine converter feedback block
6) Motor model
7) Line converter

8) Machine converter

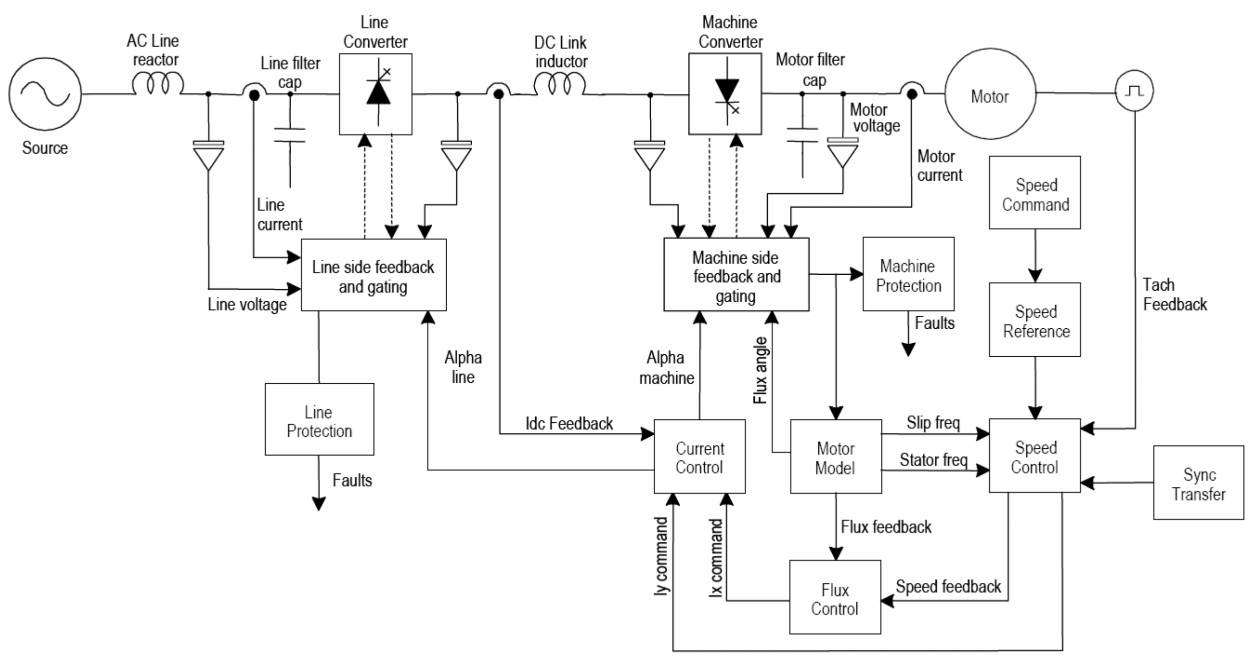

Figure 1 – High-level scheme of the PowerFlex7000 control system

2.2. Speed control block

The function of the speed control block, which is shown in Figure 2, is to determine the torque producing component (I_{sq}) of the stator current (I_s). The inputs to the block are the *Speed Reference* from the speed ramp and the *Stator Frequency* and *Slip Frequency* from the motor model. If the drive is installed with an optional tachometer, then the motor speed is determined by counting the tachometer pulses. In Sensorless operation, the *Slip Frequency* is subtracted from the *Stator Frequency* and filtered to determine the *Speed Feedback*. In *Pulse Tachometer* mode, the speed is determined directly by using *Tachometer Feedback*. The *Speed Feedback* is subtracted from the *Speed Reference* to determine the *Speed Error* which is processed by the speed PI regulator. The gains of the regulator are based on the *Total Inertia* of the system and the desired *Speed regulation Bandwidth*. The output of the speed regulator is the *Torque Reference* whose rate of change is limited by *Torque Rate Limit.* The calculated *Torque Reference* is divided by the *Flux Reference* to determine the torque component of the stator current I_{sq} *Command*. To calculate the torque producing current supplied by the inverter I_y *Command*, the current supplied by the motor filter capacitor in torque production (orthogonal to motor flux) is calculated and subtracted from I_{sq} *Command*. In *Sensorless* mode, the drive uses *Torque Command 0* and *Torque Command 1* for an open loop start-up. At frequencies greater than 3Hz, the drive closes the speed loop and disables the open loop start mode. In *Pulse Tachometer* mode, the drive is always in closed loop. The maximum torque a drive can deliver in motoring mode is determined by *Torque Limit Motoring*. In regenerative mode the torque is limited to *Torque Limit Braking*. Depending on the application, the drive can be configured in different torque control modes by setting the parameter *Torque Control Mode*. Table 1 shows different torque modes of the operation.

Torque Control Mode	Function
0	Zero toque
1	Speed regulator
2	External torque command
3	Speed torque positive
4	Speed torque negative
5	Speed sum

Table 1 – Torque modes of the operation

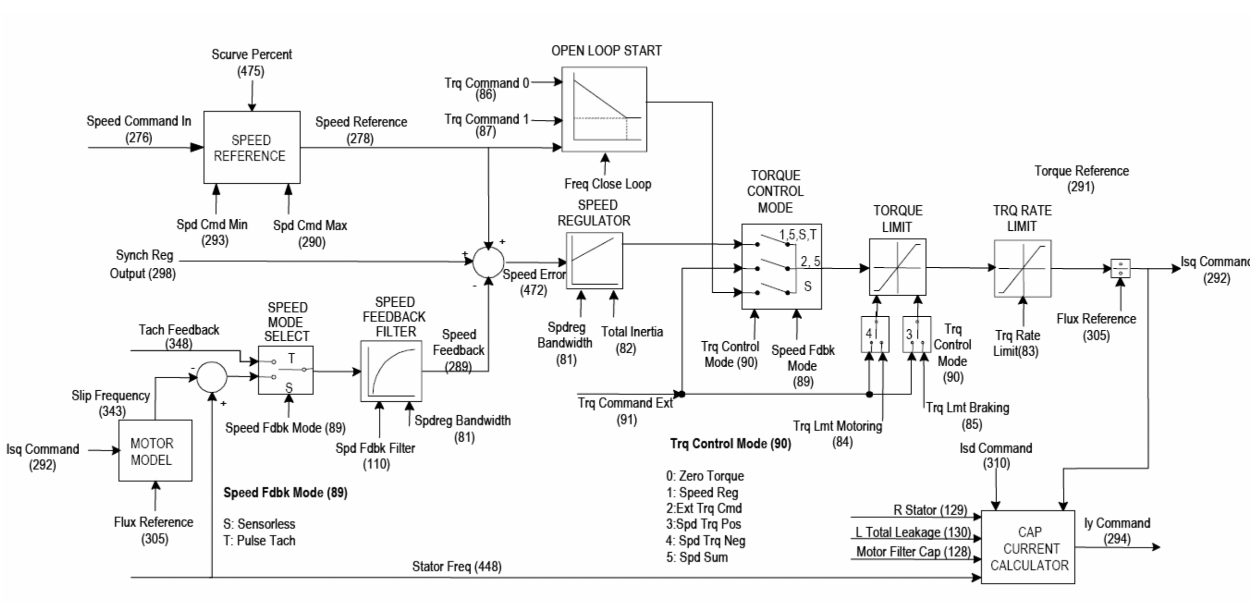

Figure 2 – Speed control block

2.3. Flux control block

The function of the flux control block, which is shown in Figure 3, is to determine the magnetizing component (I_{sd}) of the stator current (I_s) needed to maintain the desired flux profile in the motor. The inputs are *Flux Feedback* and *Stator Frequency* from the motor model, *Speed Feedback* and *Torque Reference* from the speed control block and the measured voltage at the input of the bridge *Vline Bridge*. The *Flux Feedback* is subtracted from the *Flux Reference* to determine the *Flux Error*, which is the input to the flux PI regulator. The gains are determined from desired *Flux Regulation Bandwidth* and motor parameters *T Rotor* and *L Magnetizing.* The output of the flux regulator is I_{sd} *Command 1*. An open loop estimate of the magnetizing current, I_{sd} *Command 0* is determined by dividing the *Flux Reference* by parameter *L Magnetizing*. I_{sd} *Command 0* and I_{sd} *Command 1* are added to produce I_{sd} *Command* which is the magnetizing component of the stator current command. To calculate the magnetizing current supplied by the inverter I_x *Command* (312), the current supplied by the motor filter capacitor in magnetizing is calculated and subtracted from I_{sd} *Command*. I_y *Command* from Speed Control block and I_x *Command* are then passed to the Current Control block to determine the dc link current reference (I_{dc} *Reference*) and the firing angles of the two converters (*Alpha Line* and *Alpha Machine*). The flux profile in the drive is adjusted by the parameters *Flux Command No Load* and *Flux Command Base Speed.* Using these parameters*, Flux Reference* is adjusted linearly with the desired *Torque Reference*. At light loads motor flux is decreased allowing reduction in losses while full flux is produced at rated load. The maximum flux reference is limited to *Flux Command Limit*. This limit depends on the input voltage *Vline Bridge* and the motor speed (*Speed Feedback*). If the drive operates at reduced line voltage, then *Flux Reference* is reduced. Also if the motor is running above the *Base Speed*, the flux profile is made inversely proportional to the speed of the motor resulting in the field weakening and the constant power mode of operation of the drive. This is accompanied by a decrease in the motor torque capability.

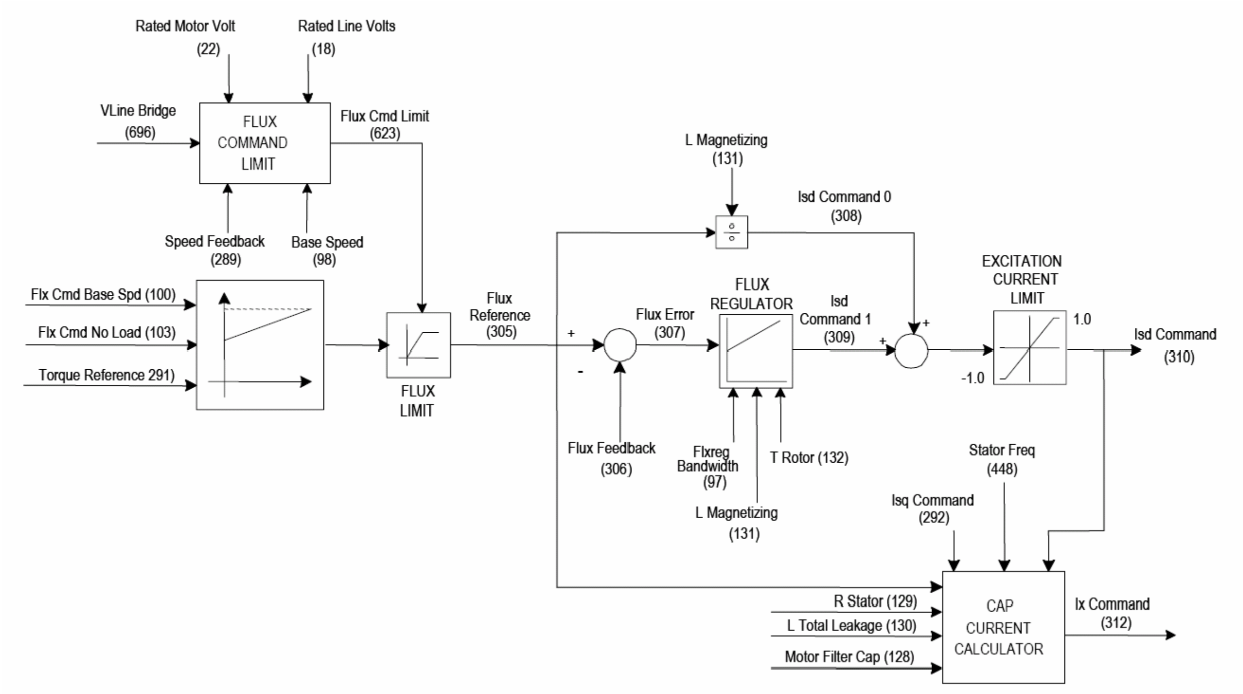

Figure 3 – Flux control block

2.4. Current control block

The function of the current control block, which is shown in Figure 4, is to determine the firing angles for the converters *Alpha Line* and *Alpha Machine*. The inputs are the torque (I_y *Command*) and flux producing (I_x *Command*) components of the dc link current command from the speed control and flux control blocks respectively, and the measured dc link current I_{dc} *Feedback*. The square root of the sum of the squares of I_x *Command* and I_y *Command* determines the dc link current reference I_{dc} *Reference*. This is subtracted from the measured dc current feedback to determine I_{dc} *Error*. This is processed by the current regulator to produce V_{dc} *Error*. To effectively control the dc link current an estimate of the motor side dc link voltage is done to calculate V_{dc} *Feed Forward* which is added to V_{dc} *Error* to produce the reference voltage for the line side converter V_{dc} *Reference*. The line converter firing angle is the inverse cosine of V_{dc} *Reference*. The machine converter firing angle is determined by taking the inverse tangent of the ratio of I_y *Command* to the I_x *Command*. The quadrant of operation is adjusted based on the signs of the current commands.

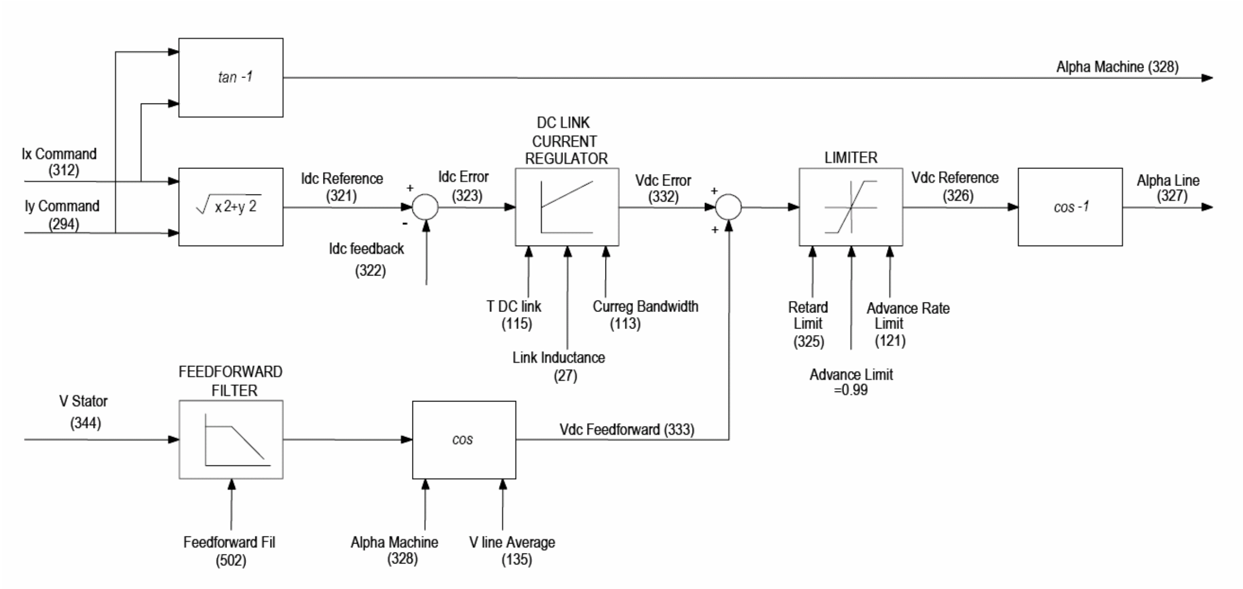

Figure 4 – Current control block

2.5. Line converter feedback block

The function of the line converter feedback block is to process (scale and filter) the line side voltage and current feedback signals before being sampled by the drive control software. The line converter feedback block provides a total of six voltage feedback signals representing the three ac (V_{a1}, V_{b1}, and V_{c1}), two dc (V_{dc+}, V_{dc-}) and one line side filter capacitor voltages referenced to ground. The three line-to-ground voltages are subtracted from each other to produce the three line to line voltages (V_{ab}, V_{bc} and V_{ca}). These line voltages are filtered and sampled by software for synchronization and protection. The two dc voltages are subtracted to determine the line side dc link voltage (V_{dc}), which is used for hardware dc link over-voltage protection. In PWM drives, the neutral point of the line filter capacitor is measured and used for line side neutral over-voltage protection. Current transformers in two of the ac input lines provide the input line current feedback (I_a, I_c,). These currents are then filtered and processed by a variable gain stage. Inverting and adding the two current feedback signals reproduce the current in the remaining phase (I_b). Moreover, the average value of the dc link current feedback is measured using a *V-f* converter and used by the dc link current controller to calculate the firing angle for the rectifier. Figure 5 shows the rectifier, DC link and the inverter.

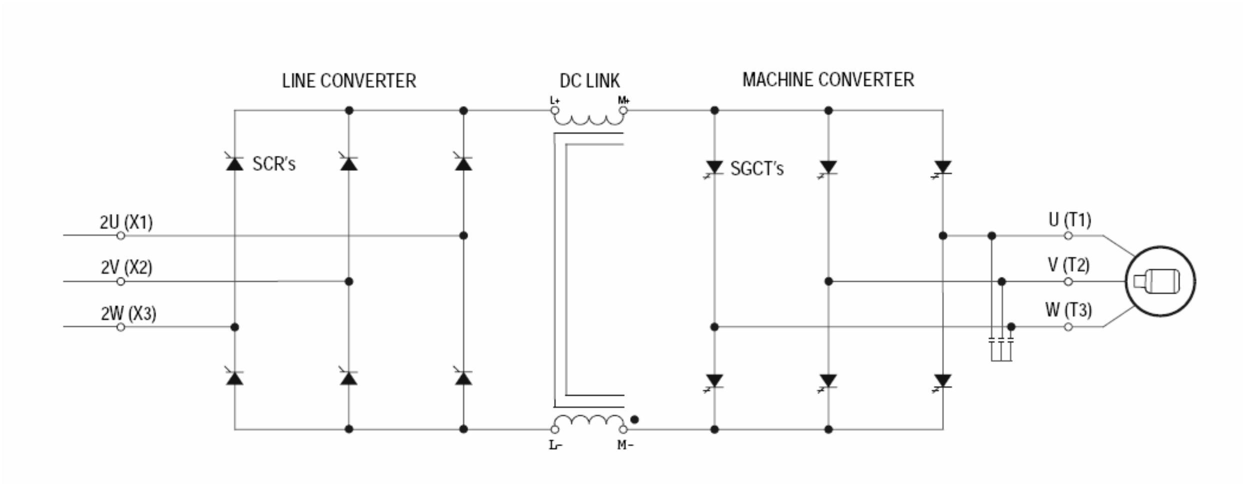

Figure 5 – Rectifier, DC link and inverter

2.6. Machine converter feedback block

The function of the machine converter feedback block is to process (scale and filter) the raw voltage and current feedback signals to the form required by the drive control software. The machine converter provides a total of six voltage feedback signals representing the three ac (V_{a1}, V_{b1}, V_{c1}), two dc (V_{dc+}, V_{dc-}) and one machine side filter capacitor neutral voltage referenced to ground. The motor line to ground voltages are subtracted from each other and filtered to produce the three motor line to line voltages (V_{ab1}, V_{bc1}, V_{ca1}). The two dc voltages are subtracted to determine the machine side dc link voltage (V_{dc}), which is used for hardware dc link over-voltage protection. The motor line-ground voltages are summed to determine the motor neutral to ground voltage (V_{ng}) and are used for motor neutral over-voltage protection. Machine Converter provides stator current feedback in two of the motor phases ($I_{a3\text{-}out}$, $I_{c3\text{-}out}$). These currents are then filtered and processed by a variable gain stage (I_{a3}, I_{c3}) before being sampled for protection. Inverting and adding the two current feedback signals reproduces the current in the remaining phase (I_{b3}). The motor line voltages and currents are further used to calculate the motor flux (F_{ab}, F_{bc}, F_{ca}) using a hardware analog model. The measured flux (V_d and V_q) is then used in the motor model block for synchronization and drive control.

2.7. Motor model block

The function of the motor model block, which is shown in Figure 6, is to determine the rotor flux position (*Flux Angle*), flux feedback (*Flux Feedback*), applied stator frequency (*Stator Frequency*), slip frequency (*Slip Frequency*) and motor operating variables like stator current (I_{Stator}), stator voltage (V_{Stator}), torque (*Torque*), power (*Motor Power*) and power factor (*Motor Power Factor*). The PowerFlex7000 uses Rotor Flux oriented control to achieve independent control of motor flux and torque. This is achieved by synchronizing the machine converter gating to *Flux Angle*. To determine the flux feedback, stator frequency and the synchronizing reference frame the drive uses either the Voltage or the Current model. For speeds greater than 3Hz, the drive uses the voltage model (hardware analogue flux model) to calculate the *Flux from Voltage, Flux Angle from Voltage* and *Stator Frequency from Voltage.* Below 3Hz, the drive uses the current model to calculate *Flux from Current, Flux Angle from Current* and *Stator Frequency from Current.* The current model is based on indirect vector control and uses the d-q components of stator current along with motor parameters *T Rotor* and *L Magnetizing*. Based on the operating speed of the drive and the speed feedback mode (*Sensorless* or *Pulse Tachometer*), a flux select algorithm determines the model to be used. Motor model also calculates the *Slip Frequency* which is used in the calculation of the motor speed (Speed Control) in *Sensorless* mode and for determining the rotor flux position in *Pulse Tachometer* mode. The synchronously rotating frame (*Flux Angle*) is used in transforming the measured motor currents and voltages into *d-q* components. The direct axis components (I_{sd} and V_{sd}) are in phase with the rotor flux, while the quadrature axis components (I_{sq} and V_{sq}) are displaced 90 degrees from the rotor flux. The stator current (I_{Stator}) and voltage magnitudes (V_{Stator}) are calculated by taking the square root of the sum of the squares of the respective d-q components. The motor *Torque* is calculated by multiplying the *Flux Feedback* and I_{sq} with motor torque constant. *Torque* multiplied by the motor speed gives the *Motor Power*. *Motor Power Factor* is determined as the ratio of motor active power and the apparent power.

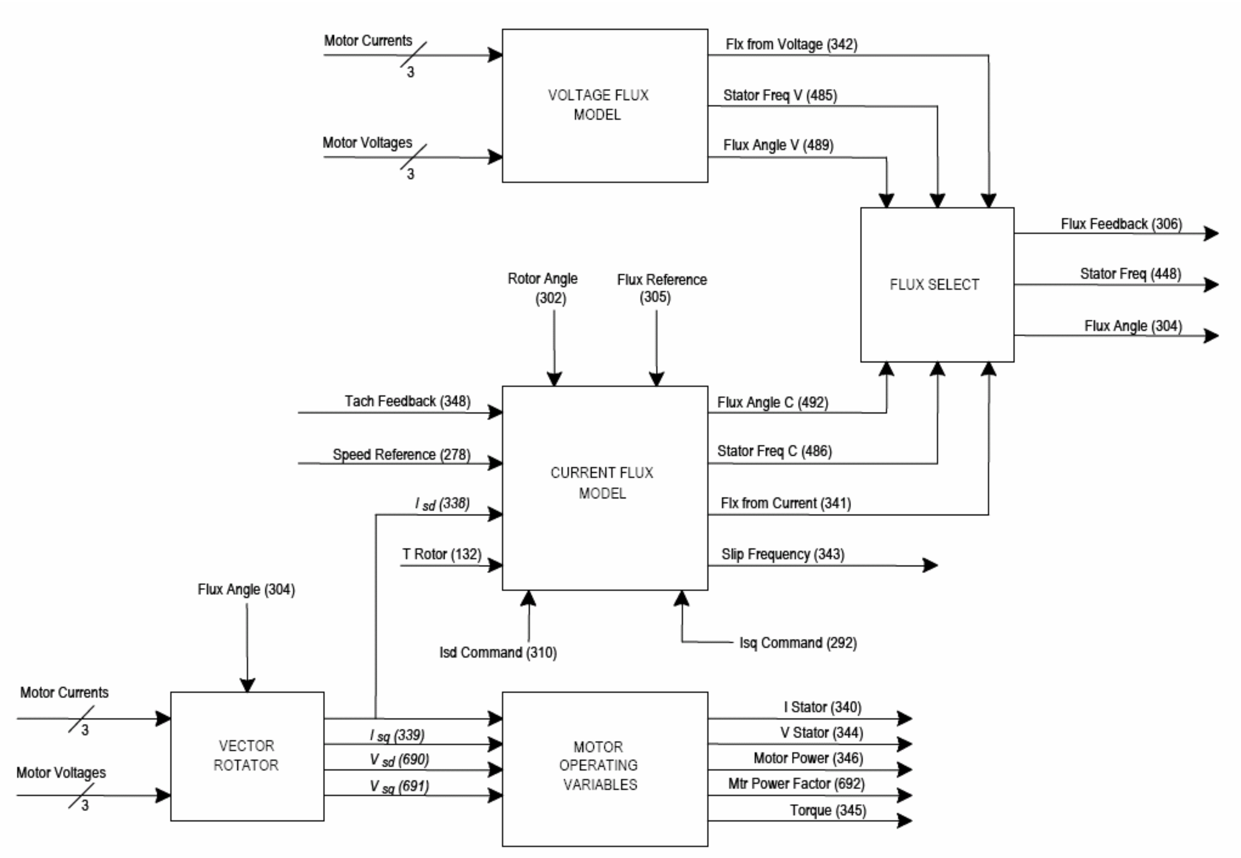

Figure 6 – Motor model block

3. Vector control

In order to fully understand the concept of vector control it is important to be familiar with various transformations and with mathematical model of the induction machine. Afterwards, the idea of vector control is very straightforward.

3.1. Transformations used in vector control

In order to implement vector control it is necessary to transform currents and voltages from three-phase stationary coordinate system of stator into rotating *dq* coordinate system of rotor flux. The main reason is that such a transformation simplifies calculation, and therefore, makes Vector control feasible in real time. This transformation could be split into two steps:

1) Transformation from three-phase stationary system into two-phase (also called $\alpha\beta$) stationary coordinate system. This transformation is also known as Clark transformation

2) Transformation from two-phase coordinate system into rotating dq coordinate system. This transformation is called Park transformation.

3.1.1. Clark transformation

In general, the vector in the two-phase coordinate system (Figure 7) could be described as follows:

$$\bar{x} = k(x_a + \bar{a}x_b + \bar{a}^2 x_c)$$

$$x_0 = k_0(x_a + x_b + x_c)$$

$$\bar{a} = e^{j\frac{2}{3}\pi} = -0.5 + \frac{\sqrt{3}}{2} j$$

$$\bar{a}^2 = e^{-j\frac{2}{3}\pi} = -0.5 - \frac{\sqrt{3}}{2} j$$

$$\mathrm{Re}\{\bar{x}\} = k\left[x_a - 0.5(x_b + x_c)\right]$$

$$\mathrm{Im}\{\bar{x}\} = k\frac{\sqrt{3}}{2}(x_b - x_c)$$

Since we want the transformation to fulfill following condition $x_a = \mathrm{Re}\{\bar{x}\} + x_0$, we can estimate k and k_0 as follows:

$$\mathrm{Re}\{\bar{x}\} = \mathrm{Re}\{k(x_a + \bar{a}x_b + \bar{a}^2 x_c)\} = \mathrm{Re}\left\{k(x_a + (-0.5 + \frac{\sqrt{3}}{2} j)x_b + (-0.5 - \frac{\sqrt{3}}{2} j)x_c)\right\} =$$

$$= k(x_a - 0.5(x_b + x_c)) = kx_a - 0.5k\left(\frac{x_0}{k_0} - x_a\right) = 1.5kx_a - 0.5k\frac{x_0}{k_0}$$

$$\mathrm{Re}\{\bar{x}\} = x_a - x_0 \text{, therefore } 1.5k = 1 \Rightarrow k = \frac{2}{3} \text{ and } 0.5\frac{k}{k_0} = 1 \Rightarrow k_0 = \frac{1}{3}$$

Finally, the transformation is defined as follows:

$$\mathrm{Re}\{\bar{x}\} = \frac{2}{3}x_a - \frac{1}{3}(x_b + x_c)$$
$$\mathrm{Im}\{\bar{x}\} = \frac{1}{\sqrt{3}}(x_b - x_c) \qquad (1a\text{-}1c)$$
$$x_0 = \frac{1}{3}(x_a + x_b + x_c)$$

Or alternatively by means of matrix notation:

$$(\alpha \quad \beta \quad o) = (x_a \quad x_b \quad x_c)\frac{2}{3}\begin{pmatrix} 1 & 0 & \frac{1}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} \end{pmatrix} \qquad (2)$$

Inverse transformation is defined as follows:

$$x_a = \mathrm{Re}\{\bar{x}\} + x_0$$
$$x_b = -\frac{1}{2}\mathrm{Re}\{\bar{x}\} + \frac{\sqrt{3}}{2}\mathrm{Im}\{\bar{x}\} + x_0 \qquad (3a\text{-}3d)$$
$$x_c = -\frac{1}{2}\mathrm{Re}\{\bar{x}\} - \frac{\sqrt{3}}{2}\mathrm{Im}\{\bar{x}\} + x_0$$

Or alternatively by means of matrix notation:

$$(x_a \quad x_b \quad x_c) = (\alpha \quad \beta \quad o)\begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ 1 & 1 & 1 \end{pmatrix} \qquad (4)$$

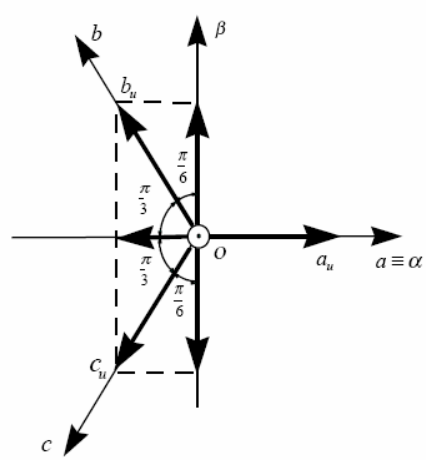

Figure 7 – Vector in two-phase coordinate system

3.2.1 Park transformation

The idea of the vector control is that we control the relative position between the rotor flux and the stator current. In order to achieve this, we need one coordinate system for both flux and current. It has been proven that equations become much simpler if we use dq rotation system of rotor flux. Equations which described Park transformation could be easily obtained from Figure 8:

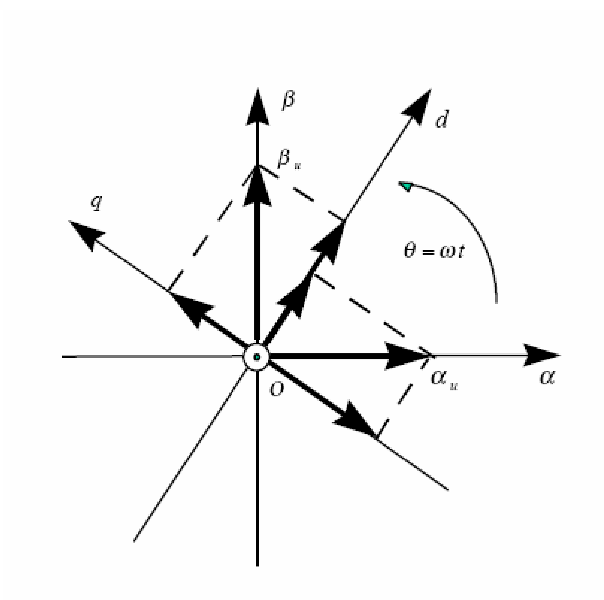

Figure 8 – Park transformation

$$
\begin{aligned}
d &= \alpha\cos(\phi) + \beta\sin(\phi) \\
q &= \beta\cos(\phi) - \alpha\sin(\phi) \\
o_{dq} &= o_{\alpha\beta}
\end{aligned}
\qquad (5a\text{-}5c)
$$

Or alternatively by means of matrix notation:

$$
\begin{pmatrix} d & q & o_{dq} \end{pmatrix} = \begin{pmatrix} \alpha & \beta & o_{\alpha\beta} \end{pmatrix} \begin{pmatrix} \cos(\phi) & -\sin(\phi) & 0 \\ \sin(\phi) & \cos(\phi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (6)
$$

Where ϕ is electrical angle (theta) which is angle between dq coordinate system and two-phase ($\alpha\beta$) stationary coordinate system.

It also should be noted that since the origin of all coordinate systems is the same and that we assume a balanced three-phase system ($x_o = 0$) then: $o_{dq} = o_{\alpha\beta} = x_0 = 0$

Inverse transformation is defined as follows:

$$\alpha = d\cos(\phi) - q\sin(\phi)$$
$$\beta = d\sin(\phi) + q\cos(\phi) \quad (7a\text{-}7c)$$
$$o_{\alpha\beta} = o_{dq}$$

Or alternatively by means of matrix notation:

$$\begin{pmatrix} \alpha & \beta & o_{\alpha\beta} \end{pmatrix} = \begin{pmatrix} d & q & o_{dq} \end{pmatrix} \begin{pmatrix} \cos(\phi) & \sin(\phi) & 0 \\ -\sin(\phi) & \cos(\phi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (8)$$

3.2.2 Mathematical model of induction machines

A dynamic model of induction machine subjected to control must be known in order to understand and design vector controlled drive. Due to the fact that every good control has to face any possible change of the plant, it could be said that the dynamic model of the machine could be just a good approximation of the real plant. Nevertheless, the model should incorporate all the important dynamic effects occurring during both steady-state and transient operations. The equivalent electrical circuit diagram of one phase of induction (asynchronous) machine is shown in Figure 9.

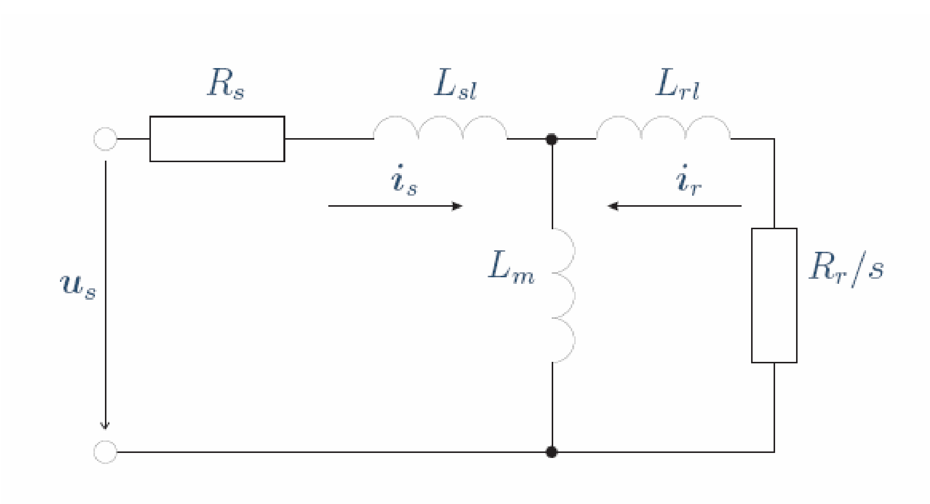

Figure 9 – Equivalent circuit diagram of one phase of an induction machine

First of all, equations which hold for induction machines are:

$$L_s = L_{sl} + L_m \tag{9}$$

$$\psi_s = L_s i_s + L_m i_r = L_{sl} i_s + L_m (i_s + i_r) = L_{sl} i_s + L_m i_m = L_{sl} i_s + \psi_m \tag{10}$$

$$L_r = L_{rl} + L_m \tag{11}$$

$$\psi_r = L_r i_r + L_m i_s = L_{rl} i_r + L_m (i_s + i_r) = L_{rl} i_r + L_m i_m = L_{rl} i_r + \psi_m \tag{12}$$

$$i_s + i_r = i_m = \frac{\psi_m}{L_m} \tag{13}$$

Substituting ψ_m from (9) into (10) we get:

$$\psi_s = \psi_r + L_{si} i_s - L_{rl} i_r \tag{14}$$

Substituting ψ_m from (12) into (14) we get:

$$i_r = -i_s + \frac{\psi_r}{L_m} - \frac{L_{rl}}{L_m} i_r \tag{15}$$

Substituting L_{rl} from (11) into (15) we get:

$$i_r = -\frac{L_m}{L_r} i_s + \frac{1}{L_r} \psi_r \tag{16}$$

Substituting i_r from (16) into (14) we get:

$$\psi_s = \psi_r + L_{si} i_s - L_{rl} i_r = \psi_r + L_{si} i_s + \frac{L_{rl} + L_m}{L_r} i_s - \frac{L_{rl}}{L_r} \psi_r = \frac{L_m}{L_r} \psi_r + \left(L_{sl} + \frac{L_m}{L_r} L_{rl} \right) i_s \tag{17}$$

Now let us first assume three coordinate systems:

I) Stator coordinate system

Axis: x,y

Velocity: $\omega_I = 0$

II) Rotor coordinate system

Axis: x,y

Velocity: $\omega_{II} = p\omega_m$

Where p is the number of pair of poles and ω_m is the angular velocity of the rotor

III) Rotor flux coordinate system

Axis: *dq*

Velocity: $\omega_{III} = \omega_\psi$

Where ω_ψ is the angular velocity of the rotor flux.

The equations, which describe the ac drive (Figure 8), are:

a) Stator equations:

$$u_{sa} = R_s i_{sa} + \frac{d\psi_{sa}}{dt}$$
$$u_{ba} = R_s i_{sb} + \frac{d\psi_{sb}}{dt} \qquad (18a\text{-}18c)$$
$$u_{sc} = R_s i_{sc} + \frac{d\psi_{sc}}{dt}$$

Where i_{sa}, i_{sb} and i_{sc} are stator currents, u_{sa}, u_{sb} and u_{sc} are stator voltages and ψ_{sa}, ψ_{sb} and ψ_{sc} are stator fluxes. And hence, the space vector in the stator coordinate system is:

$$\overline{u}_{sI} = k\left(u_{sa} + \overline{a}u_{sb} + \overline{a}^2 u_{sc}\right) = R_s \overline{i}_{sI} + \frac{d\overline{\psi}_{sI}}{dt}$$
$$u_{s0} = k_0\left(u_{sa} + u_{sb} + u_{sc}\right) = R_s i_{s0} + \frac{d\psi_{s0}}{dt} \qquad (19a\text{-}19b)$$

Since $\psi_{s0} = k_0\left(\psi_{sa} + \psi_{sb} + \psi_{sc}\right) = k_0 L_{s\sigma}\left(i_{sa} + i_{sb} + i_{sc}\right) = L_{s\sigma} i_{s0}$, if $i_{s0} = 0$ then $u_{s0} = 0$

b) Rotor equations:

$$u_{ra} = R_s i_{ra} + \frac{d\psi_{ra}}{dt}$$
$$u_{rb} = R_s i_{rb} + \frac{d\psi_{rb}}{dt} \qquad (20a\text{-}20c)$$
$$u_{rc} = R_s i_{rc} + \frac{d\psi_{rc}}{dt}$$

Where i_{ra}, i_{rb} and i_{rc} are rotor currents, u_{ra}, u_{rb} and u_{rc} are rotor voltages and ψ_{ra}, ψ_{rb} and ψ_{rc} are rotor fluxes. And hence, the space vector in the rotor coordinate system is:

$$\overline{u}_{rII} = k\left(u_{ra} + \overline{a}u_{rb} + \overline{a}^2 u_{rc}\right) = R_r \overline{i}_{rII} + \frac{d\overline{\psi}_{rII}}{dt}$$
$$u_{r0} = k_0\left(u_{ra} + u_{rb} + u_{rc}\right) = R_r i_{r0} + \frac{d\psi_{r0}}{dt} \qquad (21a\text{-}21b)$$

Since $\psi_{s0} = k_0\left(\psi_{ra} + \psi_{rb} + \psi_{rc}\right) = k_0 L_{r\sigma}\left(i_{ra} + i_{rb} + i_{rc}\right) = L_{r\sigma} i_{r0}$, if $i_{r0} = 0$ then $u_{r0} = 0$

In order to transform above equations into rotor flux coordinate system it is important to realize that:

a) Transformation from coordinate system I to coordinate system II:

$$\bar{x}_I = \bar{x}_{II} e^{j\varepsilon}$$

Where $\bar{x}_I$ and $\bar{x}_{II}$ are space vectors in the coordinate system I and II, respectively and τ is angle between coordinate system I and coordinate system II.

b) Transformation of derivatives from coordinate system I to coordinate system II:

Equation in the coordinate system I:

$$\bar{x}_I = \frac{dy_I}{dt}$$

Equation in the coordinate system II:

$$\bar{x}_{II} e^{j\varepsilon} = \frac{d}{dt}\left(\bar{y}_{II} e^{j\varepsilon}\right) = \frac{d\bar{y}_{II}}{dt} e^{j\varepsilon} + \bar{y}_{II} e^{j\varepsilon} j \frac{d\varepsilon}{dt} \Rightarrow \bar{x}_{II} = \frac{d\bar{y}_{II}}{dt} + \bar{y}_{II} j\omega$$

Where ω is a relative angular velocity between the coordinate system I and II.

So now we can transform equations (19a and 21a) into the rotor flux coordinate system:

$$\bar{u}_{sIII} = R_s \bar{i}_{sIII} + \frac{d\bar{\psi}_{sIII}}{dt} + j\omega_{III}\bar{\psi}_{sIII} = R_s \bar{i}_{sIII} + \frac{d\bar{\psi}_{sIII}}{dt} + j\omega_{\psi}\bar{\psi}_{sIII}$$

(22a-

$$0 = R_r \bar{i}_{rIII} + \frac{d\bar{\psi}_{rIII}}{dt} + j\omega_{III,II}\bar{\psi}_{rIII} = R_r \bar{i}_{rIII} + \frac{d\bar{\psi}_{rIII}}{dt} + j\left(\omega_{\psi} - p\omega_m\right)\bar{\psi}_{rIII}$$

22b)

Since for the squirrel-cage $\bar{u}_{rIII} = 0$.

Where υ is the angle between the coordinate system I and III.

$\frac{d\upsilon}{dt} = \omega_{III}$ is a angular speed of the rotor coordinate system

Where ε is the angle between the coordinate system II and III.

$\frac{d\varepsilon}{dt} = \omega_{III,II}$ is a relative angular speed between the rotor flux coordinate system and the rotor coordinate system.

Substituting $s = \frac{\omega_{\psi} - p\omega_m}{\omega_{\psi}}$ we get:

$$\bar{u}_{sIII} = R_s \bar{i}_{sIII} + \frac{d\bar{\psi}_{sIII}}{dt} + j\omega_{III}\bar{\psi}_{sIII} = R_s \bar{i}_{sIII} + \frac{d\bar{\psi}_{sIII}}{dt} + j\omega_{\psi}\bar{\psi}_{sIII}$$

(23a-

$$0 = \frac{R_r \bar{i}_{rIII}}{s} + \frac{1}{s}\frac{d\bar{\psi}_{rIII}}{dt} + js\omega_{\psi}\bar{\psi}_{rIII}$$

23b)

Substituting ψ_s from (17) into (22a) yields:

$$\bar{u}_{sIII} = R_s \bar{i}_{sIII} + \frac{d\left[\frac{L_m}{L_r}\psi_r + \left(L_{sl} + \frac{L_m}{L_r}L_{rl}\right)i_s\right]}{dt} + j\omega_{III}\left(L_{sl} + \frac{L_m}{L_r}L_{rl}\right)i_s \quad (24)$$

Complex equations (24 and 22b) in ***dq*** coordinate system (rotor flux coordinate system) are:

$$u_{sd} = R_s i_{sd} + \frac{L_m}{L_r}\frac{d\psi_{rd}}{dt} + \left(L_{sl} + \frac{L_m}{L_r}L_{rl}\right)\frac{di_{sd}}{dt} - (\frac{L_m}{L_r}\psi_{rq}\omega_{\psi} + \omega_{\psi}\left(L_{sl} + \frac{L_m}{L_r}L_{rl}\right)i_{sq}$$

$$u_{sq} = R_s i_{sq} + \frac{L_m}{L_r}\frac{d\psi_{rq}}{dt} + \left(L_{sl} + \frac{L_m}{L_r}L_{rl}\right)\frac{di_{sq}}{dt} - (\frac{L_m}{L_r}\psi_{rd}\omega_{\psi} + \omega_{\psi}\left(L_{sl} + \frac{L_m}{L_r}L_{rl}\right)i_{sd}$$

$$0 = R_r\frac{L_m}{L_r}i_s + \frac{R_r}{L_r}\psi_{rd} + \frac{d\psi_{rd}}{dt} + (\omega_{\psi} - p\omega_m)\bar{\psi}_{rq} \quad (25a\text{-}25d)$$

$$0 = R_r\frac{L_m}{L_r}i_q + \frac{R_r}{L_r}\psi_{rq} + \frac{d\psi_{rq}}{dt} + (\omega_{\psi} - p\omega_m)\bar{\psi}_{rd}$$

Equations (25a-25d) are in rotor flux coordinate system which implies:

$$\psi_{rq} = 0 \Rightarrow \frac{d\psi_{rq}}{dt} = 0 \Rightarrow \psi_{rd} = |\bar{\psi}_r|$$

Hence, equations (25a-25d) could be simplified as follows:

$$u_{sd} = R_s i_{sd} + \frac{L_m}{L_r}\frac{d\psi_{rd}}{dt} + \left(L_{sl} + \frac{L_m}{L_r}L_{rl}\right)\frac{di_{sd}}{dt} - \omega_{\psi}\left(L_{sl} + \frac{L_m}{L_r}L_{rl}\right)i_{sq}$$

$$u_{sq} = R_s i_{sq} + \left(L_{sl} + \frac{L_m}{L_r}L_{rl}\right)\frac{di_{sq}}{dt} - (\frac{L_m}{L_r}\psi_{rd}\omega_{\psi} + \omega_{\psi}\left(L_{sl} + \frac{L_m}{L_r}L_{rl}\right)i_{sd}$$

$$0 = R_r\frac{L_m}{L_r}i_{sd} + \frac{R_r}{L_r}\psi_{rd} + \frac{d\psi_{rd}}{dt} \quad (26a\text{-}26d)$$

$$0 = R_r\frac{L_m}{L_r}i_{sq} + (\omega_{\psi} - p\omega_m)\bar{\psi}_{rd}$$

Realizing that torque could be defined as follows:

$$T_e = \frac{3}{2}\frac{L_m}{L_r} p \operatorname{Re}\left\{ j \overline{\psi}_r \overline{i}_r^* \right\} = \frac{3}{2}\frac{L_m}{L_r} p \left(\psi_{rd} i_{sq} - \psi_{rq} i_{sd} \right) = T + J \frac{d\omega_m}{dt} + F\omega_m$$

(27)

Where T is torque of the load on the shaft, T_e is electromagnetic torque on the shaft produced by motor, J is inertia of the motor, F is friction factor of the motor and p is pole pairs. Then (26a-26d) could be expressed in state space:

$$\dot{x} = Ax + Bu$$
$$y = Cx$$

Letting:

$$\lambda = L_{sl} + L_{rl} \frac{L_m}{L_r}$$

$$\alpha = \frac{R_s + R_r \frac{L_m^2}{L_r^2}}{\lambda}$$

$$\beta = \frac{R_r \frac{L_m}{L_r^2}}{\lambda}$$

$$\gamma = \frac{\frac{L_m}{L_r^2}}{\lambda} p$$

$$\delta = \frac{1}{\lambda}$$

$$\varepsilon = \frac{3}{2}\frac{L_m}{L_r}\frac{1}{J} p$$

$$\chi = \frac{3}{2}\frac{L_m}{L_r}\frac{1}{F} p$$

$i_{sd}=x_1$, $i_{sq}=x_1$, $\psi_{rd} = x_3$, $\psi_{rq} = x_4$, $\omega = x_5$, $u_{sd}=u_1$, $u_{sq}= u_2$, $T=u_3$, $T_e=y_1$,

we get:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{pmatrix} = \begin{pmatrix} -\alpha & 0 & \beta & \gamma x_5 & 0 \\ 0 & -\alpha & -\gamma x_5 & \beta & 0 \\ R_r \frac{L_m}{L_r} & 0 & -\frac{R_r}{L_m} & -x_5 & 0 \\ 0 & R_r \frac{R_r}{L_m} & x_5 & \frac{R_r}{L_m} & 0 \\ -\varepsilon x_4 & \varepsilon x_3 & 0 & 0 & \chi \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{pmatrix} + \begin{pmatrix} \delta & 0 & 0 \\ 0 & \delta & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{J} \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix} \tag{28}$$

$$y_1 = \begin{pmatrix} -\frac{3}{2}\frac{L_h}{L_r} p x_4 & \frac{3}{2}\frac{L_h}{L_r} p x_5 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{pmatrix} \tag{29}$$

Equation (28) fully describes mathematical model of induction machine and in following sections will be used to derive the concept of Vector control.

3.2.3 Mathematical concept of Vector control and relation to the control of DC machines

Since one may be familiar with the control of DC machines, I will introduce Vector control in relation to the control used in DC machines.

The construction of a DC machine is such that the field flux is perpendicular to the armature flux. Being orthogonal, these two fluxes produce no net interaction on one another. Adjusting the field current can therefore control the DC machine flux, and the torque can be controlled independently of flux by adjusting the armature current. Equations describing DC machines are:

$$T = k\psi I_a$$
$$\psi = L_m I_m \tag{30a-30c}$$
$$\psi(s) = U_m(s)\frac{\tau}{1+s\tau}$$

Where I_a is armature current, ψ is flux in the motor, I_m is field (magnetizing) current, U_m is field voltage and τ is time constant of DC motor.

An AC machine is not so simple because of the interactions between the stator and the rotor fields, whose orientations are not held at 90 degrees but vary with the operating conditions. You can obtain DC machine-like performance in holding a fixed and orthogonal orientation between the field and armature fields in an AC machine by orienting the stator current with respect to the rotor flux in order to attain independently controlled flux and torque. In order to achieve this it is important to split stator current into two parts:

a) Component which is aligned with rotor flux and which produces magnetic field in the motor - I_{sd}
b) Component which is perpendicular to rotor flux and produces torque - I_{sq}

Equations (28) fully described the induction machine. In order to control both I_{sq} and I_{sd} it is necessary to estimate the position and magnitude of rotor flux. So the magnitude could be estimated from (28) or rather from (26c):

$$|\overline{\psi}_r|(s) = \frac{L_m}{1 + s\tau_r} i_{sd}(s)$$

(31)

Where $\tau_r = \frac{L_r}{R_r}$ is the rotor time constant and $|\overline{\psi}_r| = \psi_{rd}$ because we use *dq* coordinate system where d axis is aligned with rotor flux.

The position could be estimated from (28) or rather from (26d):

$$\omega_\psi = R_r \frac{L_m}{L_r} \frac{1}{\psi_{rd}} i_{sq} + p\omega_m = R_r \frac{L_m}{L_r} \frac{1}{|\overline{\psi}_r|} i_{sq} + p\omega_m \qquad (32)$$

Now it is obvious that vector control is fairly similar to the control of DC machines:

DC Machine	AC Machine
$M = k\psi I_a$	$M = k\psi_{rd} I_{sq}$
$\psi(s) = U_m(s)\frac{\tau}{1+s\tau}$	$\lvert\overline{\psi}_r\rvert(s) = \psi_{rd}(s) = \frac{L_m}{1+s\tau} I_{sd}(s)$

Table 2 – Comparison of the control of DC and AC motors

I_{sq} in induction machines corresponds to armature current I_a in DC machines. However, in terms of dynamics I_{sd} in induction machines corresponds to field voltage U_m in DC machines. Nonetheless, the control of the stator current is achieved by the control of the stator voltage. So, all in all, we shall say that Vector control is conceptually the same as the control of DC machines.

3.2.4 Vector control in the nutshell

Let us summarize the concept of Vector control. The Vector control, which basic principle is shown in Figure 10, could be described in following steps:

1) Transforming stator currents i_a, i_b, i_c from three-phase stator stationary coordinate system into **dq** rotating rotor flux coordinate system. This step performed by Clark and Park transformation according to (2) and (4), respectively.
2) Finding new position of the rotor flux using i_{sq}, rotor angular speed ω_m and magnitude of the rotor flux $|\overline{\psi}_r|$. This is calculated by (32).
3) Finding the new magnitude of the rotor flux using i_{sd}. This is calculated by (31).
4) Setting new value of i_d according to the flux reference and magnitude of the flux profile in the motor. The relation between flux and i_{sd} is:

$$i_{sd} = \frac{\psi}{L_m} \tag{33}$$

5) Setting new value of i_q according to the flux reference and the torque which is adjusted according to the speed error This is calculated by:

$$i_{sq} = \frac{2}{3}\frac{1}{p}\frac{L_r}{L_m}\frac{M}{\psi} \tag{34}$$

6) Transforming i_d and i_q from *dq* rotating rotor flux coordinate system into three-phase stator stationary coordinate system using Inverse Park and Clark transformation. This is done by (6) and (8), respectively.

It should be noted that the Vector control hugely depends on knowing parameters of the motor. However, when the Vector control is used in close-loop speed regulation, the uncertainties of motor parameters could affect only the dynamics of the motor but not the accuracy since the torque is adjusted according to speed error.

VECTOR CONTROL

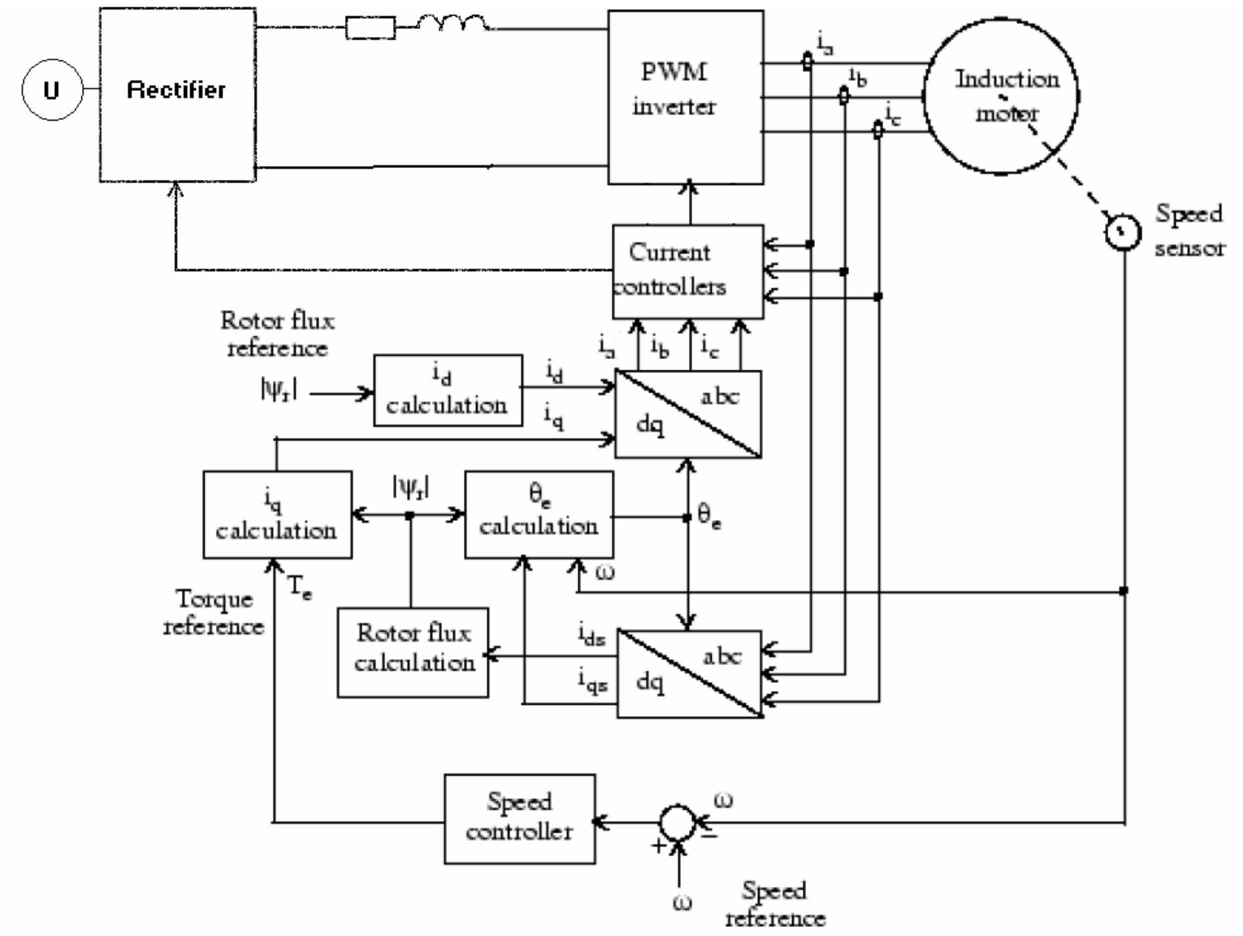

Figure 10 – The basic principle of Vector control

4. Implementation of PowerFlex7000 in Simulink

The model, which is shown in Figure 11, is divided into 8 main parts. First five parts functionally and logically correspond to its counterparts of the Frequency Converter PowerFlex7000. However, some changes have been made in order to improve the simulation and to make the model easier implement. These changes are discussed in detail at the end of this chapter.

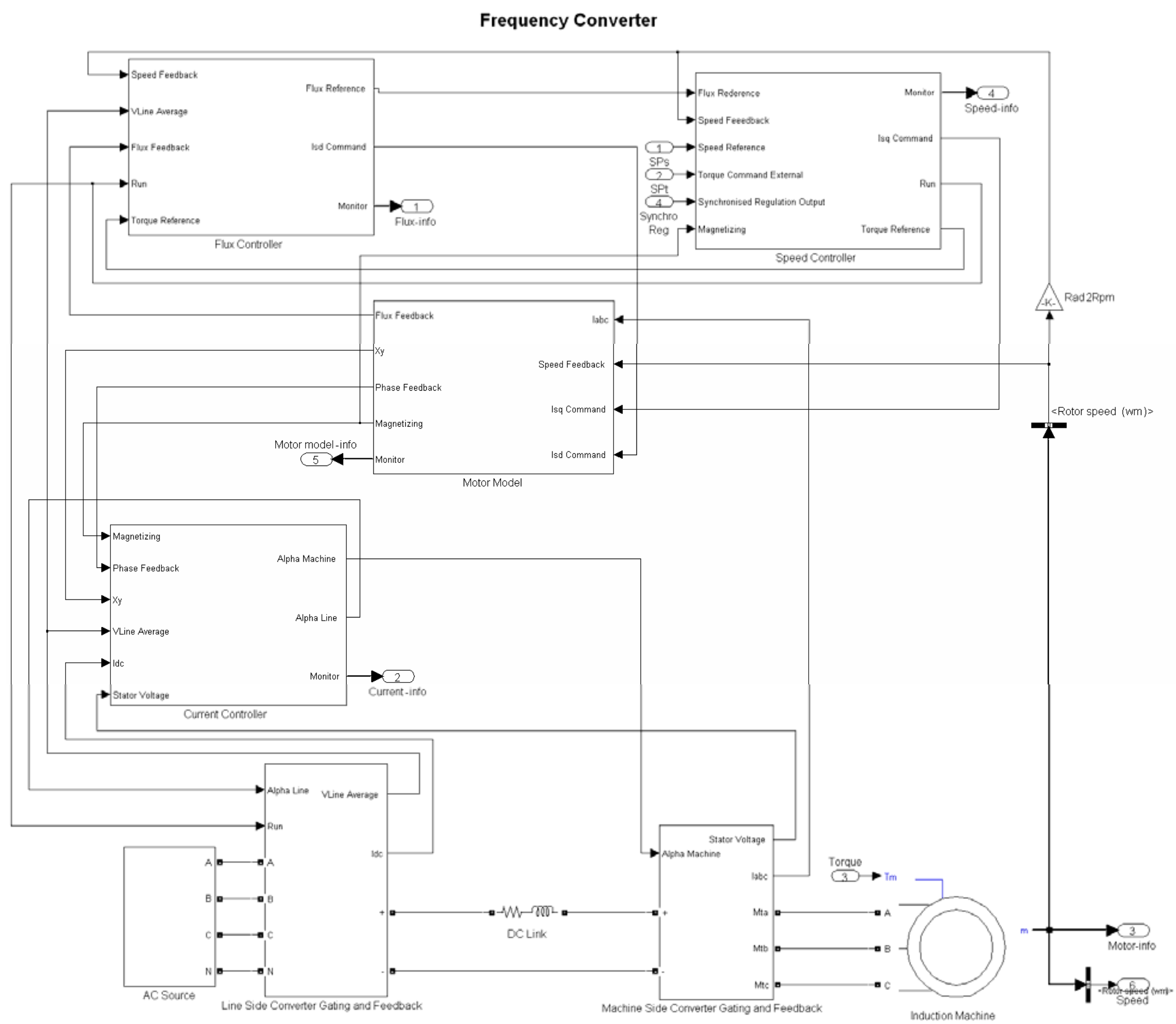

Figure 11 – High-level scheme of the model in Simulink

Input	Function and Description
Torque	It defines load on the motor shaft
SPs	Set point for speed
SPt	Set point for torque
Synchro Reg	“Flying start”

Table 3 – List of inputs of Frequency Converter

Output	Function and Description
Speed-info	Information regarding speed variables
Flux-info	Flux variables
Motor model-info	Motor model variables
Current-info	Current variables
Motor-info	Motor-induction machine variables
Speed	Speed of the motor [rad/s]

Table 4 – List of outputs of Frequency Converter

Parameter
Sample time [s][1]

Table 5 – List of parameters of Frequency Converter

4.1. Speed Control block

The Speed control block determines the torque-producing component of the stator current. This block provides four modes of operation:

1) Speed regulation

Speed control block in the speed regulation determines the torque-producing current. First of all, speed reference is processed by Speed Reference block, where the reference speed is being clamped to minimal and maximal value and its rate of change is also limited. This should prevent drive from oscillating when the load on the shaft of the motor is low and, therefore, there is possibility that the motor could accelerate too fast and there is a danger of motor being damaged. Alternatively, it could define the start-up speed characteristic. Next input to this block is speed feedback, which is filtered, then is subtracted form speed reference to produce speed error. Subsequently, speed error is processed by PI Speed

[1] This parameter should be set exactly the same as the Sample time of the simulation (Simulation->Configuration Parameters->sample time -when using discrete solver) or the sample time in GUI SimPowerToolbox

regulator which adjusts torque according to speed error. Finally, Speed control block determines I_q command and passes command to Motor model block. Calculating the current is done according to (34).

2) Torque regulation

PI Speed regulator is being by-passed and requested torque defines I_q according to (34). Since the regulating of torque is done in open loop, the accuracy is much less precise than the regulation of the speed. Requested torque is passed to Speed control block via Torque Command External.

3) Speed sum

In this mode of operation reference speed is obtained from two different sources (Speed Reference and Torque command External) and then is summed up and controlled as described in Section 1.

4) Zero torque

This mode enables tuning drive since the input is zero.

Another input is Magnetizing, which defines normal and magnetizing modes of operation. When this input is set to zero, motor needs to be magnetized further. Whereas, magnetizing equals one indicates normal mode of operation, which means one of abovementioned operation.

Next input to this block is Synchronized Regulation Output. The function of this signal is to speed up or slow down the motor from outside when the drive is to be shut down or when the motor is to be control from different source (e.g. another frequency converter). This so-called flying start could come in handy when the frequency converter needs to be serviced and the motor must run continually. This provides a smoother, safer and, moreover, predictable reaction.

Last input to this block is Flux Reference which is used in calculating I_{sq} command according to (34).

The only output of this block (with the exception of I_{sq} Command and Monitor) is Torque Reference, which is passed to Flux Control block to set Flux Reference.

Last block which is implemented in this block is "Detect start". This block, which is shown in Figure 13, emulates the situation when the converter is being turned on for the first time, but stand still state is required. Therefore, this block disables 6-pulse Synchronized Generator (part of Line Side Converter Gating and Feedback) and also prevents Flux Control block from starting magnetizing mode. When the regulation is required, the change is detected and 6-pulse Synchronized Generator is unlock and magnetizing operation of the motor is enabled.

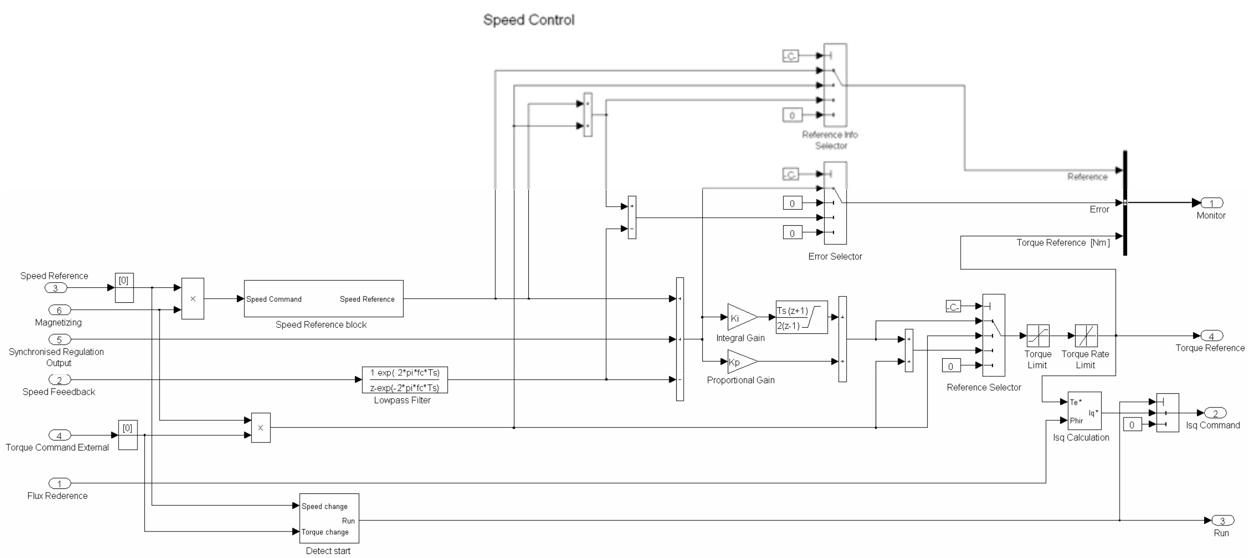

Figure 12 – Speed Control block in Simulink-

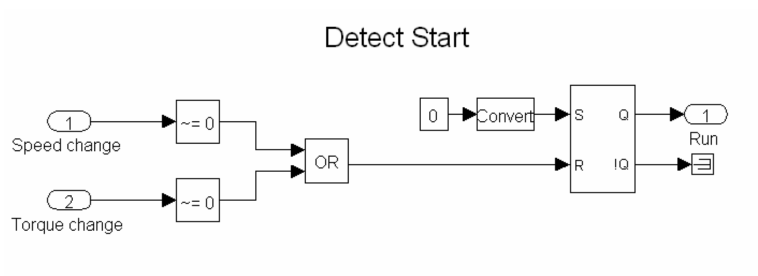

Figure 13 – Detect Start Control block in Simulink

Input	Function and Description
Speed Feedback	Set point for speed
Magnetizing	Determines normal mode of operation
Synchronized Regulation Output	Used in “Flying Start”
Speed Feedback	Signal from tachometer
Torque Command External	Set point for torque
Flux Reference	Signal from Flux Control block

Table 6 – List of inputs of Speed Control block

Output	Function and Description
Torque Reference	Desired torque
I_{sq} Command	Desired torque-producing current
Monitor	Monitoring Speed Control block variables
Run	Determines start of the drive

Table 7 – List of outputs of Speed Control block

Parameter
Regulation type
Speed controller - proportional gain
Speed controller - integral gain
Speed measurement - low-pass filter cutoff frequency [Hz]
Controller output torque saturation [N.m] [negative, positive]
Torque rate limit [N.m/s] [negative, positive]
Mutual inductance [H]
Rotor leakage inductance [H]
Motor pairs of poles
Maximal speed [rpm]
Minimal speed [rpm]
Speed ramp [rmp/s] [negative, positive]

Table 8 – List of parameters of Speed Control block

4.2. Flux Control block

The main aim of flux Control block, which is shown in Figure 13 is to determine the flux-producing stator current I_d. This is achieved by setting the reference flux. Reference flux depends on desired torque, which is passed from Speed Control block and on parameters Initial flux, Nominal flux and Nominal torque. The desired reference flux is linearly proportional to torque (Figure 14) and it is adjusted in Flux Table block (Figure 16). When the drive operates under Base speed of the motor or at reduced line voltage then Nominal flux is reduced by Flux Command Limit block (Figure 17). Next stage is to determine flux command according to flux error this is achieved by PI Flux Regulator. The final step is to determine I_{sd} command which is done by dividing Flux command by Mutual inductance (L_m). I_{sd} command is then pass to Motor model to determine absolute value of I_{stator} and angle between I_{stator} and rotor flux.

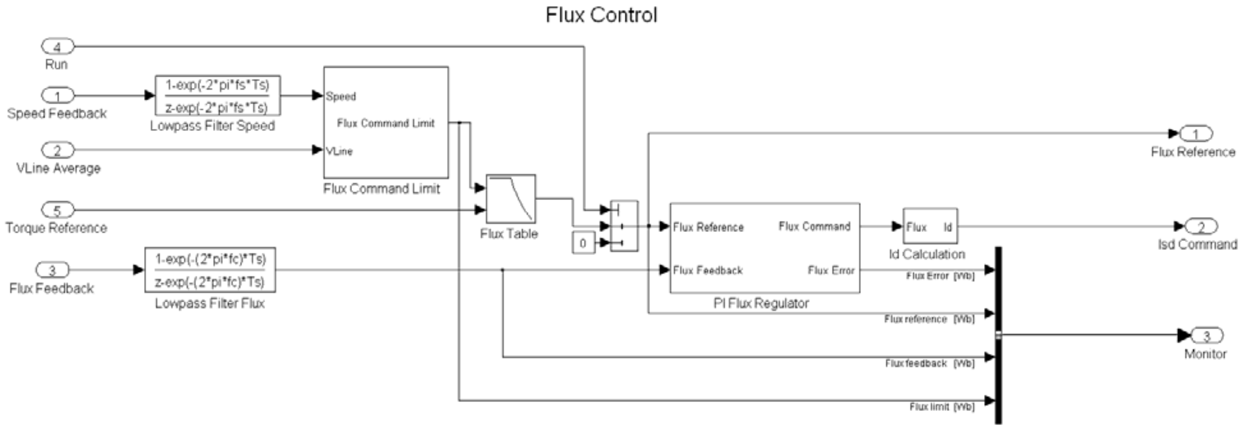

Figure 14 – Flux Control block in Simulink

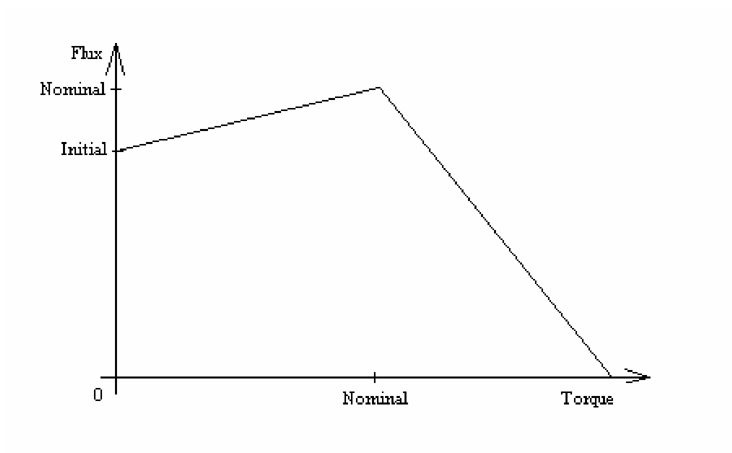

Figure 15 – Flux reference

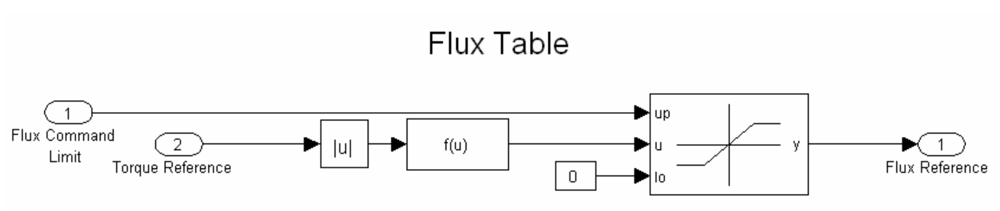

Figure 16 – Flux Table block in Simulink

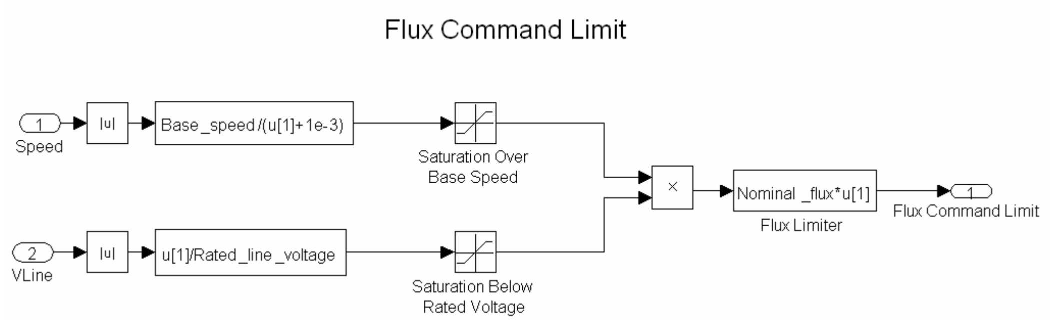

Figure 17 – Flux Command Limit block in Simulink

Input	Function and Description
Run	Determine start of the drive
Speed Feedback	Signal from tachometer
VLine Average	Input voltage of Frequency Converter
Toqrue Reference	Torqe Reference form Speed control
Flux Feedback	Estimation of Flux from Motor model

Table 9 – List of inputs of Flux Control block

Output	Function and Description
Flux Reference	Desired flux profile
Isd Command	Desired fux-producing current
Monitor	Monitoring Flux Control block variables

Table 10 – List of outputs of Flux Control block

Parameter
Speed feedback – low-pass filter cut-off frequency [Hz]
Flux controller - flux estimation low-pass filter cut-off frequency [Hz]
Flux controller - proportional gain
Flux controller - integral gain
Flux controller - flux limit [Wb] [negative, positive]
Nominal torque [Nm]
Base speed [rpm]
Initial flux [Wb]
Nominal flux [Wb]
Mutual inductance [H]
Rated line voltage [V]

Table 11 – List of parameters of Flux Control block

4.3. Current Control block

The aim of this block is to set I_a ,I_b and I_c stator currents as required from Motor model block. The currents are passed from motor model in *xy* ($\alpha\beta$) stator stationary coordinates. The absolute value of the desired current is controlled by changing firing angle of the Line side rectifier, whereas the frequency of the current is set by changing the gating sequence of the inverter. This block is shown in Figure 18.

a) Control of I_{dc}:

I_{dc} feedback is filtered and subtracted from the absolute value of desired current. However, since I_{dc} and absolute value of desired current is related as follows:

$$I_{DC} = \frac{\pi}{2\sqrt{3}}\left|I_{stator}\right|$$

Absolute value must be reduced before being subtracted. Then PI Current regulator processes I_{dc} error and produces V_{dc} voltage. Nonetheless, in order to control I_{dc} effectively feedforward voltage is filtered and divides by VLine Average, which is the absolute value of voltage before the rectifier. Then voltage is limited by Current limiter in order to limit current. It should be noted that voltage could be reduced only relatively to the input voltage. The desired voltage is then processed by Cos^{-1} block. This block determines Alpha line angle by using arcos of desired output voltage. Since output voltage tends to oscillate, the firing angle could be limited. Limiting the firing angle could improve the regulation of current significantly. However, sometimes it slows down the response, especially when the reference current drops rapidly down.

b) Control of frequency of stator voltage

The frequency of stator voltage is control by changing the rate of inverter sequence. The scheme of vector current modulator is shown in Figure 18. First of all, the desired angle of the current is adjusted by PI Phase regulator. This is the result of the fact that the combined electrical circuit of the inverter and the motor is frequency dependent. So, in fact, the reference current is phase shifted. And vector control is based on the idea that the stator current is precisely control relatively to the rotor flux. In another words, stator current must be synchronized accurately to rotor flux. Therefore, it is important to maintain the desired angle. If this control was not the vector one, the phase shift would not be an issue and the only difference would be that the dynamic response would be slightly slower. The adjusted reference phase is than divided into 6 sectors each having 60° in Sector Selector. Switching time calculator block is each cycle triggered (this block processes only when is triggered) by Ramp Generator. This time is determined by switching frequency of vector modulator. On-times and off-times for 6 switches of the inverter are determined in Switching Time Calculator block. The idea is straightforward (Figure 20):

7) In each cycle only two switches are in on-state
8) In each cycle only two switches are modulated and in such a way that on-time of one switch is 0 and off-time depends on the reference sin wave, which has unit amplitude , the other switch has its off-time set to on-time of the first switch and off-time set to1.
9) Between on and off-times some short delay (death time) must be placed due to commutation.
10) The change of current flow is achieved by switching upper and lower switches.

The final stage is to compare on and off-times with unit ramp and turn on or off corresponding switches. Figure 16 shows the principle of this modulation. In order to demonstrate the modulation, there were no inductances in the circuit so the current is not smooth and also the frequency was chosen to be much lower than in the model. Hence, the parts which are not modulated are quite wide compared to parts which are modulated.

In order to get almost maximal breakaway torque it is necessary to reach certain level of magnetic saturation. This level is determined by Motor model and prior to normal operation the vector modulator is by-passed and the current flows through 2 phases.

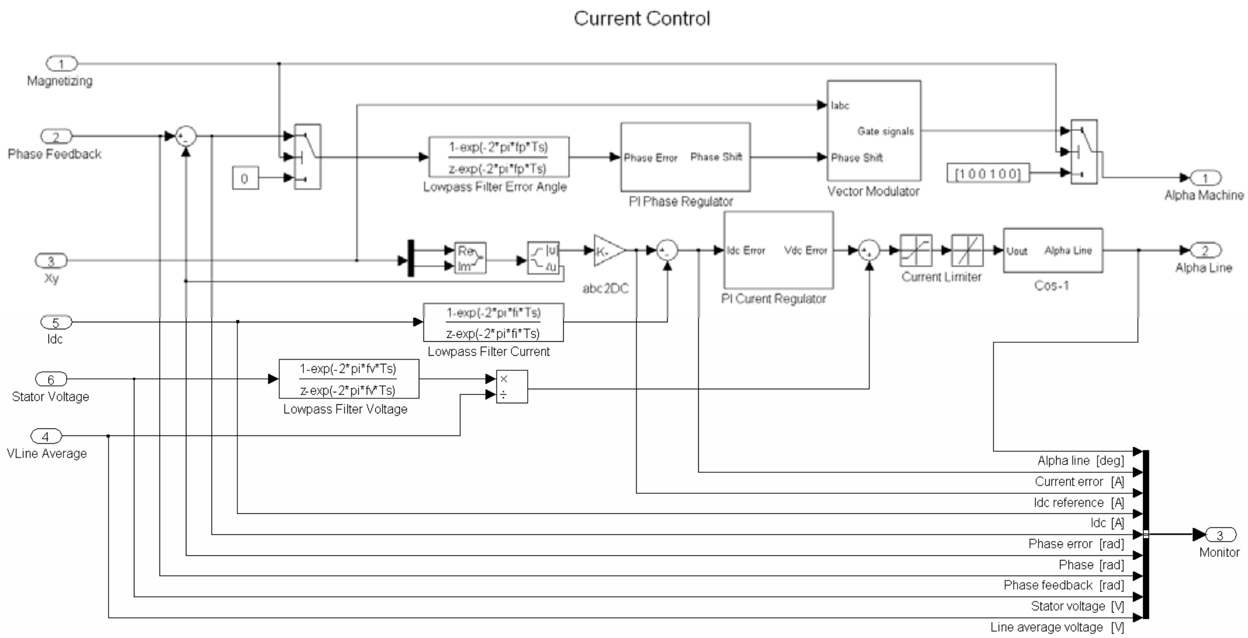

Figure 18 – Current control block in Simulink

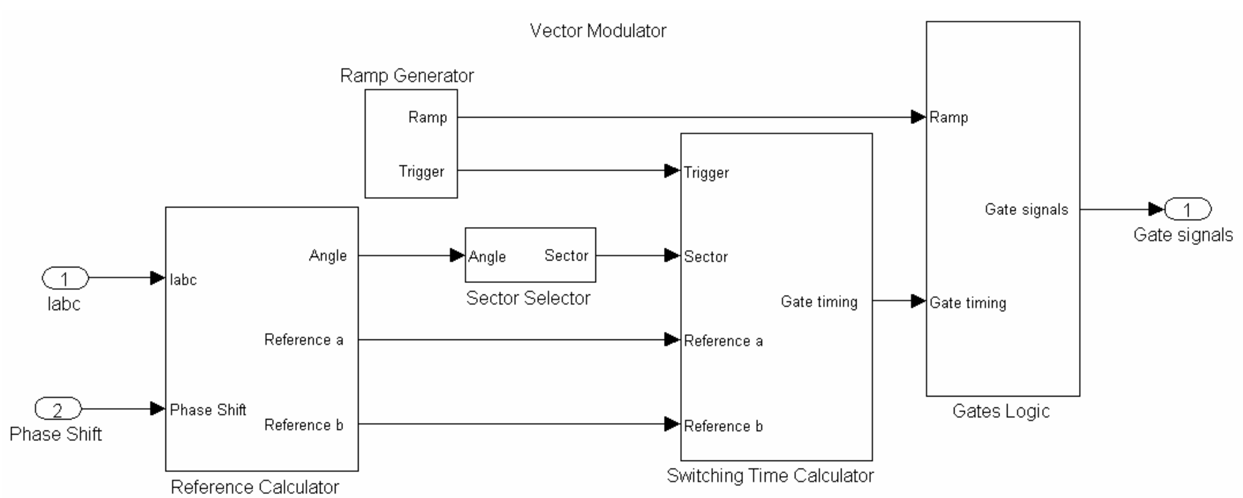

Figure 19 – Vector modulator in Simulink

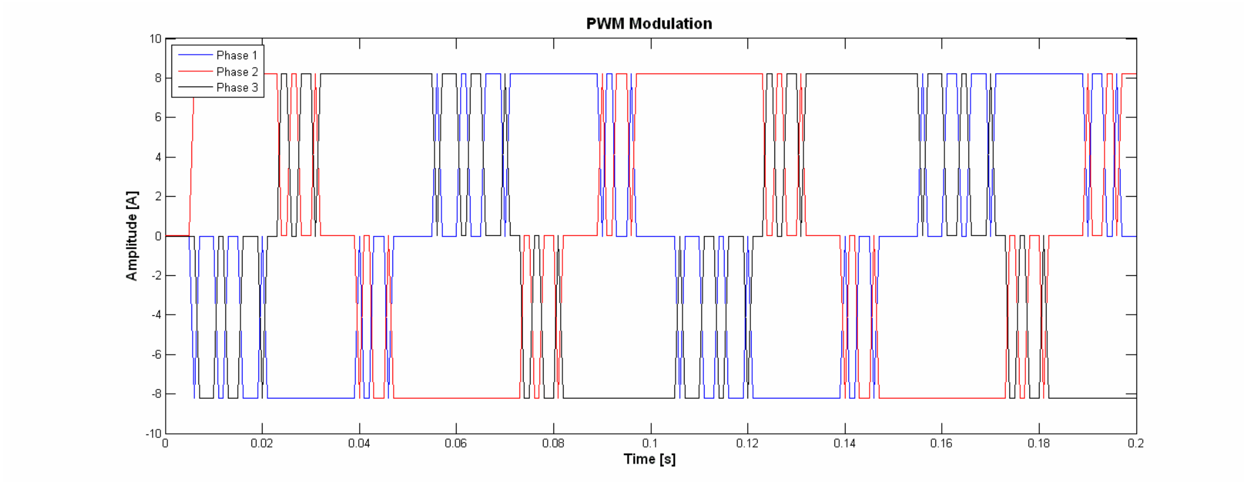

Figure 20 – PWM modulation – the principle

Input	Function and Description
Magnetizing	Determine the start of normal operation
Phase Feedback	Phase of stator voltage
Xy	Desired stator current
I_{dc}	Current feedback from DC link
Stator Voltage	Stator voltage in ab coordinates
VLine Average	Voltage before the rectifier

Table 12 – List of inputs of Current Control block

Output	Function and Description
Alpha Machine	Firing angle for the Inverter
Alpha Line	Firing angle for the Rectifier
Monitor	Monitoring Current Control variables

Table 13 – List of outputs of Current Control block

Parameter
Current controller - proportional gain
Current controller - integral gain
Relative current limit [negative, positive]
Current rate limit [negative, positive]
Current feedback – low-pass filter cut-off frequency [Hz]
Voltage feedback – low-pass filter cut-off frequency [Hz]
Phase feedback – low-pass filter cut-off frequency [Hz]
Phase controller - proportional gain
Phase controller - integral gain
Phase controller - phase limit [rad] [negative, positive]
Switching frequency of vector modulator [Hz]

Table 14 – List of parameters of Current Control block

4.4. Motor model

Motor model, which is shown in Figure 21, transforms stator currents i_c, i_b and i_c from three-phase stationary stator coordinate system into *dq* rotating system of the rotor flux. This is exactly done by (2) and (4). Subsequently, this block estimates the magnitude of rotor flux and position this is done according to (31) and (32), respectively. Then the Motor model processes I_q and I_d Commands from Speed Control block and Flux Control block, respectively, and transforms these currents from *dq* rotating system of rotor flux into three-phase stationary stator coordinate system using (6) and (8). Afterwards, Motor model passes desired current to Current control block. Another output to Current control block is Phase Feedback which is phase of the stator current. This signal is then used by PI Phase regulator to adjust the reference phase in order to match desired phase. Block Magnetizing detects when the flux profile in the motor reaches certain level which is user-defined.

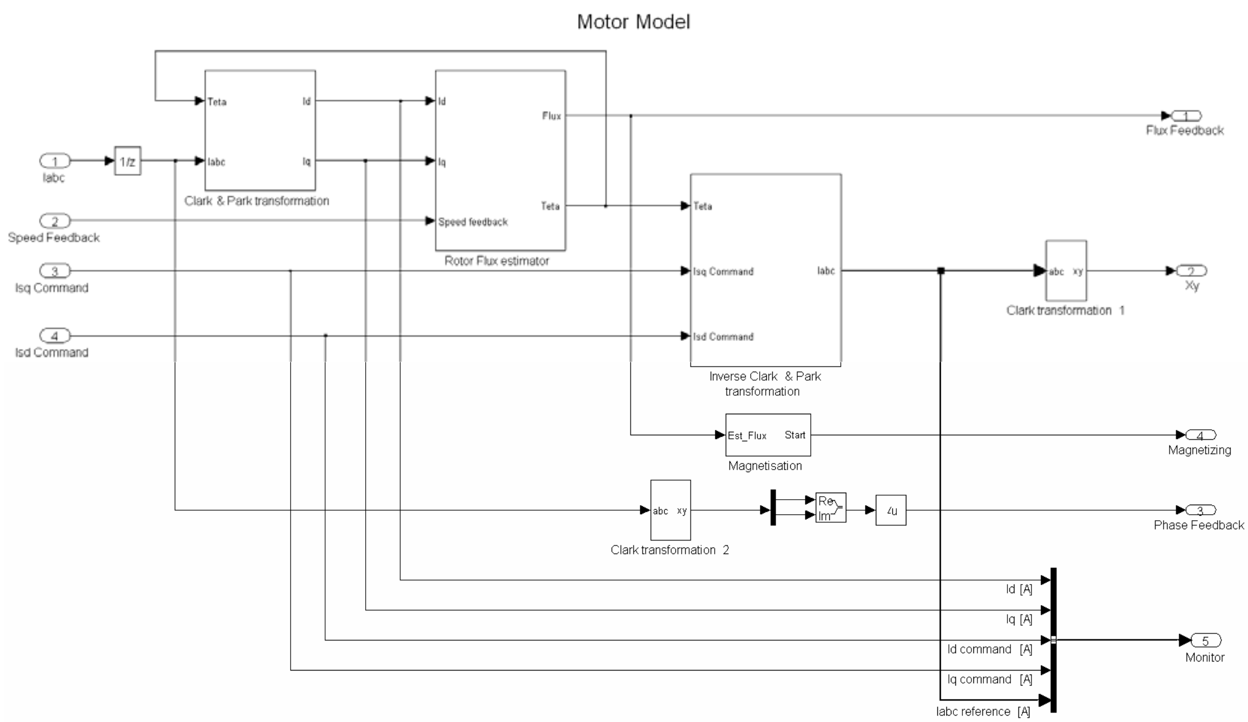

Figure 21 – Motor model

Input	Function and Description
I_{abc}	Stator current
Speed Feedback	Signal from tachometer
I_{sd} Command	Desired flux-producing current
I_{sq} Command	Desired torque-producing current

Table 15 – List of inputs of Motor model block

Output	Function and Description
Flux feedback	Estimation of magnitude of rotor flux
Magnetizing	Start the normal mode of operation
Phase Feedback	Phase of stator current
Monitor	Monitoring Motor model variables

Table 16 – List of outputs of Current cntrol block

Parameter
Motor mutual inductance (H)
Motor rotor resistance (ohms)
Motor rotor leakage inductance (H)
Motor pairs of poles
Magnetizing flux (Wb)

Table 17 – List of parameters of Motor model block

4.5. Line side converter gating and feedback

Line side converter, which is shown in Figure 22, includes two standard blocks from SimPowerToolbox:

a) Synchronized 6 –Pulse Generator

This block is always in double-pulsing mode

b) Thyristors Rectifier

This block processes firing angle from Current Control block and, hence, controls indirectly the stator current.

The only output from this block is Vline Average, which is used in Flux Control block to determine flux profile in the motor and in the Current Control block to effectively control DC link current.

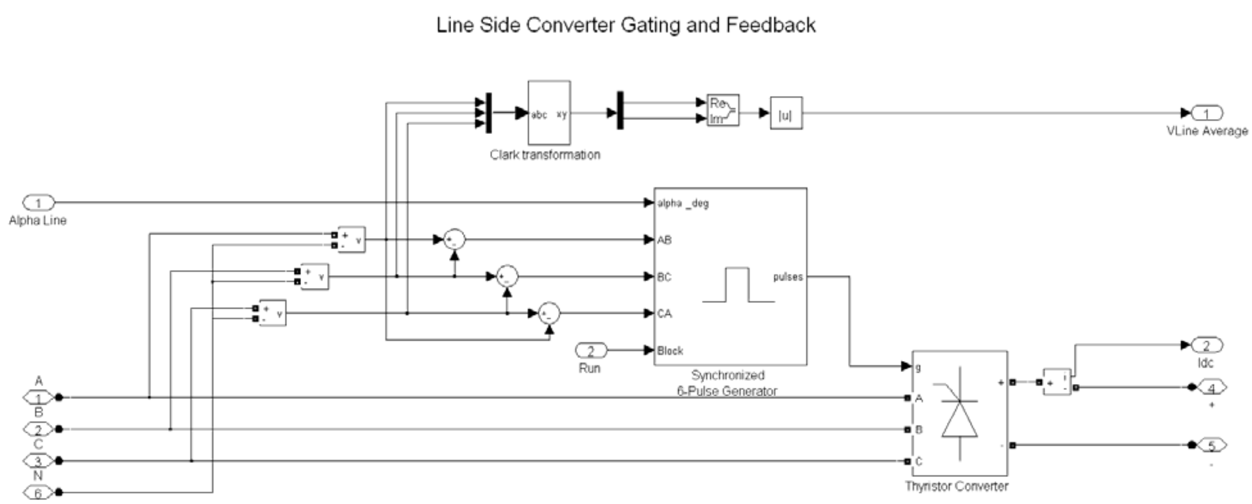

Figure 22 – Line side converter gating and feedback

Input	Function and Description
Alpha Line	Determines the firing angle for rectifier
A,B,C,N	A,B,C phase and neutral wiring

Table 18 – List of inputs of Line side converter gating and feedback

Output	Function and Description
VLine Average	Voltage at the input of the Converter
I_{DC}	DC Link current
+,-	DC Voltage

Table 19 – List of outputs of Line side converter gating and feedback

Parameter
Synchronizing frequency of rectifier [Hz]
Pulse width of rectifier [deg]
Snubber resistance of thyristors [ohm]
Snubber capacitance of thyristors [F]
On-state resistance of thyristors [ohm]

Table 20 – List of parameters of line Side converter gating and feedback

4.6. Motor side converter gating and feedback

Machine Side Converter Gating and Feedback, which is shown in Figure 23, provides the converter with reference stator currents i_a, i_b and i_c. These currents are further used in Motor model block in estimating the magnitude and the position of the rotor flux. The phase is also detected in order to synchronize the inverter with the reference current. Another output is the stator voltage which is used in the Current Control block to effectively control DC link current. The next input is Alpha Machine. This signal is passed from Current Control block and it controls Three-phase Inverter. Gating is passed as a vector containing always six numbers each corresponding to one switch (phase A-upper, phase A-lower, phase B-upper, phase B-lower, phase C-upper, phase C-lower). Each vector always contains 4 zeros or more (more when the Vector Modulator uses death times due to the commutation). Number 1 indicates on-state of the switch. Whereas number 0 indicates off-state of the switch. Since Powerflex7000 maintains SGCT (Symmetrical Gate Commutated Thyristors), which is rather new silicon device and it is not a part of SimPowerToolbox, I modeled such an device as a ideal switch (with non-zero resistance in on-state) with RC snubber circuit. The inverter is shown in Figure 24.

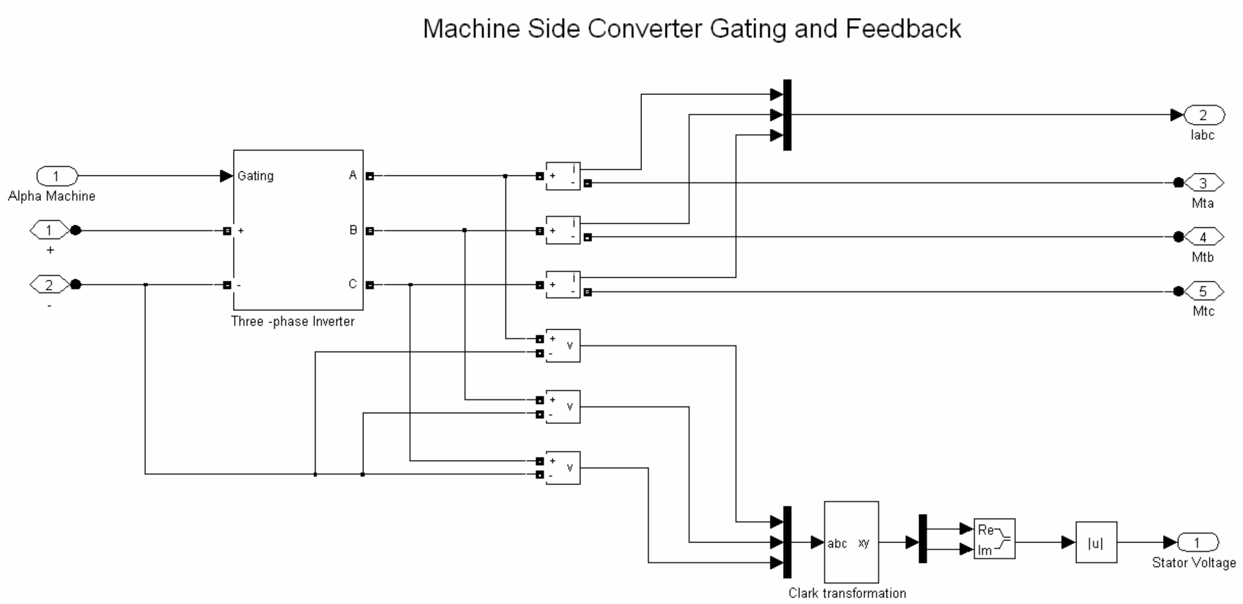

Figure 23 – Motor side converter gating and feedback

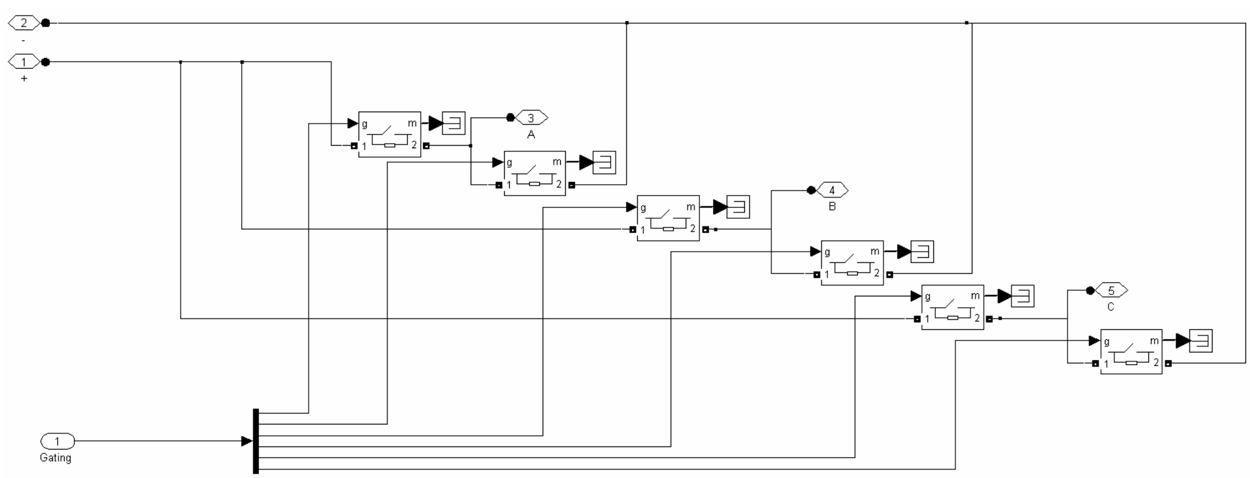

Figure 24 – Three-phase inverter

Input	Function and Description
Alpha Machine	Gating for the inverter
+,-	DC Voltage

Table 21 – List of inputs of Machine side converter gating and feedback

Output	Function and Description
I_{abc}	Stator currents
Mta,Mtb,Mtc	Motor wirings
Stator Voltage	Stator Voltage

Table 22 – List of outputs of Machine Side converter gating and feedback

Parameter
Snubber resistance [ohm]
Snubber capacitance [F]
On-state resistance [ohm]

Table 23 – List of parameters of Machine side converter gating and feedback

4.7. Differences between the model and PowerFlex7000

The model differs in some way; however, the performance of the model should not be affected significantly.

4.7.1. Speed control block

The main difference is that the model implements only simplified Speed reference block, which means that the model provides neither four acceleration and deceleration ramps nor S-curve ramp. Although I have designed and fully tested flip-flop circuit with delays, which implements four acceleration and deceleration ramps, I could not use this block in the model since I used sample time of 1μs and I was warned by Simulink that delay blocks may behave in an unpredictable way, which , in fact, really occurred. The solution to this problem could be to use different sample times for individuals block. This, however, could lead to problems with transition rates and further testing would be required. As a result, Speed control block implements only one acceleration and one deceleration ramp and speed is limited to the minimal and maximal value. Since the model is always in close-loop, there was no need to implement Open loop start-up block and also Speed feedback is always determined from tachometer. The model could be set not in six modes, but only in four modes, since speed torque negative and speed torque positive mode were omitted. Last difference is that the model does not include CAP

Current Calculator; the reason is that I did not figure out how to calculate the current supplied by the capacitor. The calculation is not trivial since the circuit depends on the frequency and also the current must be split into two orthogonal parts.

4.7.2. Flux control block

The flux controller does not include CAP Current Calculator. The reason is the same as in Speed control block. Next difference is that Flux command limit block does not take into account Rated Motor voltage, since I have not figured out the correlation between Rated motor voltage, Rated line voltage and Vline bridge. The last difference is that the model uses close-loop calculation of I_{sq} command.

4.7.3. Current control block

Current control block, which computes Alpha-line, works exactly according to the given specification. The only minor difference is that V_{dc} feedforward is obtained directly by dividing the magnitude of the stator voltage by V line Average. Whereas PowerFlex7000 measures the voltage in one-phase and then using Alpha Machine (phase) to calculate the magnitude of the stator voltage. This alternation was done because there is a problem with the phase-shift. In order to tune the model more effectively, I add a block which only limits the maximal machine angle. This adjustment has proven to improve the control of DC link in same cases. In terms of vector modulator, I must admit that this block is implemented probably differently than in PoweFlex7000. However, there is no exact documentation of such a modulator and, moreover, this block may be implemented by hardware (e.g. phase-locked loop).

4.7.4. Motor model block

This block includes two main sub-blocks: Voltage flux model and Current flux model. Voltage flux model is to certain degree know-how of Rockwell Automation since it is designed by hardware. The reason is simple. Vector control hugely depends on motor parameters and, therefore, PowerFlex7000 somehow tries to reduce the impact of uncertainties of motor parameters by combining software and hardware. On the other hand, Current control block is implemented by software and the algorithm is well described in [2] or [3].

5. Conclusion

This thesis has helped me to understand different types of control of not only induction machines but also DC machines. Although this work was practically oriented, I have acquainted myself with the concept of a vector control. Since induction machines are the most common actuators and due to the accessibility of microcontrollers and power electronic devices, the vector control will attract more attention in the future. Hence, I could deal with induction machines and with Vector control in the future even more intensively.

Nonetheless, the main aim which was to simulate PowerFlex7000 with Siemens ARNRY-6 has not been accomplished. The reason may be that I have not managed to find out the flux profile in this motor.

In this section I would like to summarize the objectives which have been accomplished but also the problems which have not been solved or have been solved only partially and will need to be addressed in the future.

5.1. Accomplishments

In this thesis I achieved following objectives:

1) I have acquainted myself with the concept of vector control.
2) I have demonstrated the concepts, disadvantages and advantages of vector control in simulations of 3HP and 200HP motor in both speed and torque regulations.
3) I have implemented an algorithm of Vector control in Simulink.

5.2. Unsolved problems

In this thesis I have not solved following problems:

1) I have not managed to tune the frequency converter for motor Siemens ARNRY-6.
2) I have not solved the problem with the phase shift
3) I have not fully implemented the model of PowerFlex7000.

6. Literature

[1] Rockwell Automation: PowerFlex 7000, Medium Voltage AC Drive “B” Frame (Air-Cooled), User Manual (Publication 7000-UM150F-EN-P), Cambridge, Canada 2005

[2] Bimal K. Bose (editor), Adjustable Speed AC Drive Systems, Institute of Electrical and Electronics Engineers, New York 1981

[3] Karel Zeman, Zdeněk Peroutka, Martin Janda: Automatická regulace pohonů s asynchronními motory, Západočeská univerzita, Elektrotechnická fakulta, Plzeň 2004

[4] Gilbert Sybille: SimPoweSystems 4, User’s Guide, Natick, MA 2007

[5] Jan Bašta: Teorie elektrických strojů, Nakladatelství technické literatury Alfa, Praha 1968

[6] Arias Pujol: Improvements in direct torque control of induction motors, Doctoral thesis, Technical University of Catalonia 2001

LITERATURE

7. Appendixes

In this section I will not only show results from simulations but also demonstrate typical properties of frequency converters. This section is divided into following parts:

1) Induction machine 3HP, speed regulation below the base speed, both directions, pump type load, Vector control
2) Demonstration of the torque ripple and the phase shift
3) Induction machine 3HP, speed regulation above the base speed, one direction, pump type load, comparison between the flux-constant region and the power-constant region
4) Induction machine 3HP, torque regulation
5) Induction machine 200HP, speed regulation below the base speed, both directions, pump type load, reaction to disturbances
6) Induction machine 200HP, speed regulation above the base speed, one direction, pump type load
7) Induction machine 200HP, heavy duty start-up, traction type load, comparison between the start-up of induction machines with scalar frequency converters, vector frequency converters and the start-up of DC motors
8) Induction machine 200HP, torque regulation
9) Induction machine 200HP, torque regulation, uncertainty in all parameters
10) Induction machine 200HP, torque regulation, uncertainty in one parameter
11) Robustness of Vector control
12) Comparison between 3HP, 200HP induction machine and PowerFlex7000

I implemented a model of the pump type load in order to define speed-torque characteristic of the motor. Pump has its torque proportional to the square of the speed:

$T_l = K\omega^2$

This type of the load was used in all speed simulations with the exception of simulation 7.
The scheme of all simulations is shown in Figure 25.

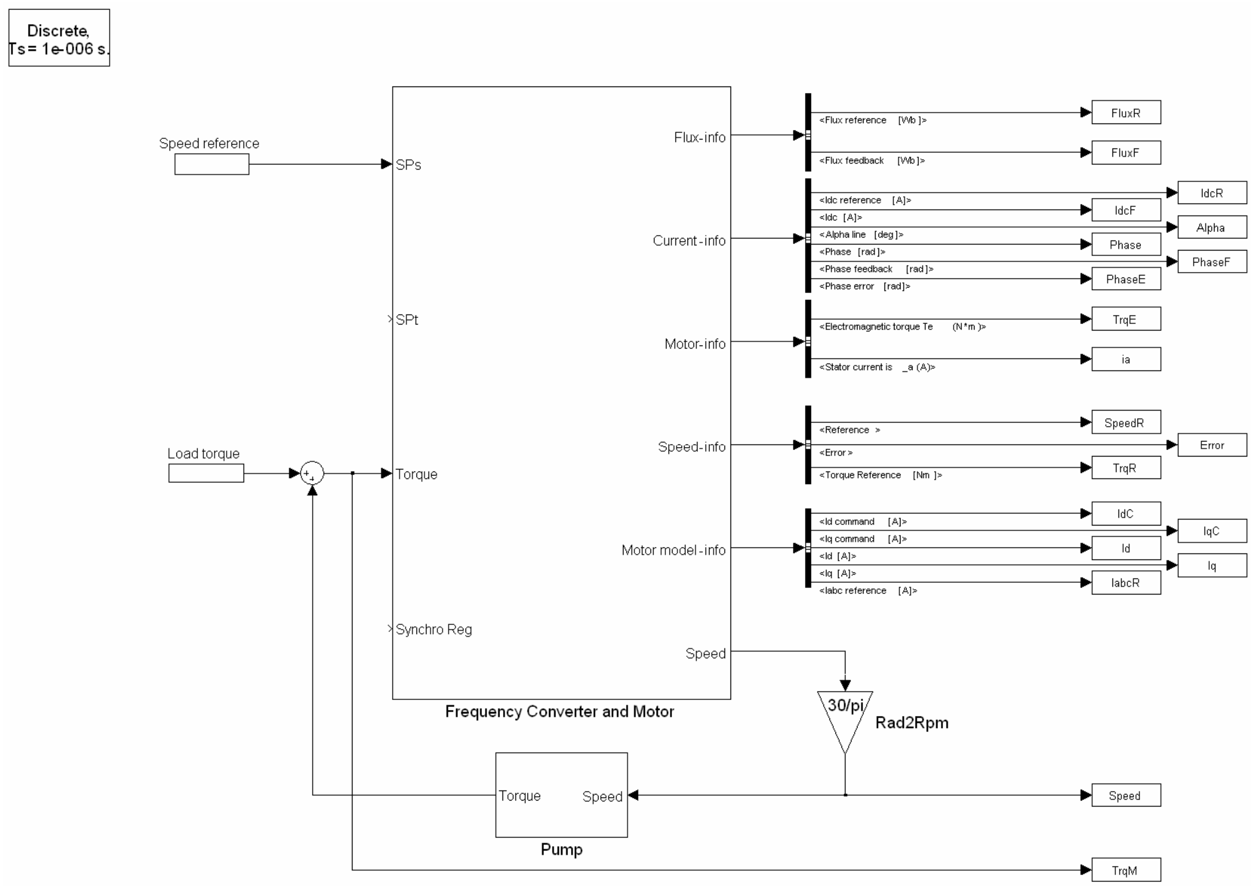

Figure 25 – Schema of the simulation

7.1. Induction machine 3HP: speed regulation below the base speed, both directions, pump type load, Vector control

There are three set points (-800,800 and 1400 rpm). The type of the load is a pump. I will use the results of this simulation to demonstrate the torque ripple and also the phase shift in the following section.

7.1.1. Parameters

Parameter	
Length [s]	10
Solver	ode45(Dormant-Prince)
Relative tolerance	1e-3
T_s[2] [s]	1e-6

Table 24 – Parameters of the simulation

[2] Model was discretized by GUI SimPowerToolbox

APPENDIXES

Parameter	
Type	pump
K [N.m/rpm^2]	6e-6

Table 25 – Parameters of the load

Parameter	
Mechanical input	Torque
Rotor type	Squirrel-cage
Reference frame	Rotor
Nominal power [kW]	2.238
Voltage line-line [V]	220
Base speed [rpm]	1760
Nominal torque [N.m][3]	12.14
Stator resistance [ohm]	0.435
Stator leakage inductance [H]	2e-3
Rotor resistance [ohm]	0.816
Rotor leakage inductance [H]	2e-3
Magnetizing(mutual) inductance [H]	69.31e-3
Inertia [kg.m^2]	0.2
Friction factor [N.m.s]	0.005
Pole pairs	2

Table 26 – Parameters of the motor

Parameter	
Speed controller	
Regulation type	Speed
Speed controller-proportional gain	2
Speed controller-integral gain	12
Speed measurement - low-pass filter cut-off frequency [Hz]	50
Controller output torque saturation [N.m] [negative, positive]	[-15,15]
Torque rate limit [N.m/s] [negative, positive]	[-10000,10000]
Maximal speed [rpm]	2500
Minimal speed [rpm]	50
Speed ramp [rmp/s] [negative, positive]	[-1500,1500]
Flux controller	
Speed feedback – low-pass filter cut-off frequency [Hz]	100
Flux controller - flux estimation low-pass filter cut-off frequency [Hz]	16
Flux controller - proportional gain	30
Flux controller - integral gain	40

[3] Nominal torque was calculated: $M_n = \frac{P}{\omega_n}$ where P [W] is the nominal power and ω_n is the base speed [rad/s]

Flux controller - flux limit [Wb] [negative, positive]	[-20,20]
Nominal torque [Nm]	15
Base speed [rpm]	1760
Initial flux [Wb]	0.3
Nominal flux [Wb]	0.3
Rated line voltage [V]	300
Current controller	
Current controller - proportional gain	1
Current controller - integral gain	1
Current controller - phase limit [rad] [negative, positive]	[-1,1]
Relative current limit [negative, positive]	[-1000,1000]
Current rate limit [negative, positive]	[-10000,10000]
Current feedback – low-pass filter cutoff frequency [Hz]	100
Voltage feedback – low-pass filter cutoff frequency [Hz]	1
Phase feedback – low-pass filter cutoff frequency [Hz]	8
Phase controller – proportional gain	100
Phase controller - integral gain	100
Phase controller - phase limit [rad] [negative, positive]	[-10,10]
Phase limit [deg] [lower, upper]	[0,120]
Switching frequency of vector modulator [kHz]	50
Motor model	
Initial machine flux (Wb)	0.3
Line side converter gating and feedback	
Synchronizing frequency of rectifier [Hz]	60
Pulse width of rectifier [Deg]	10
Snubber resistance of thyristors [ohm]	500
Snubber capacitance of thyristors [F]	1e-6
On-state resistance of thyristors [ohm]	1e-9
Line side converter gating and feedback	
Snubber resistance [ohm]	10
Snubber capacitance [F]	1e-6
On-state resistance [ohm]	1e-9
AC Source	
Amplitude	300
Frequency	60

Table 27 – Parameters of the frequency converter[4]

[4] Parameters regarding induction machine were set exactly the same as induction machine

7.1.2. Results

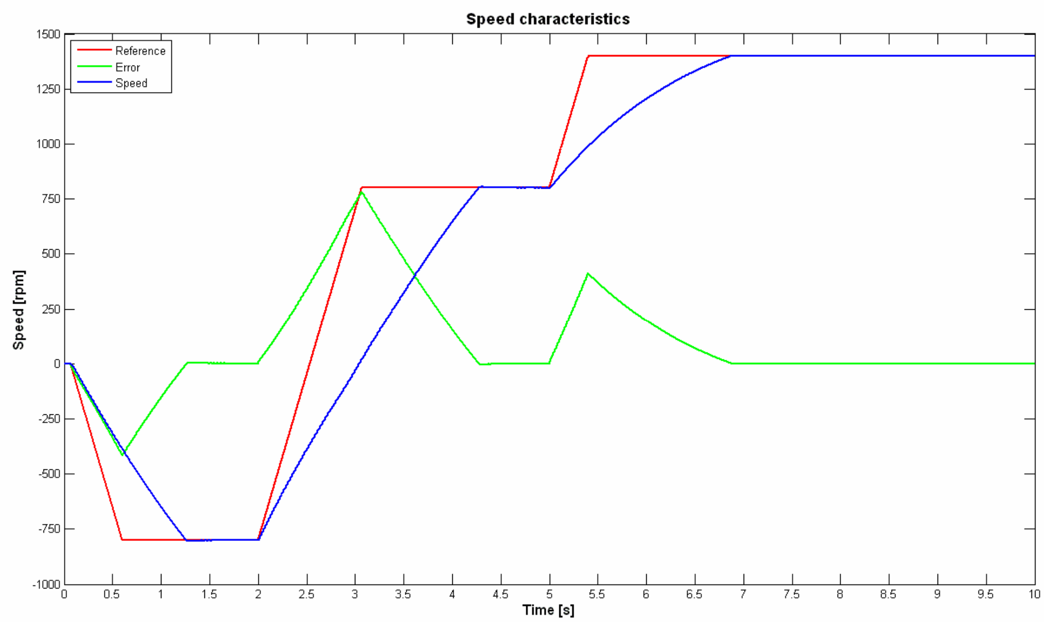

Figure 26 – Speed characteristics

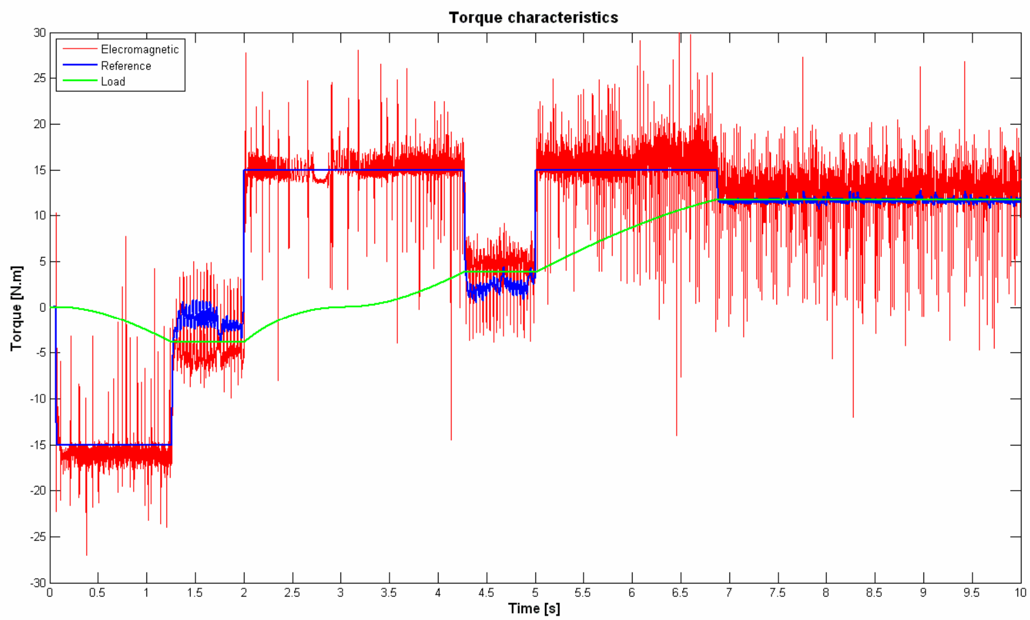

Figure 27 – Torque characteristics

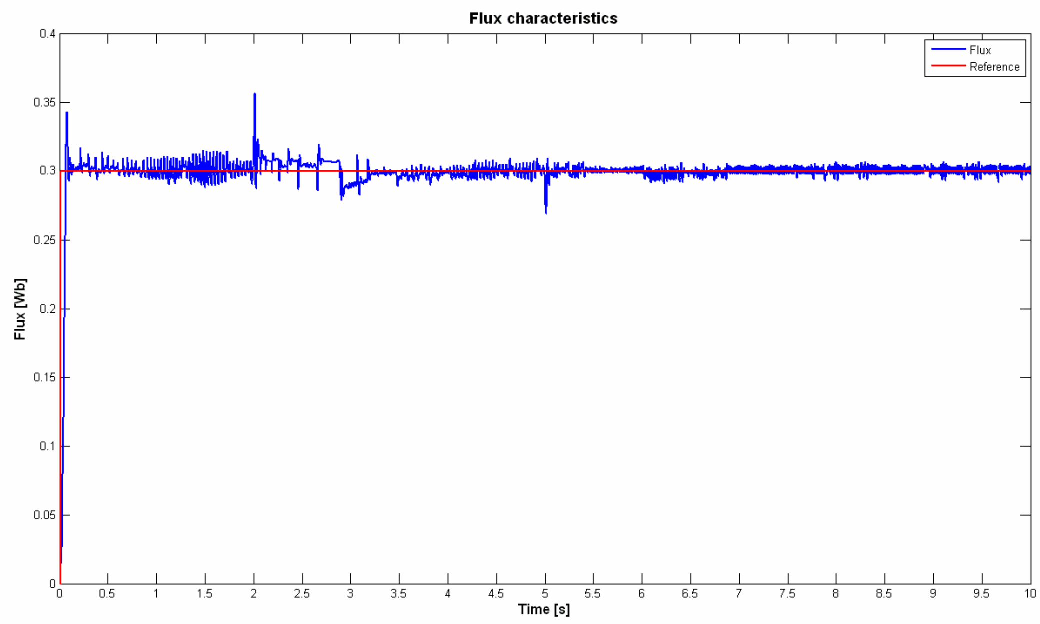

Figure 28 – Flux characteristics

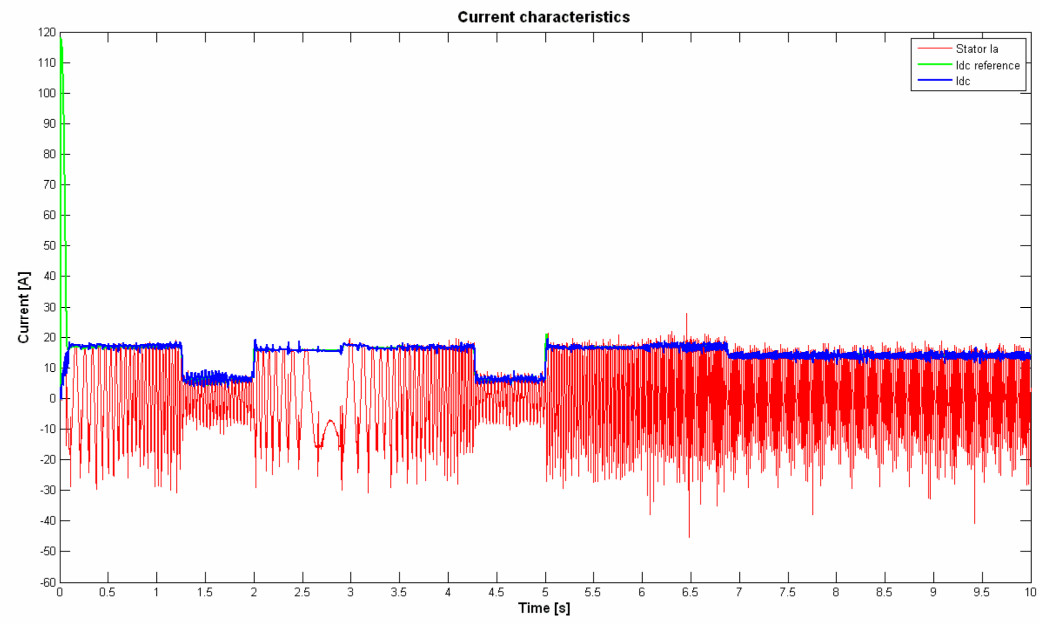

Figure 29 – Current characteristics

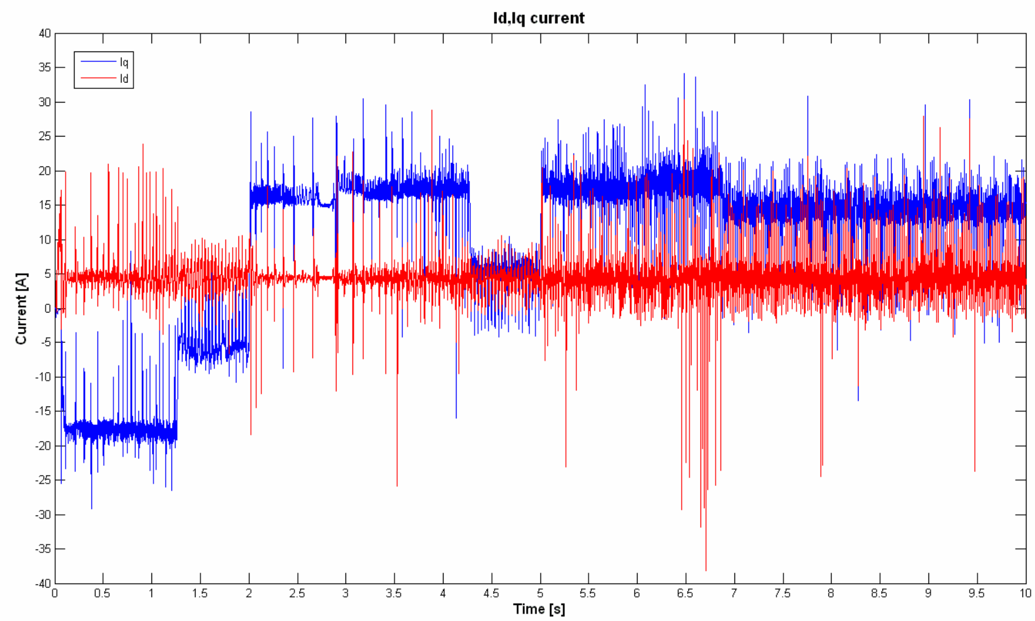

Figure 30 – I_d,I_q current

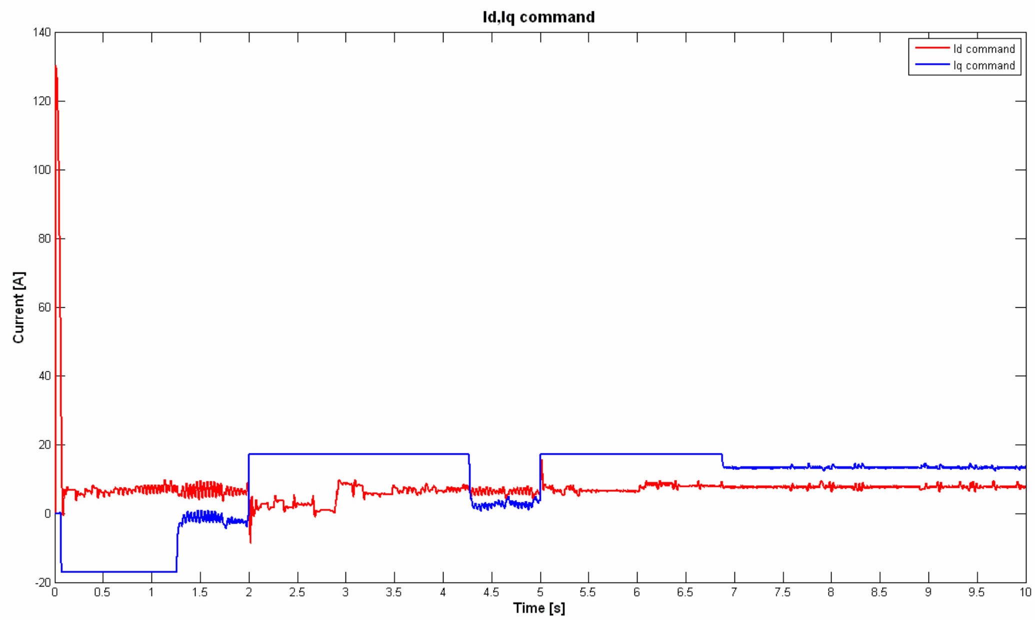

Figure 31 – I_d,I_q command

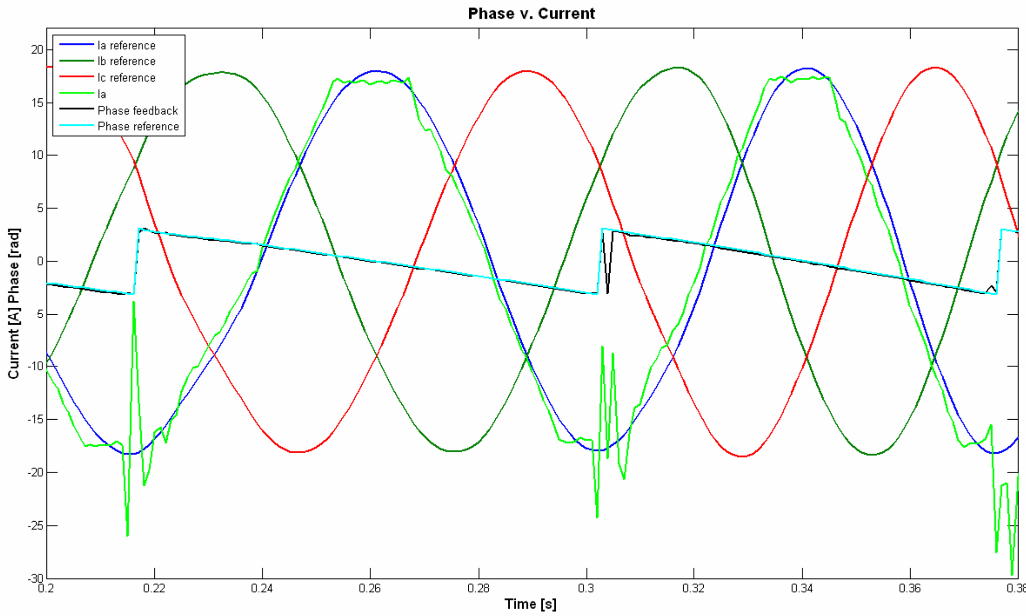

Figure 32 – Current in detail and the phase shift

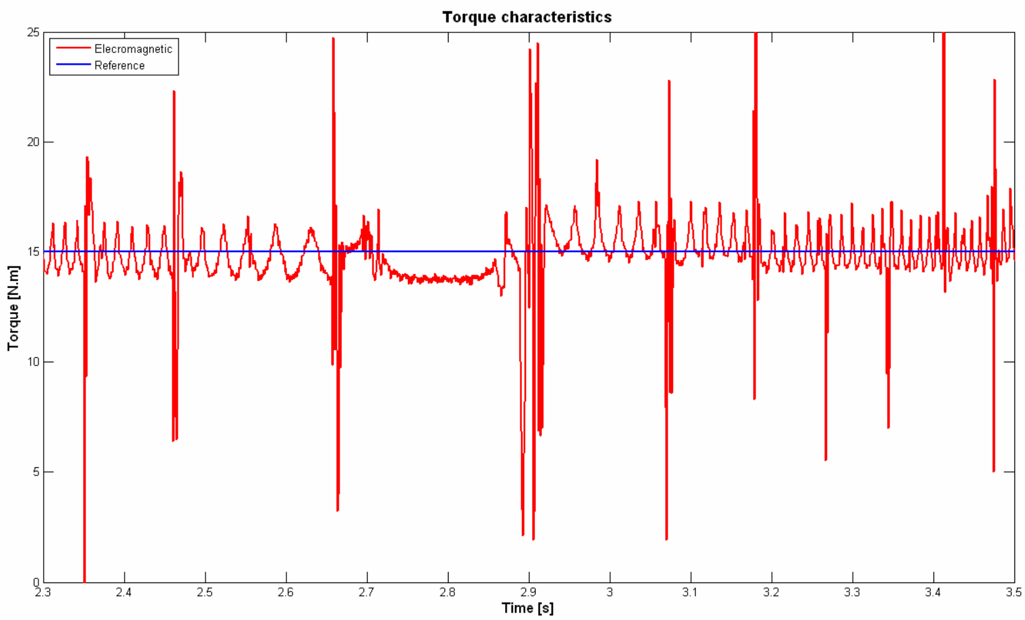

Figure 33 – Torque in detail

Set point [rpm]	-800	800	1400
T_r [s][5]	1.052	1.992	1.528
T_s [s][6]	1.114	2.13	1.702
OS [%]	0.1	0.1	0.04
Steady-state error [rpm]	0.7	0.6	0.2
Steady-state error [%][7]	0.04	0.034	0.01

Table 28 – Results of the simulation

7.1.3. Vector control

This simulation shows very important aspect of Vector control, which is the synchronism between the rotor flux and the stator current. This is shown in Figure 32, where the stator current is synchronized with the current reference which is determined by the position of the rotor flux. If the frequency and the amplitude of the stator current was the same as the current reference but the phase was different, the motor could not be controlled. This simulation has also shown that the torque is defined by I_q current, since the torque always follows this current. Whereas the flux is determined by I_d current and since the flux is almost constant this current is almost constant as well. Figure 29 shows two modes of operation. First one is magnetizing, which lasts some 80ms and during this mode there is only I_d component of the stator current, I_q component is zero and, therefore, the torque is zero as well. When the field reaches a certain level of saturation there is a normal mode of operation which is characterized by non-zero value of I_q and non-zero value of I_d current resulting in non-zero value of the torque. It could be also observed in Figure 31 that I_q and I_d current interacts with each other. Although I_q command is not correlated with I_d command or with the flux (I_q command depends on the flux reference which is constant in this simulation), each fluctuation of I_d current and, therefore, of I_d command is accompanied by the fluctuation of I_q current and, therefore, of I_q command and visa versa. This shows that these currents interact within the motor itself. Moreover, this simulation has proven that I_q current could be changed immediately resulting in minimal overshot of the speed.

Figure 33 shows torque ripple which will be discussed in the following section.

[5] Time when the speed reaches 90% of the reference
[6] Time when the speed settles between 5% of the steady-state value
[7] Related to the base speed

7.2. Demonstration of the torque ripple and the phase shift

7.2.1. Torque ripple

1) Theoretical background

In an ideal three-phase induction machine, which is fed by a balanced harmonic current, the flux cannot be produced by the third harmonic and, therefore, only harmonics of $(6n \pm 1)^{th}$ order must be taken into account. Furthermore, the $(6n - 1)^{th}$ harmonic produces the flux rotating in the opposite direction to that produced by the fundamental frequency, whereas the $(6n + 1)^{th}$ harmonic produces the flux rotating in the same direction to that produced by the fundamental frequency. The torque defined by (27) could be also defined as a reaction between the rotor flux and the stator one (in fact, definition (27) is based on the same principle). So the torque could be also defined as follows:

$$T_e = f(\overline{\psi}_s \overline{\psi}_r) = k \psi_s \psi_r \sin \upsilon_{sr} \qquad (35)$$

, where υ_{sr} is the angle between the stator and the rotor flux and *k* is the machine constant.

From (35) follows that the angle is the same if the frequency of the stator and the rotor flux (current) is the same. If the angle is the same then the torque is always steady. Since the angle varies at the rate which is the difference between the speeds of fluxes (currents) then the torque pulsation is at frequencies $6n$.

2) Analysis of the input signal

In order to show that the pulsation of the torque at 6^{th} harmonic is caused by the stator current of 5^{th} and 7^{th} harmonic, I inspected the frequency spectrum of the stator current. Moreover, in order to demonstrate that the modulation I used reduces the torque pulsation significantly, I compared two other modulation used in CSI (current-source inverters). Since there is the problem with the phase shift I did not use the current obtained from the simulation but I used signal, which well approximates the stator current (Signal 3):

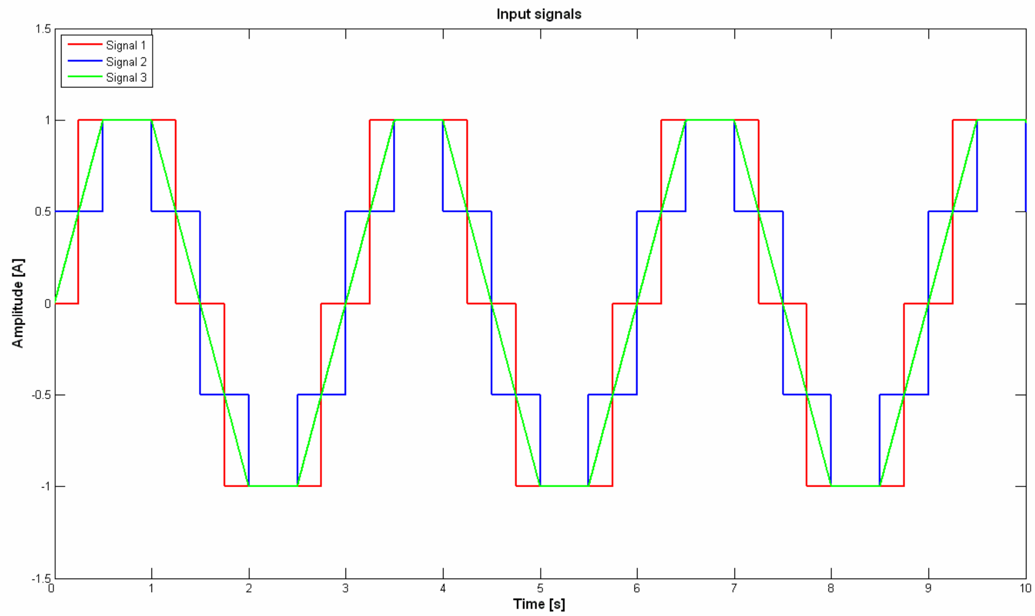

Figure 34 – Common modulations used in CSI

With the help of Signal processing toolbox, I obtained following FFT spectrum:

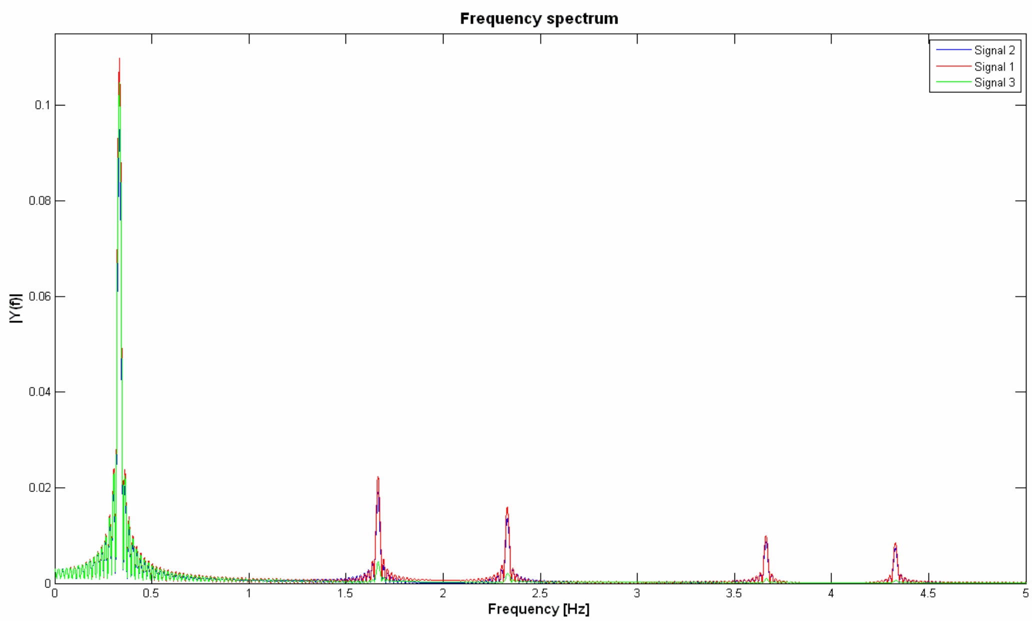

Figure 35 – FFT spectrum of stator currents

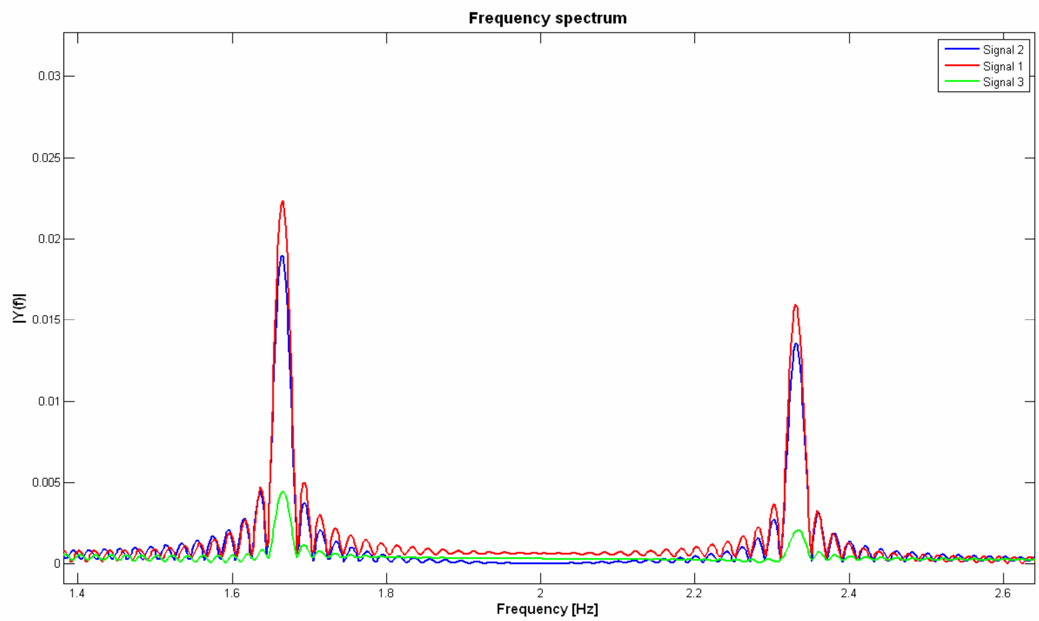

Figure 36 – FFT spectrum in detail

Signal	1	2	3
1st/5th	4.91	5.02	23.56
1st/7th	6.87	6.99	51.2

Table 29 – Harmonic distortion of the input signal caused by 5th and 7th

So it is obvious that the modulation I used is far better than the others as far as the suppressing of the ripple is concerned. The previous simulation (see Figure 33) shows that the torque ripple is at the 6*th* harmonic of the fundamental frequency. There is not need to use FFT analyses or autocorrelation function in order to prove this since it could be easily calculate the number of ripples in each period since there is the problem with the phase shift.

7.2.2. Phase shift

Since the inverter and also the induction machine or rather the equivalent circuit diagram depend on the frequency, it was necessary to implement a phase regulator. In order to demonstrate the phase shift, I used following simulation:

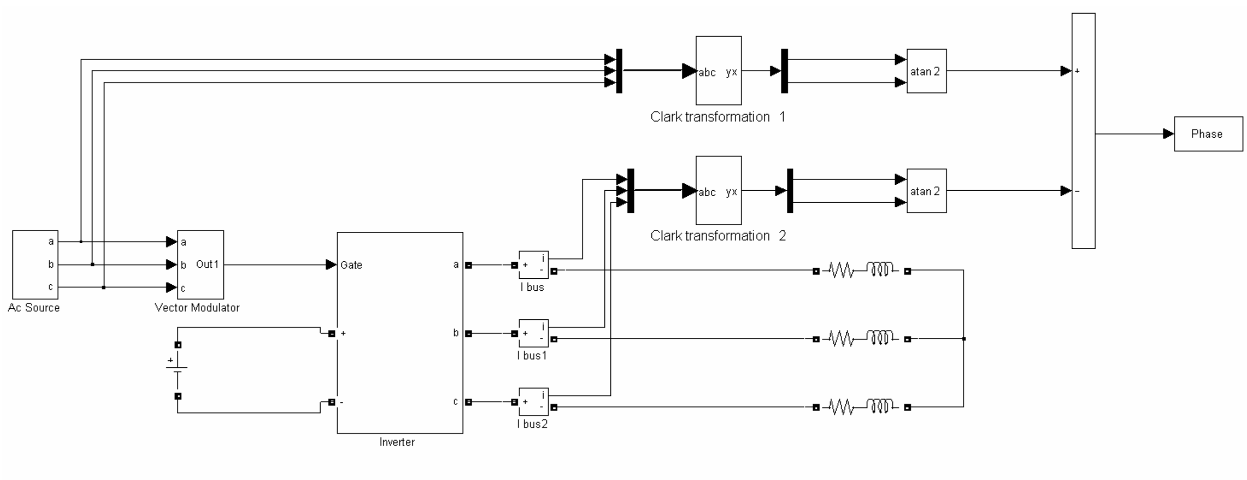

Figure 37 – Schema of the simulation demonstrating the phase shift

The advantage of this simulation scheme over the frequency converter with the induction machine is that I could use wider range of frequencies and also the frequency could be changed immediately. The disadvantage is that only the stator part of the induction machine was modeled. However, this cannot affect the demonstration of the principle and the solution of the phase shift. I obtained following results:

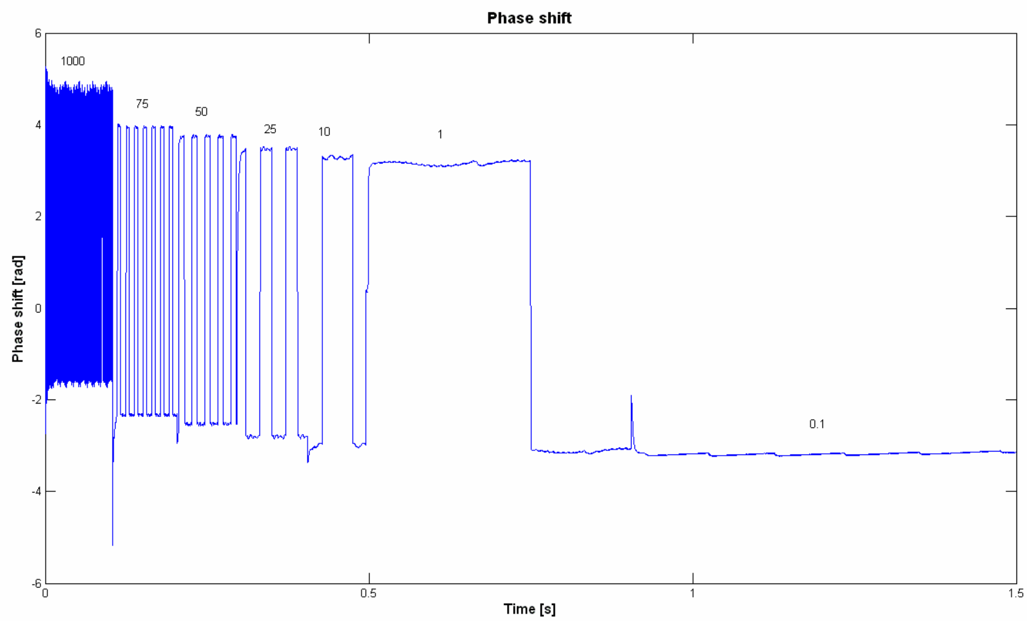

Figure 38 – Demonstration of the phase shift

The text implies the frequency in Hz which was used. The discontinuities in the phase are caused by a significant phase shift. This simulation shows two different phase-shifts:

a) Off-set phase shift

The reason of this shift is that the vector modulator and the inverter are not set properly. However, this problem could be easily fixed by adding off-set phase to the reference phase.

b) Frequency phase shift

This shift is caused by capacitors of the inverter and inductors of the induction machine. In fact, the induction machine depends even more on the frequency since the rotor (which was not modeled in this simulation) depends on the slip (see Figure 9). This problem could be fixed only by employing a regulator. The regulator compensates not only the off-set shift but mainly the frequency-induced shift. The problem I had to face up was the response of the regulator. Since when the phase changes it is necessary to react as fast as possible in order not to step out of the synchronism between the stator current and the rotor flux. In order to achieve this it is important, on one hand, to keep the cut-off frequency of the phase low-pass filter as high as possible. On the other hand, the phase is modulated and, therefore, the phase must be filtered. So the solution I have come up with is to modulate the current at very high frequency (tens of kHz). In fact, this makes the current very similar to the signal 3 in Figure 32 and then the cut-off frequency of phase low-pass filter could be higher (tens of Hz). This solution or rather compromise should be solved in order to model PowerFlex7000 more closely. The most effective solution would be to somehow make the phase continuous, which would result in reducing the modulation frequency.

The phase shift affects the performance of the system very negatively. It worsens not only the accuracy but also the dynamics of the system. The phase shift is noticeable in all characteristics (speed, torque, current, flux).

7.3. Induction machine 3HP: speed regulation above the base speed, one direction, pump type load, comparison between the flux-constant region and the power-constant region

There are three set points (1700, 2000 and 2200 rpm). The type of the load is a pump. I will use results of this simulation to compare the flux-constant region and the power-constant region.

7.3.1. Parameters

Parameter	
Length [s]	8
Solver	ode45(Dormant-Prince)
Relative tolerance	1e-3
T_s[8] [s]	1e-6

Table 30 – Parameters of the simulation

Parameter	
Type	pump
K [N.m/rpm^2]	2e-6

[8] Model was discretized by GUI SimPowerToolbox

APPENDIXES

Table 31 – Parameters of the load

Parameter	
Mechanical input	Torque
Rotor type	Squirrel-cage
Reference frame	Rotor
Nominal power [kW]	2.238
Voltage line-line [V]	220
Base speed [rpm]	1760
Nominal torque [N.m]	12.14
Stator resistance [ohm]	0.435
Stator leakage inductance [H]	2e-3
Rotor resistance [ohm]	0.816
Rotor leakage inductance [H]	2e-3
Magnetizing(mutual) inductance [H]	69.31e-3
Inertia [kg.m^2]	0.2
Friction factor [N.m.s]	0.005
Pole pairs	2

Table 32 – Parameters of the motor

Parameter	
Speed controller	
Regulation type	Speed
Speed controller-proportional gain	2
Speed controller-integral gain	12
Speed measurement - low-pass filter cut-off frequency [Hz]	50
Controller output torque saturation [N.m] [negative, positive]	[-15,15]
Torque rate limit [N.m/s] [negative, positive]	[-10000,10000]
Maximal speed [rpm]	2500
Minimal speed [rpm]	50
Speed ramp [rmp/s] [negative, positive]	[-1500,1500]
Flux controller	
Speed feedback – low-pass filter cut-off frequency [Hz]	100
Flux controller - flux estimation low-pass filter cut-off frequency [Hz]	16
Flux controller - proportional gain	30
Flux controller - integral gain	40
Flux controller - flux limit [Wb] [negative, positive]	[-20,20]
Nominal torque [Nm]	15
Base speed [rpm]	1760
Initial flux [Wb]	0.3

Nominal flux [Wb]	0.3
Rated line voltage [V]	300
Current controller	
Current controller - proportional gain	1
Current controller - integral gain	1
Current controller - phase limit [rad] [negative, positive]	[-1,1]
Relative current limit [negative, positive]	[-1000,1000]
Current rate limit [negative, positive]	[-10000,10000]
Current feedback – low-pass filter cutoff frequency [Hz]	100
Voltage feedback – low-pass filter cutoff frequency [Hz]	1
Phase feedback – low-pass filter cutoff frequency [Hz]	8
Phase controller - proportional gain	100
Phase controller - integral gain	100
Phase controller - phase limit [rad] [negative, positive]	[-10,10]
Phase limit [deg] [lower, upper]	[0,120]
Switching frequency of vector modulator [kHz]	50
Motor model	
Initial machine flux (Wb)	0.3
Line side converter gating and feedback	
Synchronizing frequency of rectifier [Hz]	60
Pulse width of rectifier [Deg]	10
Snubber resistance of thyristors [ohm]	500
Snubber capacitance of thyristors [F]	1e-6
On-state resistance of thyristors [ohm]	1e-9
Line side converter gating and feedback	
Snubber resistance [ohm]	10
Snubber capacitance [F]	1e-6
On-state resistance [ohm]	1e-9
AC Source	
Amplitude	300
Frequency	60

Table 33 – Parameters of the frequency converter[9]

[9] Parameters regarding induction machine were set exactly the same as induction machine

7.3.2. Results

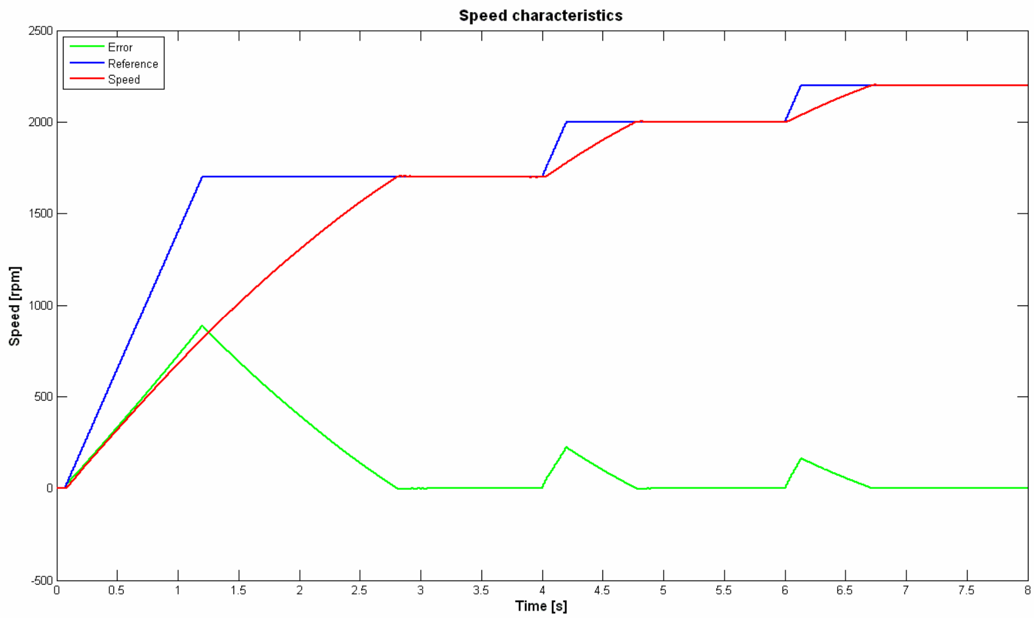

Figure 39 – Speed characteristics

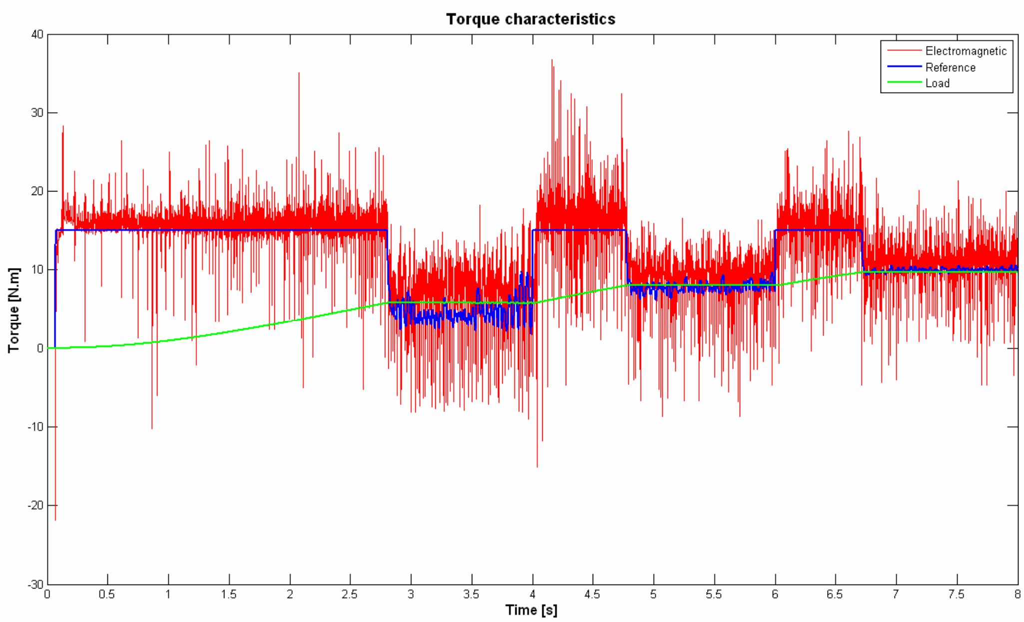

Figure 40 – Torque characteristics

APPENDIXES

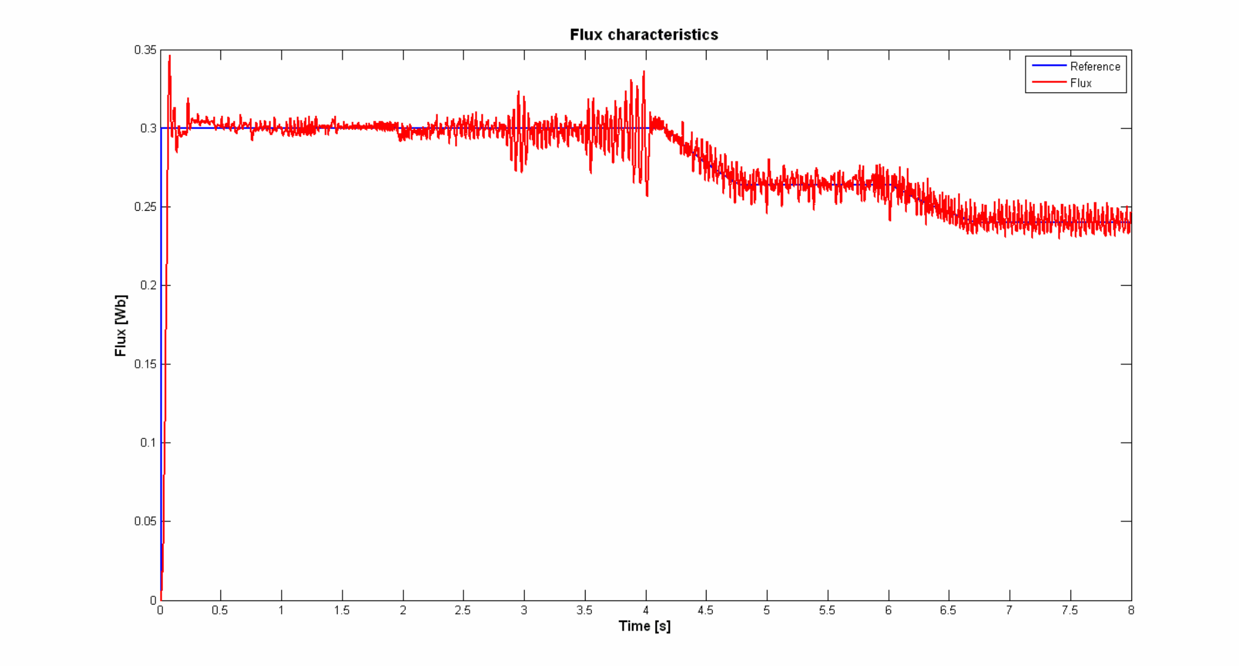

Figure 41 – Flux characteristics

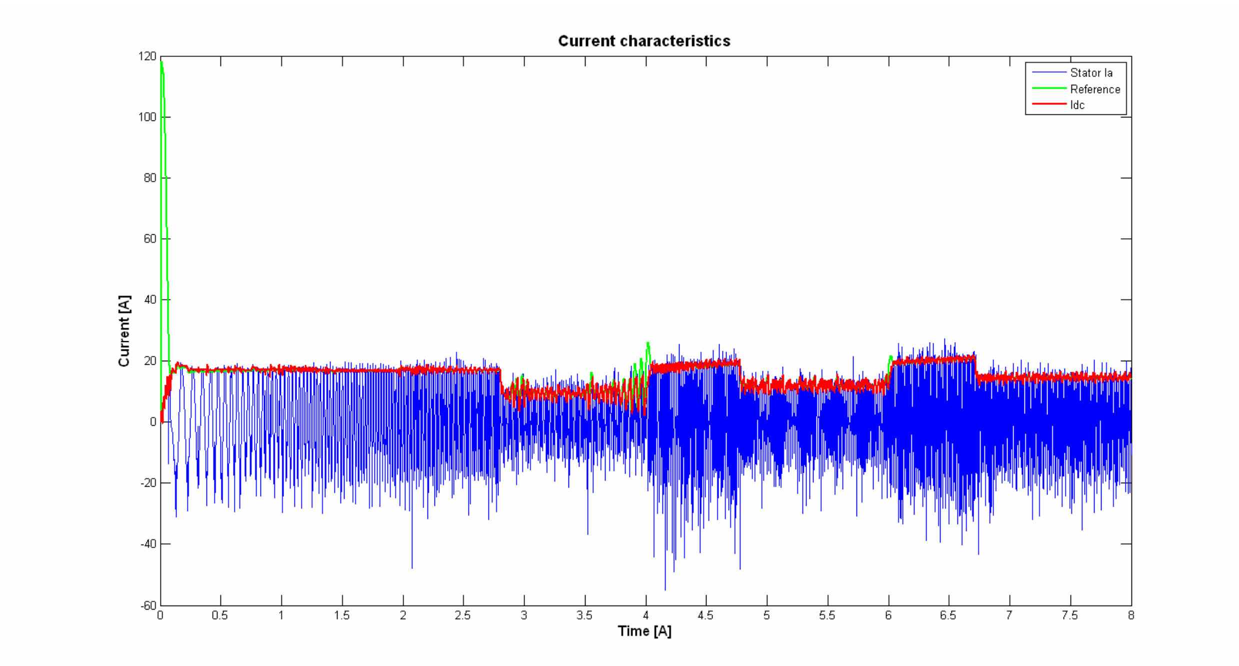

Figure 42 – Current characteristics

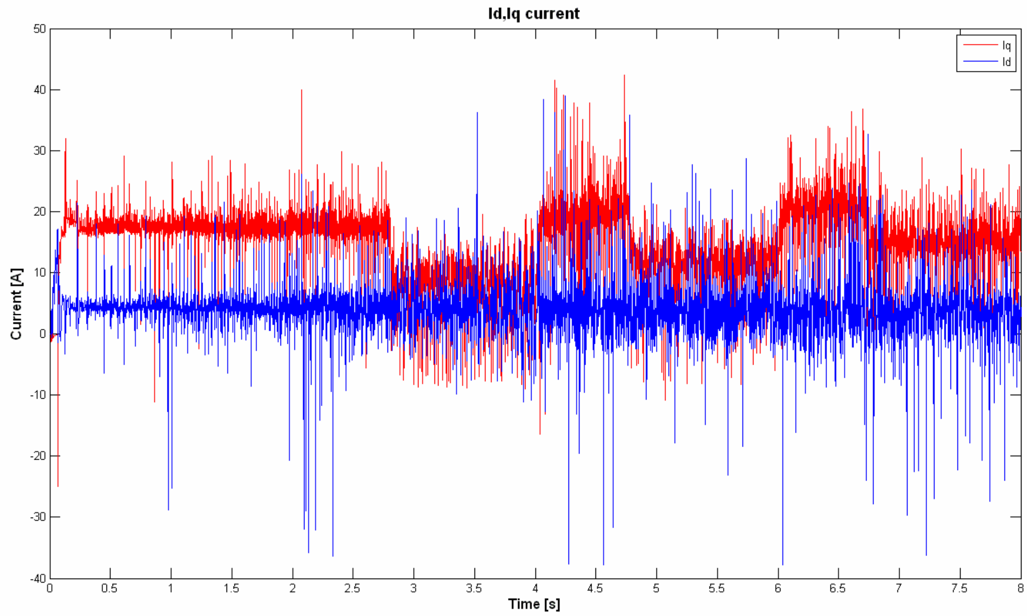

Figure 43 – I_d,I_q current

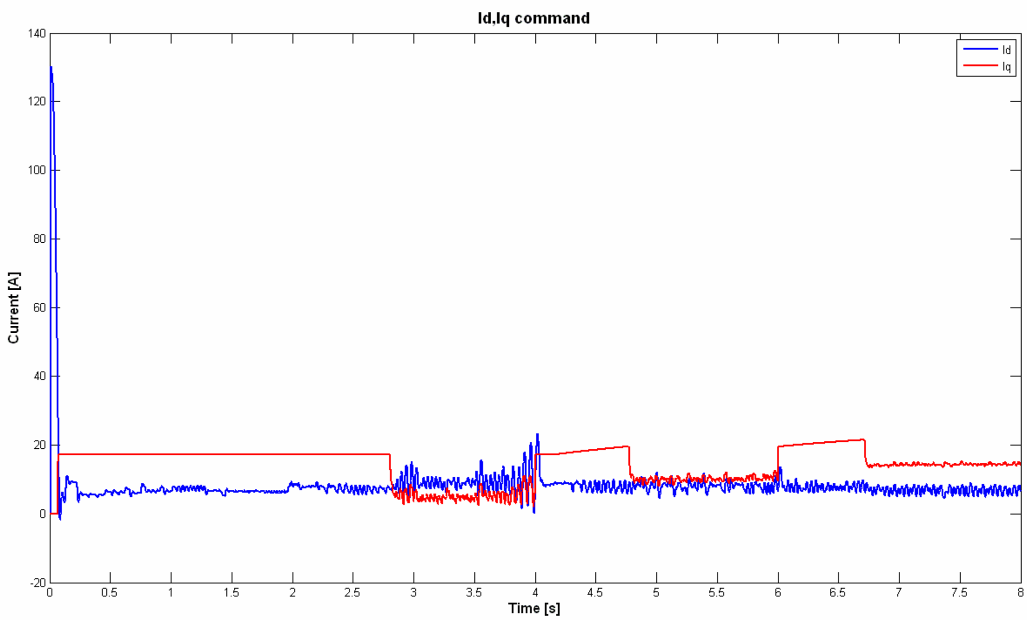

Figure 44 – I_d, I_q command

Set point [rpm]	1700	2000	2200
T_r [s]	2.374	0.69	0.636
T_s [s]	2.548	0.73	0.69
OS [%]	0.18	0.11	0.07
Steady-state error [rpm]	2	0.6	0.32
Steady-state error [%]	0.11	0.034	0.018

Table 34 – Results of the simulation

7.3.3. Comparison between the flux-constant region and the power-constant region

The frequency converters operate in two different modes- flux-constant region (below the base speed) and power-constant region (under the base speed) which are shown in Figure 45. However, PowerFlex7000 allows the flux to be set below the base speed not constant but proportional to the torque, but in majority cases the initial flux is set equal to the nominal flux (as it happens in each simulation). Above the base speed the flux is reduced resulting in lower torque and, therefore, the power is constant (speed has increased). From the previous simulation could be observed that the drive delivers nominal torque above the base speed which results in overloading the motor. As far as PowerFlex7000 is concerned the control of the torque is more complex, since there is a factory setting which defines different power modes of the operation (heavy-duty and normal-duty), which means that the motor could be overloaded but only for certain time. This is done by limiting the output current.

However, the result from the previous simulation demonstrates that when the flux decreases (see Figure 41) the torque also decreases and if the drive should deliver the nominal torque above the base speed it is necessary to overload the motor. This could be observed in Figure 44 which shows that in order to deliver the nominal torque above the base speed the I_q command has to be increased compared to I_q command below the base speed.

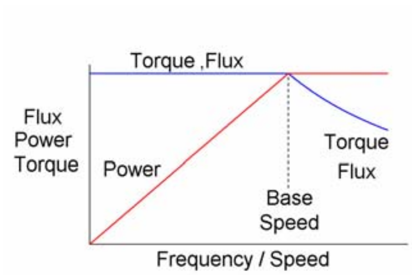

Figure 45 – Operation modes of frequency converters

7.4. Induction machine 3HP, torque regulation

There are 10 torque set points (5, 0, 1, 4, 8, 14,-5, 11, -2 and 8 N.m). This simulation should show an open loop simulation, since the speed PI regulator is to be by-passed. In order to reduce the speed there is a constant load of 4 N.m.

7.4.1. Parameters

Parameter	
Length [s]	10
Solver	ode45(Dormant-Prince)
Relative tolerance	1e-3
T_s[10][s]	1e-6

Table 35 – Parameters of the simulation

Parameter	
Mechanical input	Torque
Rotor type	Squirrel-cage
Reference frame	Rotor
Nominal power [kW]	2.238
Voltage line-line [V]	220
Stator resistance [ohm]	0.435
Stator leakage inductance [H]	2e-3
Rotor resistance [ohm]	0.816
Rotor leakage inductance [H]	2e-3
Magnetizing(mutual) inductance [H]	69.31e-3
Inertia [kg.m^2]	0.2
Friction factor [N.m.s]	0.005
Pole pairs	2

Table 36 – Parameters of the motor

Parameter	
Speed controller	
Regulation type	Torque
Controller output torque saturation [N.m] [negative, positive]	[-15,15]
Torque rate limit [N.m/s] [negative, positive]	[-10000,10000]
Flux controller	
Speed feedback – low-pass filter cut-off frequency [Hz]	100
Flux controller – flux estimation low-pass filter cut-off frequency [Hz]	16
Flux controller – proportional gain	30

[10] Model was discretized by GUI SimPowerToolbox

Flux controller – integral gain	40
Flux controller – flux limit [Wb] [negative, positive]	[-20,20]
Nominal torque [Nm]	15
Base speed [rpm]	1760
Initial flux [Wb]	0.3
Nominal flux [Wb]	0.3
Rated line voltage [V]	300
Current controller	
Current controller – proportional gain	1
Current controller – integral gain	1
Current controller – phase limit [rad] [negative, positive]	[-1,1]
Relative current limit [negative, positive]	[-1000,1000]
Current rate limit [negative, positive]	[-10000,10000]
Current feedback – low-pass filter cutoff frequency [Hz]	100
Voltage feedback – low-pass filter cutoff frequency [Hz]	1
Phase feedback – low-pass filter cutoff frequency [Hz]	8
Phase controller – proportional gain	100
Phase controller – integral gain	100
Phase controller – phase limit [rad] [negative, positive]	[-10,10]
Phase limit [deg] [lower, upper]	[0,120]
Switching frequency of vector modulator [kHz]	50
Motor model	
Initial machine flux (Wb)	0.3
Line side converter gating and feedback	
Synchronizing frequency of rectifier [Hz]	60
Pulse width of rectifier [Deg]	10
Snubber resistance of thyristors [ohm]	500
Snubber capacitance of thyristors [F]	1e-6
On-state resistance of thyristors [ohm]	1e-9
Line side converter gating and feedback	
Snubber resistance [ohm]	10
Snubber capacitance [F]	1e-6
On-state resistance [ohm]	1e-9
AC Source	
Amplitude	300
Frequency	60

Table 37 – Parameters of the frequency converter[11]

[11] Parameters regarding induction machine were set exactly the same as induction machine

7.4.2. Results

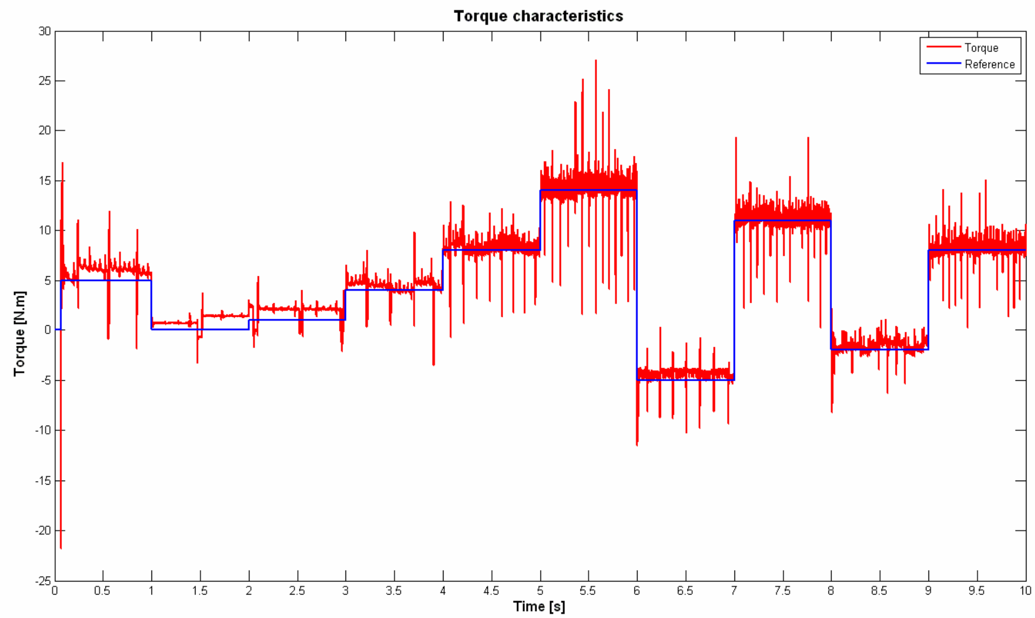

Figure 46 – Torque characteristics

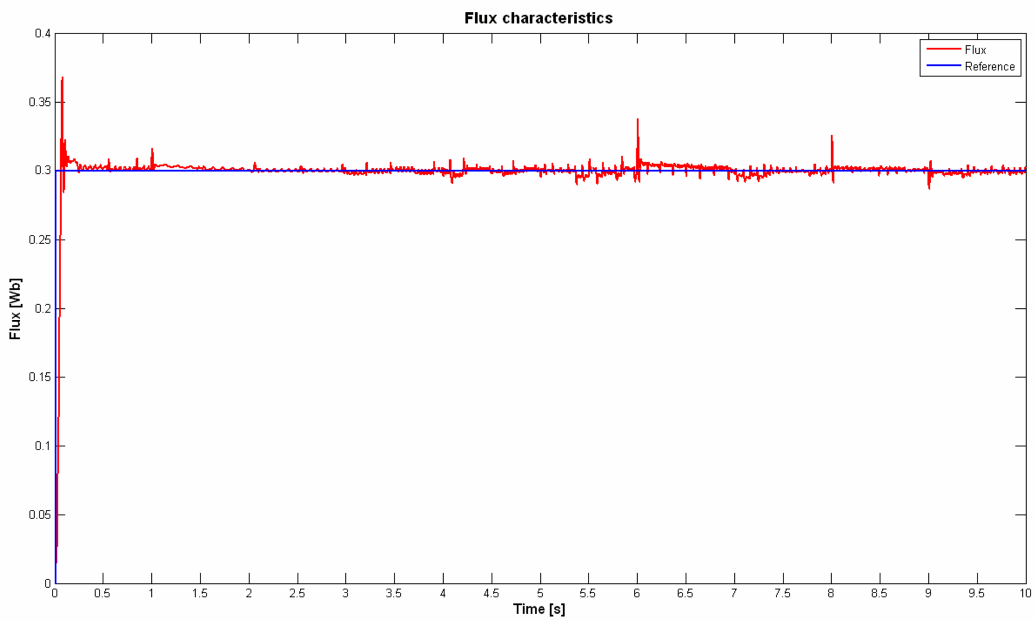

Figure 47 – Flux characteristics

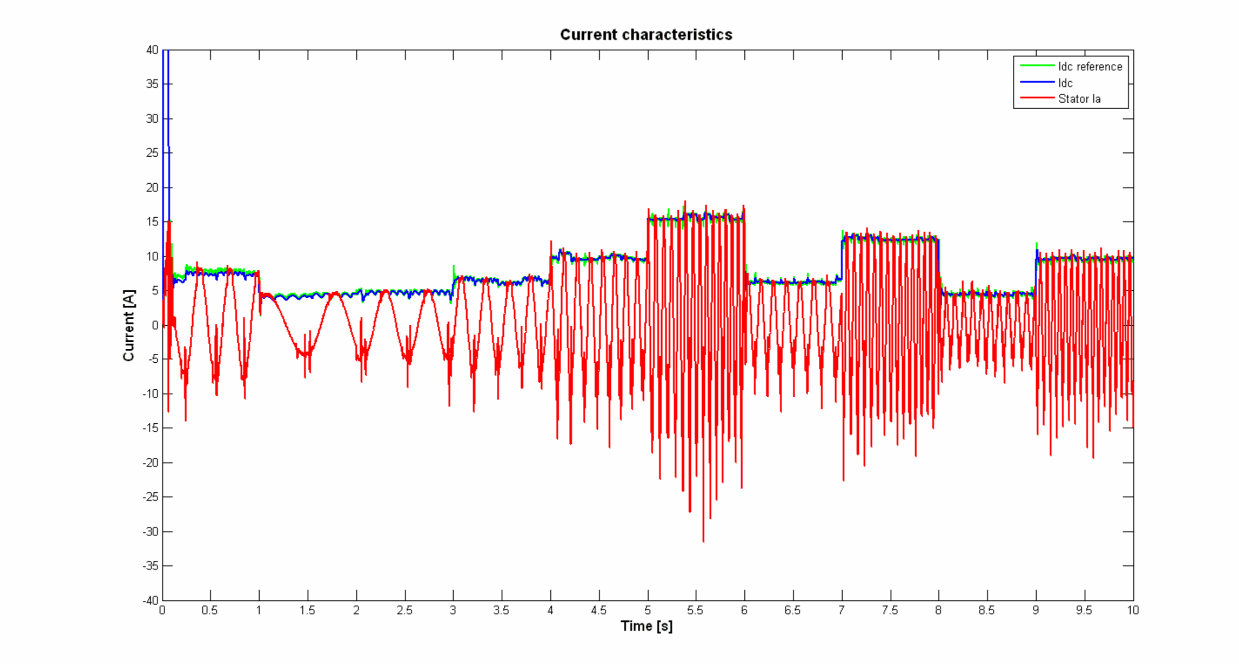

Figure 48 – Current characteristics

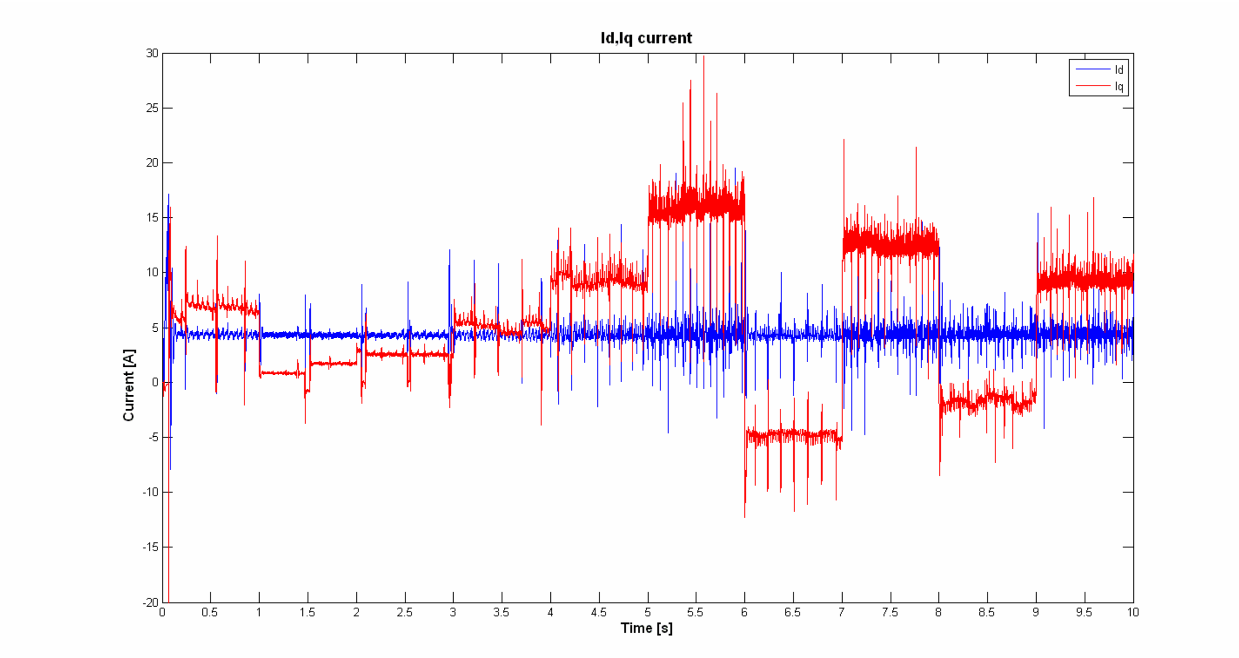

Figure 49 – I_d, I_q current

Since the torque regulation is an open loop one the accuracy is lower than when regulating the speed.

7.5. Induction machine 200HP: speed regulation below the base speed, both directions, pump type load, reaction to disturbances

There are three speed set points (-1000, 1300 and 900 rpm). The type of the load is again a pump. Moreover, in order to emulate a disturbance there is a malfunction of the pump at 5.0 s, which increases immediately the load torque by 400N.m and at 7.5s the torque drops back to the previous value. This simulation should show not only a speed regulation in both directions, but also the reaction to disturbances.

7.5.1. Parameters

Parameter	
Length [s]	20
Solver	ode45(Dormant-Prince)
Relative tolerance	1e-8
T_s[12] [s]	1e-6

Table 38 – Parameters of the simulation

Parameter	
Type	pump
K [N.m/rpm^2]	6e-4

Table 39 – Parameters of the load

Parameter	
Mechanical input	Torque
Rotor type	Squirrel-cage
Reference frame	Rotor
Nominal power [kW]	150
Voltage line-line [V]	460
Base speed [rpm]	1785
Nominal torque [N.m]	800
Frequency [Hz]	60
Stator resistance [ohm]	0.01818
Stator leakage inductance [H]	0.00019
Rotor resistance [ohm]	0.009956
Rotor leakage inductance [H]	0.00019
Magnetizing(mutual) inductance [H]	0.009415
Inertia [kg.m^2]	8
Friction factor [N.m.s]	0.04789
Pole pairs	2

[12] Model was discretized by GUI SimPowerToolbox

APPENDIXES

Table 40 – Parameters of the motor

Parameter	
Speed controller	
Regulation type	Speed
Speed controller-proportional gain	5
Speed controller-integral gain	20
Speed measurement - low-pass filter cut-off frequency [Hz]	50
Controller output torque saturation [N.m] [negative, positive]	[-1200,1200]
Torque rate limit [N.m/s] [negative, positive]	[-5000,5000]
Maximal speed [rpm]	2500
Minimal speed [rpm]	50
Speed ramp [rmp/s] [negative, positive]	[-900,900]
Flux controller	
Speed feedback – low-pass filter cut-off frequency [Hz]	100
Flux controller - flux estimation low-pass filter cut-off frequency [Hz]	16
Flux controller - proportional gain	100
Flux controller - integral gain	30
Flux controller - flux limit [Wb] [negative, positive]	[-2,2]
Nominal torque [Nm]	1200
Base speed [rpm]	1785
Initial flux [Wb]	0.73
Nominal flux [Wb]	0.73
Rated line voltage [V]	500
Current controller	
Current controller - proportional gain	1
Current controller - integral gain	1
Current controller - phase limit [rad] [negative, positive]	[-1,1]
Relative current limit [negative, positive]	[-100,100]
Current rate limit [negative, positive]	[-1000,1000]
Current feedback – low-pass filter cutoff frequency [Hz]	100
Voltage feedback – low-pass filter cutoff frequency [Hz]	1
Phase feedback – low-pass filter cutoff frequency [Hz]	10
Phase controller - proportional gain	100
Phase controller - integral gain	100
Phase controller - phase limit [rad] [negative, positive]	[-10,10]
Alpha line [deg] [lower, upper]	[0.01,180]

Switching frequency of vector modulator [kHz]	50
Motor model	
Initial machine flux (Wb)	0.73
Line side converter gating and feedback	
Synchronizing frequency of rectifier [Hz]	60
Pulse width of rectifier [Deg]	10
Snubber resistance of thyristors [ohm]	500
Snubber capacitance of thyristors [F]	1e-6
On-state resistance of thyristors [ohm]	1e-9
Line side converter gating and feedback	
Snubber resistance [ohm]	1
Snubber capacitance [F]	1e-5
On-state resistance [ohm]	1e-9
AC Source	
Amplitude	500
Frequency	60
DC link	
Inductance [H]	0.25
Resistance [ohm]	0.5

Table 41 – Parameters of the frequency converter[13]

[13] Parameters regarding induction machine were set exactly the same as the induction machine

7.5.2. Results

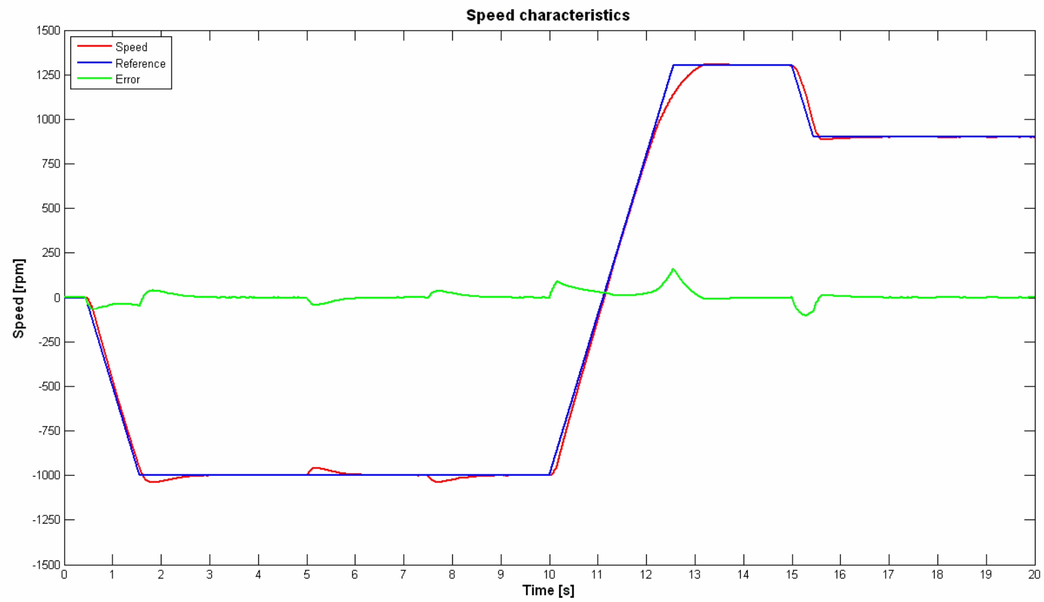

Figure 50 – Speed characteristics

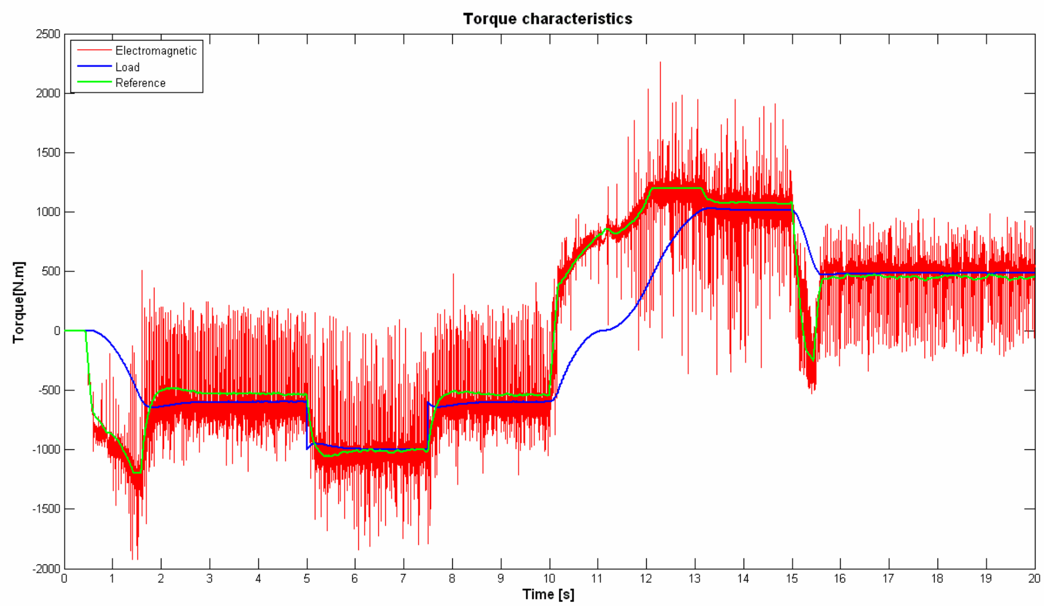

Figure 51 – Torque characteristics

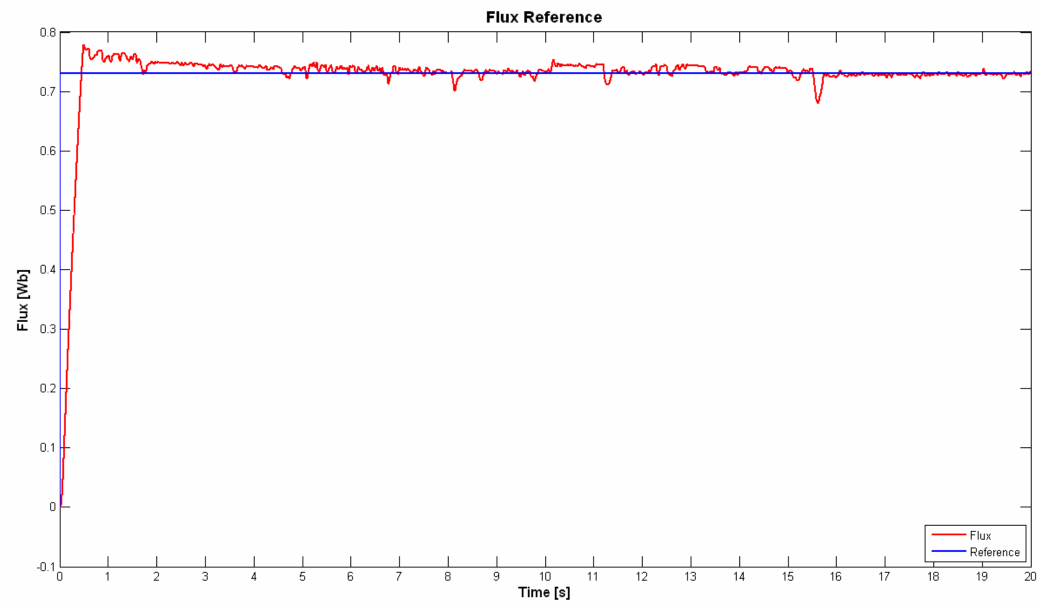

Figure 52 – Flux characteristics

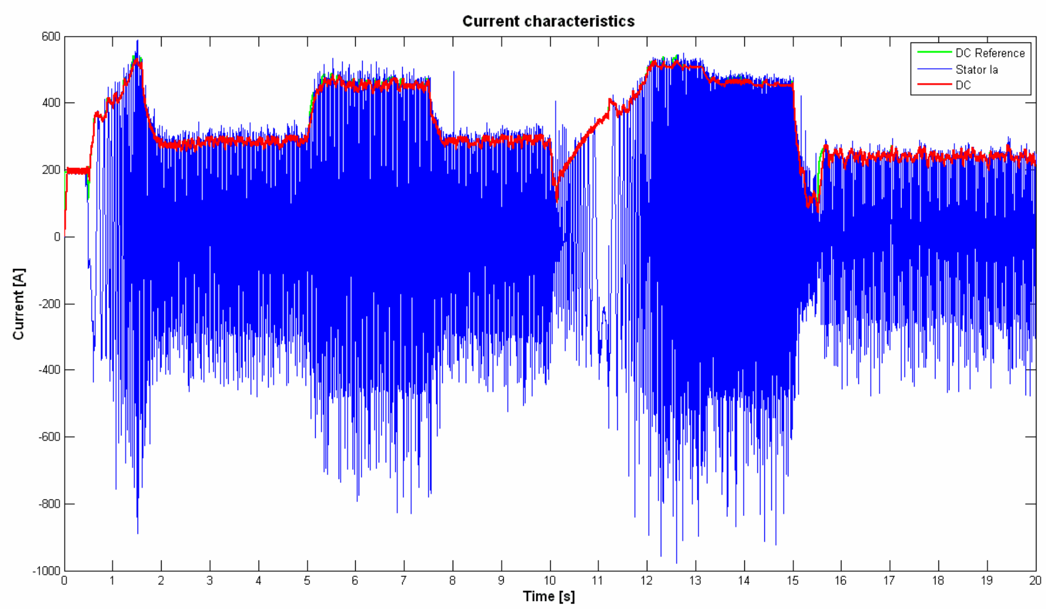

Figure 53 – Current characteristics

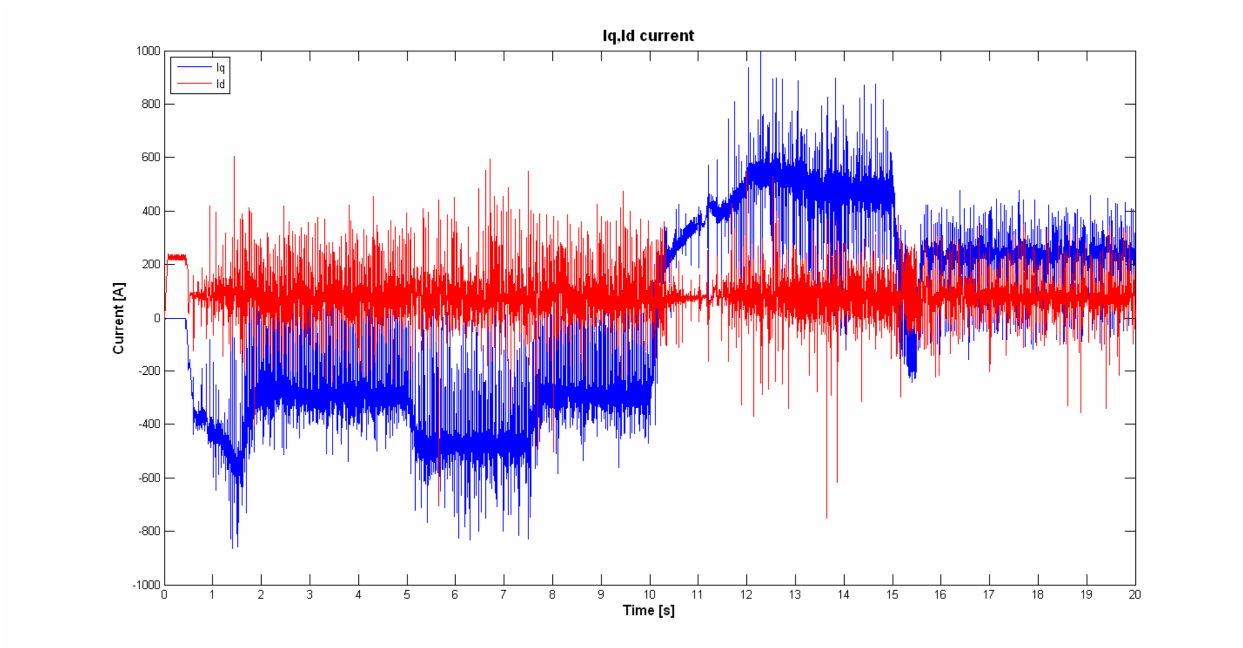

Figure 54 – I_d,I_q characteristics

Set point [rpm]	**-1000**	**1300**	**900**
T_r [s]	1.043	2.41	0.48
T_s [s]	1.793	2.99	0.52
OS [%]	4	1	1.7
Steady-state error [rpm]	1.6	1	1.7
Steady-state error [%]	0.1	0.06	0.1

Table 42 – Results of the simulation

7.5.3. Reaction to disturbances

It could be observed that even the disturbances were significant (50% of the nominal torque); the frequency converter coped well and was able to recover the steady state speed within 1000ms. Furthermore, the overshot was minimal.

7.6. Induction machine 200HP: speed regulation above the base speed, one direction, pump type load

There are three speed set points (1700, 2000 and 2200 rpm). The type of the load is again a pump. This simulation should show how the model behaves above the base speed, which means how the flux changes, torque changes and, consequently, how the speed is affected by these changes.

7.6.1. Parameters

Parameter	
Length [s]	13
Solver	ode45(Dormant-Prince)
Relative tolerance	1e-8
T_s[14] [s]	1e-6

Table 43 – Parameters of the simulation

Parameter	
Type	pump
K [N.m/rpm^2]	16e-5

Table 44 – Parameters of the load

Parameter	
Mechanical input	Torque
Rotor type	Squirrel-cage
Reference frame	Rotor
Nominal power [kW]	150
Voltage line-line [V]	460
Base speed [rpm]	1785
Nominal torque [N.m]	800
Frequency [Hz]	60
Stator resistance [ohm]	0.01818
Stator leakage inductance [H]	0.00019
Rotor resistance [ohm]	0.009956
Rotor leakage inductance [H]	0.00019
Magnetizing(mutual) inductance [H]	0.009415
Inertia [kg.m^2]	8
Friction factor [N.m.s]	0.04789
Pole pairs	2

[14] Model was discretized by GUI SimPowerToolbox

APPENDIXES

Table 45 – Parameters of the motor

Parameter	
Speed controller	
Regulation type	Speed
Speed controller-proportional gain	5
Speed controller-integral gain	20
Speed measurement – low-pass filter cut-off frequency [Hz]	50
Controller output torque saturation [N.m] [negative, positive]	[-1200,1200]
Torque rate limit [N.m/s] [negative, positive]	[-5000,5000]
Maximal speed [rpm]	2500
Minimal speed [rpm]	50
Speed ramp [rmp/s] [negative, positive]	[-900,900]
Flux controller	
Speed feedback – low-pass filter cut-off frequency [Hz]	100
Flux controller - flux estimation low-pass filter cut-off frequency [Hz]	16
Flux controller - proportional gain	100
Flux controller - integral gain	30
Flux controller - flux limit [Wb] [negative, positive]	[-2,2]
Nominal torque [Nm]	1200
Base speed [rpm]	1785
Initial flux [Wb]	0.73
Nominal flux [Wb]	0.73
Rated line voltage [V]	500
Current controller	
Current controller - proportional gain	1
Current controller - integral gain	1
Current controller – phase limit [rad] [negative, positive]	[-1,1]
Relative current limit [negative, positive]	[-100,100]
Current rate limit [negative, positive]	[-1000,1000]
Current feedback – low-pass filter cutoff frequency [Hz]	100
Voltage feedback – low-pass filter cutoff frequency [Hz]	1
Phase feedback – low-pass filter cutoff frequency [Hz]	10
Phase controller - proportional gain	100
Phase controller – integral gain	100

Phase controller - phase limit [rad] [negative, positive]	[-10,10]
Alpha line [deg] [lower, upper]	[0.01,180]
Switching frequency of vector modulator [kHz]	50
Motor model	
Initial machine flux (Wb)	0.73
Line side converter gating and feedback	
Synchronizing frequency of rectifier [Hz]	60
Pulse width of rectifier [deg]	10
Snubber resistance of thyristors [ohm]	500
Snubber capacitance of thyristors [F]	1e-6
On-state resistance of thyristors [ohm]	1e-9
Line side converter gating and feedback	
Snubber resistance [ohm]	1
Snubber capacitance [F]	1e-5
On-state resistance [ohm]	1e-9
AC Source	
Amplitude	500
Frequency	60
DC link	
Inductance [H]	0.25
Resistance [ohm]	0.5

Table 46 – Parameters of the frequency converter[15]

[15] Parameters regarding induction machine were set exactly the same as the induction machine

7.6.2. Results

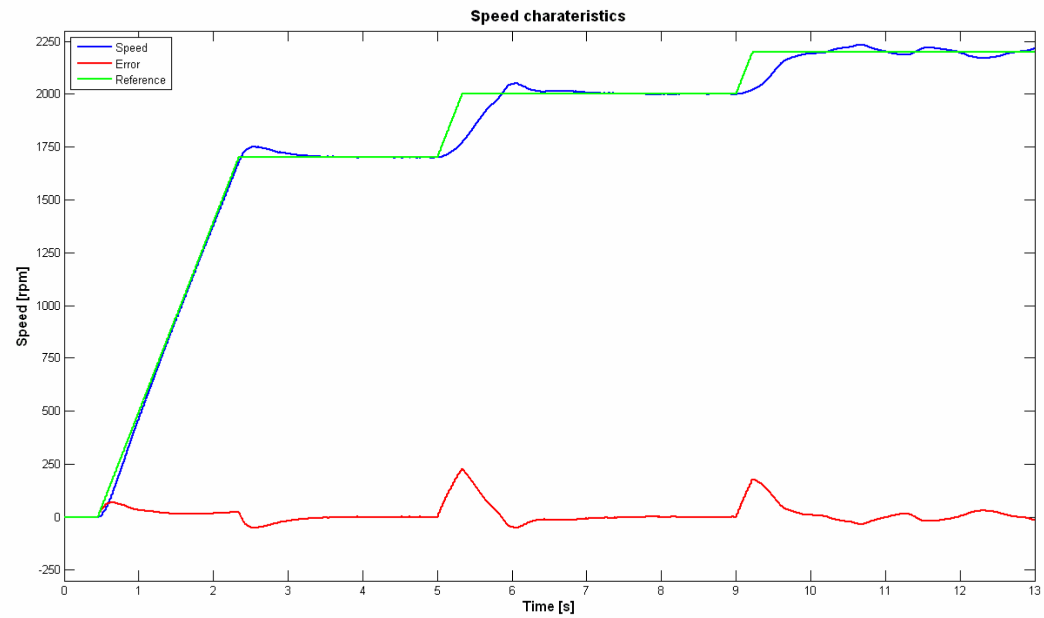

Figure 55 – Speed characteristics

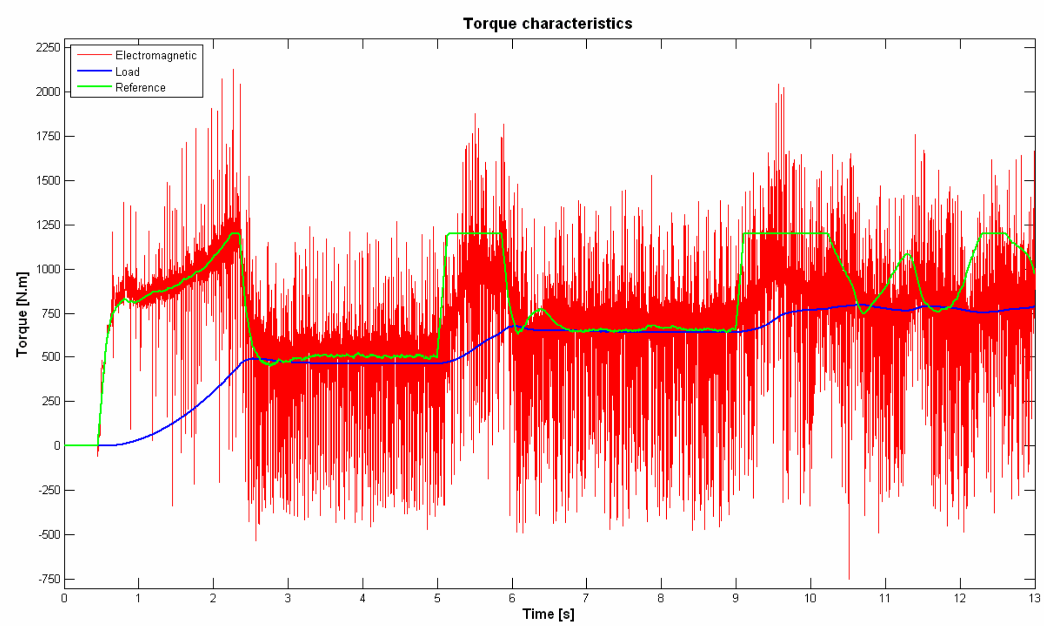

Figure 56 – Torque characteristics

APPENDIXES

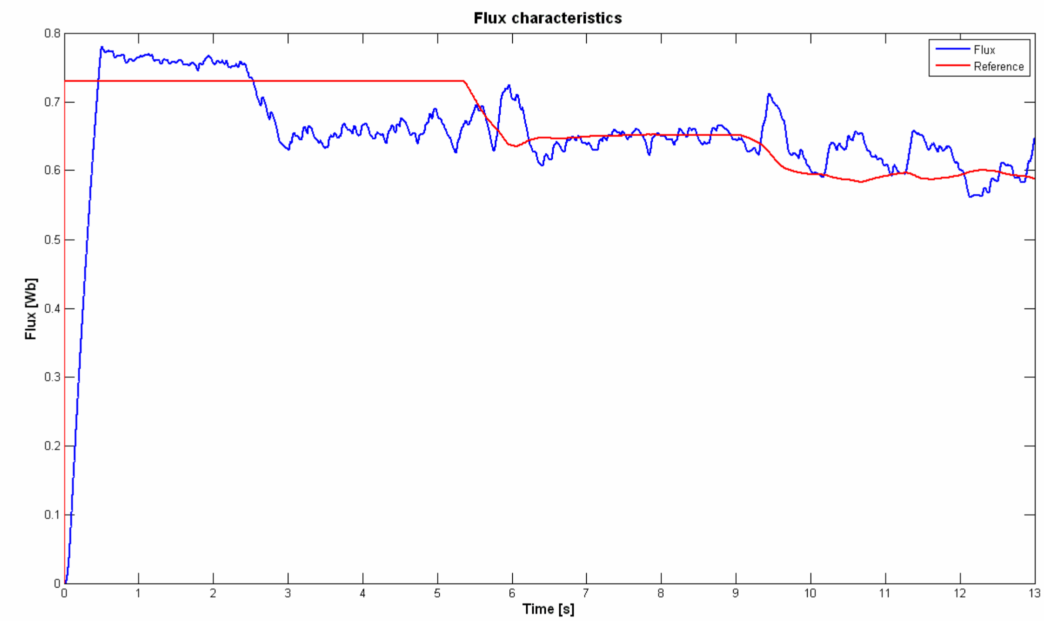

Figure 57 – Flux characteristics

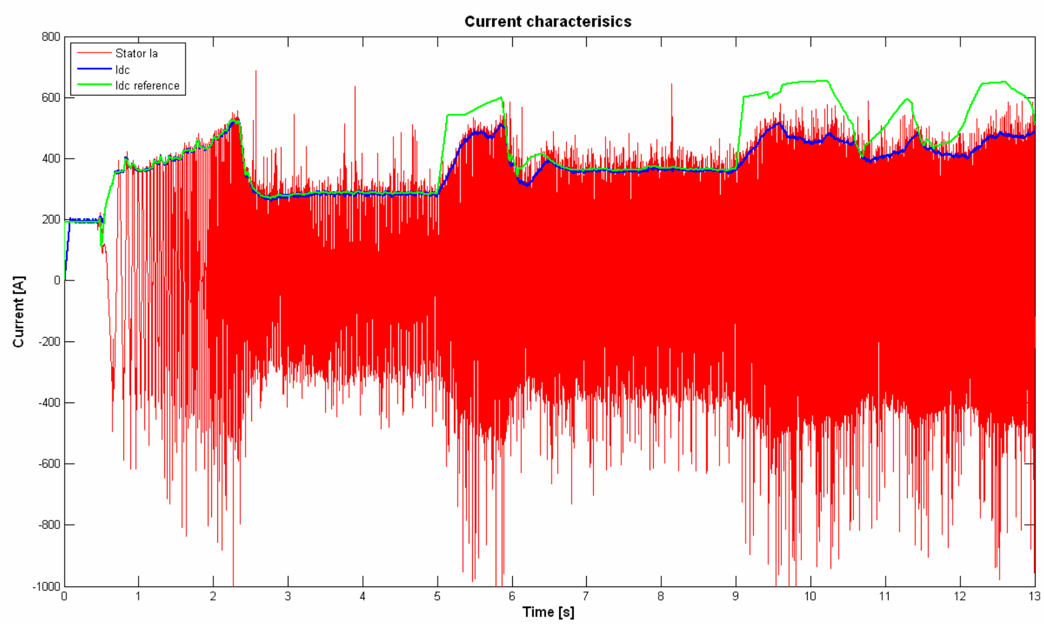

Figure 58 – Current characteristics

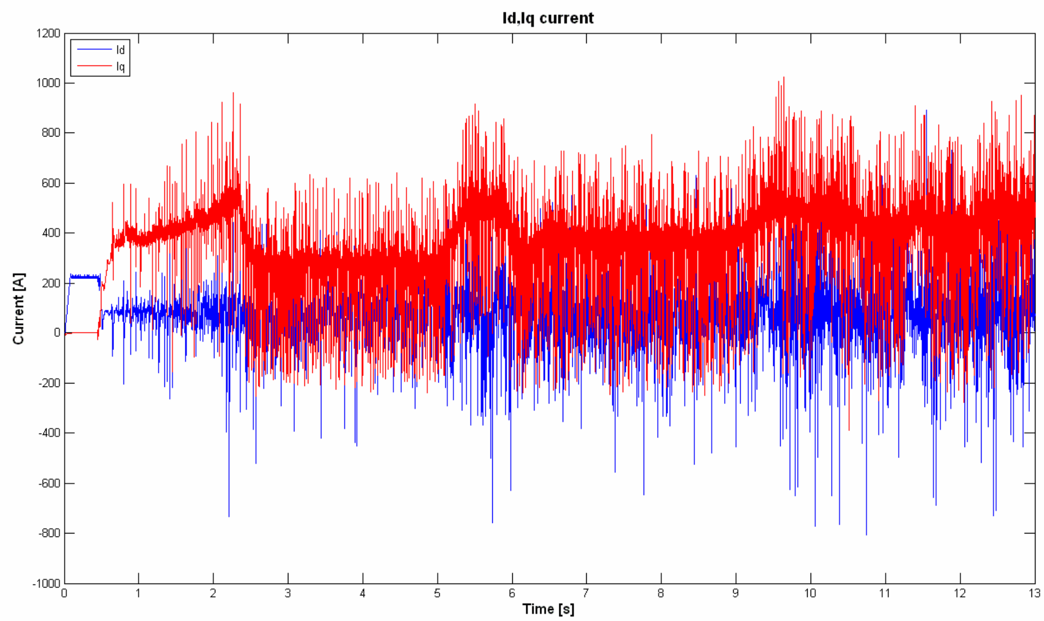

Figure 59 – I_d,I_q characteristics

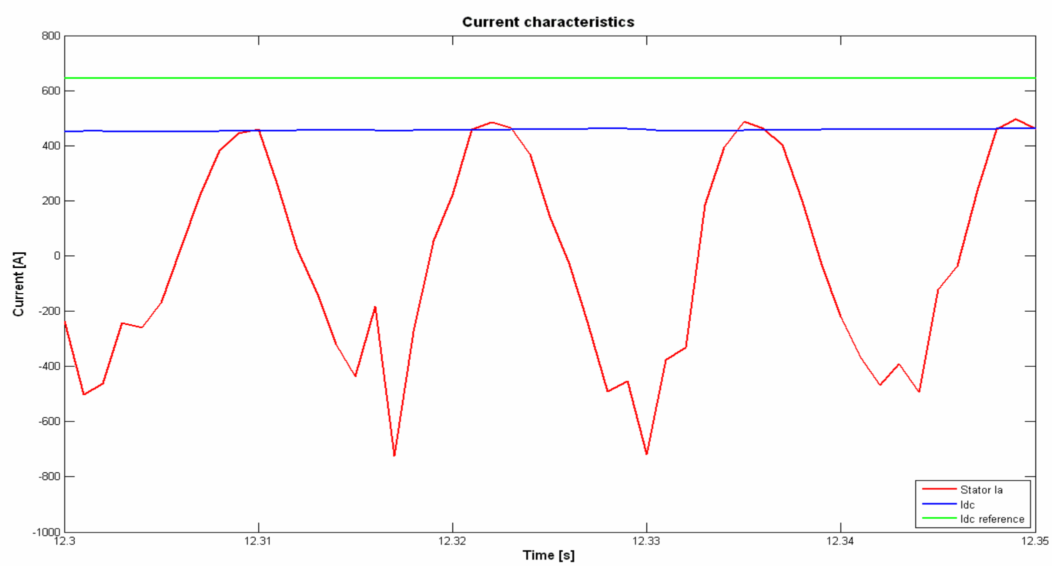

Figure 60 – Current at full speed

Set point [rpm]	**1700**	**2000**	**2200**
T_r [s]	1.69	0.79	-
T_s [s]	1.83	1.146	-
OS [%]	3	17	-
Steady-state error [rpm]	2	2	-
Steady-state error [%]	0.11	0.12	-

Table 47 – Results of the simulation

It could be observed that above the speed of 2000rpm, the frequency converter is not able to follow the reference. The reason is that DC link is not capable of delivering the reference current (see Figure 58). Figure 60 shows the stator current at full speed. It is obvious (compare with Figure 32) that at higher speeds the stator current is more sinusoidal since as the speed increases the ability of the stator windings of smoothing the stator current improves ($\frac{L_s / R_s}{f^{-1}}$ is higher, f is the frequency of the drive).

7.7. Induction machine 200HP: heavy duty start-up, traction type load, comparison of the start-up of induction machines with scalar frequency converters, vector frequency converters and the start-up of DC motors

This simulation should demonstrate that the vector frequency converters are capable of delivering breakaway torque of 150% of the nominal one.

In this simulation I will use traction type of the load (e.g. locomotive). The typical feature of this load is very high breakaway torque, but almost constant running torque. This simulation models only simplified model of the locomotive; it does not take into account the fact that since the motor is connected to the locomotive by the gear-box it produces the force which makes the train accelerate. At the same time the speed of the train determines the speed of the motor and due to the high weight of the train the acceleration would last much longer than in the simulation. The traction type of the load was modeled as follows:

$T_l = \frac{780}{v} + 400$ [N.m], where the speed of the motor was limited to: $v \in \langle 1{,}100 \rangle$ [rpm]

7.7.1. Parameters

Parameter	
Length [s]	3
Solver	ode45(Dormant-Prince)
Relative tolerance	1e-8
T_s[16][s]	1e-6

Table 48 – Parameters of the simulation

Parameter	
Mechanical input	Torque
Rotor type	Squirrel-cage
Reference frame	Rotor
Nominal power [kW]	150
Voltage line-line [V]	460
Base speed [rpm]	1785
Nominal torque [N.m]	800
Frequency [Hz]	60
Stator resistance [ohm]	0.01818
Stator leakage inductance [H]	0.00019
Rotor resistance [ohm]	0.009956
Rotor leakage inductance [H]	0.00019
Magnetizing(mutual) inductance [H]	0.009415
Inertia [kg.m^2]	40
Friction factor [N.m.s]	0.04789
Pole pairs	2

Table 49 – Parameters of the motor

Parameter	
Speed controller	
Regulation type	Speed
Speed controller-proportional gain	20
Speed controller-integral gain	20
Speed measurement – low-pass filter cut-off frequency [Hz]	50
Controller output torque saturation [N.m] [negative, positive]	[-1200,1200]
Torque rate limit [N.m/s] [negative, positive]	[-50000,50000]
Maximal speed [rpm]	2500
Minimal speed [rpm]	50
Speed ramp [rmp/s] [negative, positive]	[-10000,10000]
Flux controller	
Speed feedback – low-pass filter cut-off frequency [Hz]	100

[16] Model was discretized by GUI SimPowerToolbox

Flux controller - flux estimation low-pass filter cut-off frequency [Hz]	16
Flux controller - proportional gain	100
Flux controller - integral gain	30
Flux controller - flux limit [Wb] [negative, positive]	[-2,2]
Nominal torque [Nm]	1200
Base speed [rpm]	1785
Initial flux [Wb]	0.73
Nominal flux [Wb]	0.73
Rated line voltage [V]	500
Current controller	
Current controller - proportional gain	1
Current controller - integral gain	1
Current controller – phase limit [rad] [negative, positive]	[-1,1]
Relative current limit [negative, positive]	[-100,100]
Current rate limit [negative, positive]	[-1000,1000]
Current feedback – low-pass filter cutoff frequency [Hz]	100
Voltage feedback – low-pass filter cutoff frequency [Hz]	1
Phase feedback – low-pass filter cutoff frequency [Hz]	10
Phase controller - proportional gain	100
Phase controller – integral gain	100
Phase controller - phase limit [rad] [negative, positive]	[-10,10]
Alpha line [deg] [lower, upper]	[0.01,180]
Switching frequency of vector modulator [kHz]	50
Motor model	
Initial machine flux (Wb)	0.73
Line side converter gating and feedback	
Synchronizing frequency of rectifier [Hz]	60
Pulse width of rectifier [deg]	10
Snubber resistance of thyristors [ohm]	500
Snubber capacitance of thyristors [F]	1e-6
On-state resistance of thyristors [ohm]	1e-9
Line side converter gating and feedback	
Snubber resistance [ohm]	1
Snubber capacitance [F]	1e-5
On-state resistance [ohm]	1e-9
AC Source	
Amplitude	500
Frequency	60
DC link	
Inductance [H]	0.25
Resistance [ohm]	0.5

Table 50 – Parameters of the frequency converter[17]

[17] Parameters regarding induction machine were set exactly the same as the induction machine

7.7.2. Results

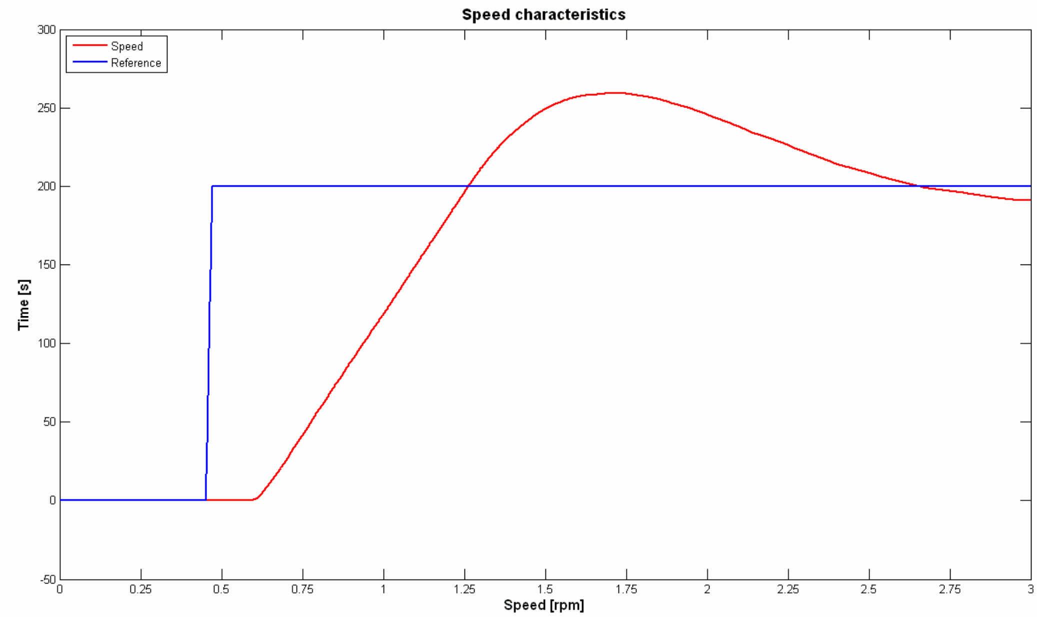

Figure 61 – Speed characteristics

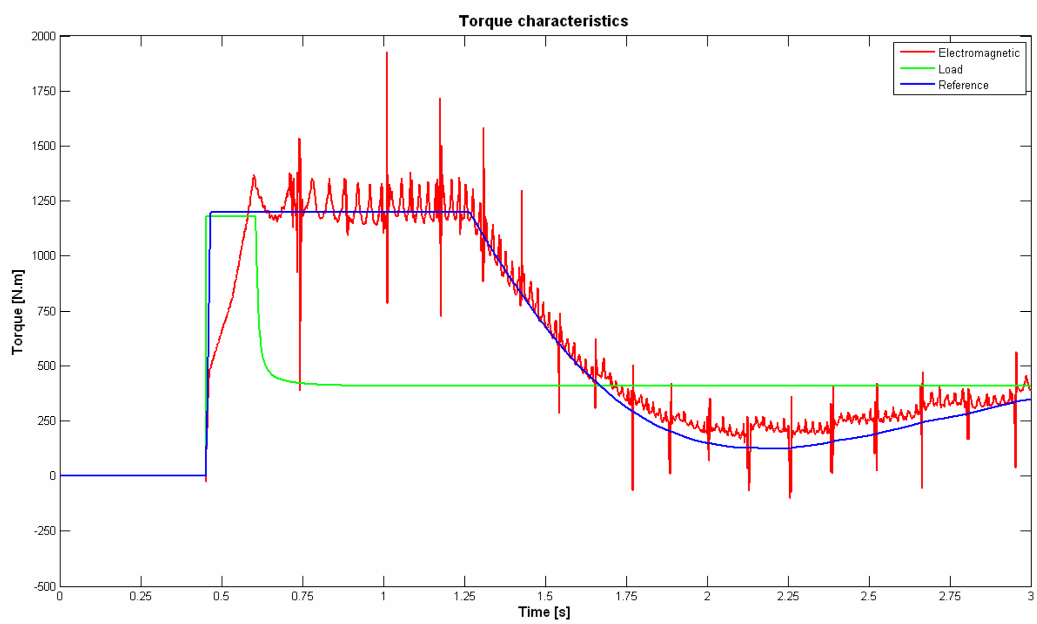

Figure 62 – Torque characteristics

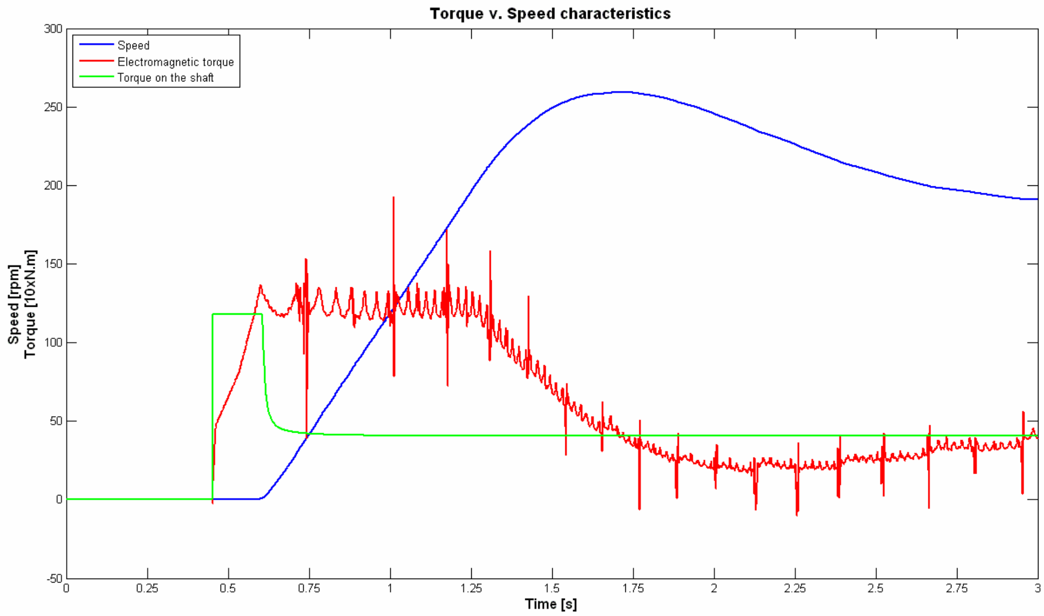

Figure 63 – Torque v Speed

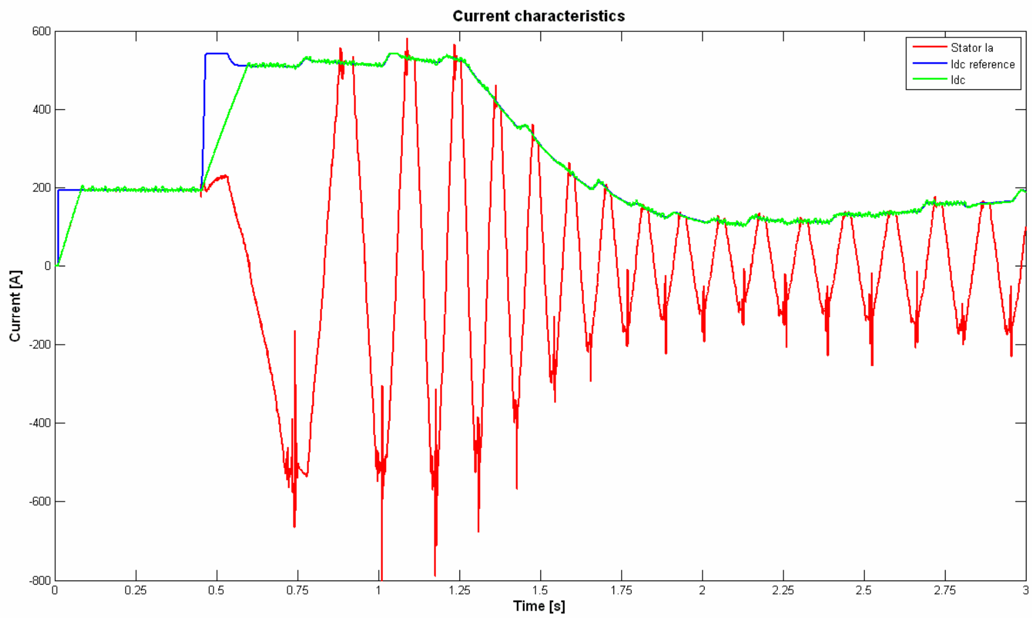

Figure 64 – Current characteristics

7.7.3. Comparison of the start-up of induction machines with scalar frequency converters, vector frequency converters and the start-up of DC motors

This simulation (see Figure 62) has shown that the induction machine controlled by the vector frequency converter is able to deliver 150 % breakaway torque. This feature is significant advantage over scalar frequency converters, which speed-torque characteristics is shown in Figure 65. Vector control enables induction machines to be used in traction and, hence, nowadays trend is to replace DC series excitation motors (high breakaway torque) by induction machines. The best examples of this trend are suburban train 471 and pendolino.

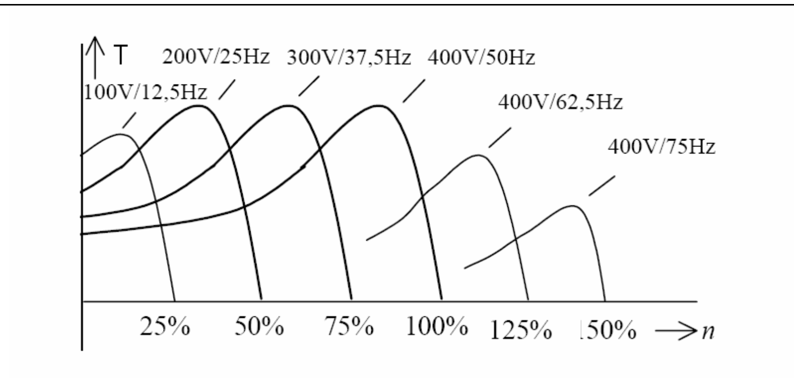

Figure 65 – Speed/Torque characteristic of scalar frequency converters

7.8. Induction machine 200HP: torque regulation

Let us imagine this situation. We are supposed to control the power of a coil power plant. There is a coil conveyor, which load varies in an unpredictable way. So the amount of coil and, therefore, the power could be controlled by changing the torque of the coil conveyor (P=kM).

7.8.1. Parameters

Parameter	
Length [s]	10
Solver	ode45(Dormant-Prince)
Relative tolerance	1e-8
T_s[18][s]	1e-6

Table 51 – Parameters of the simulation

Parameter	
Mechanical input	Torque
Rotor type	Squirrel-cage
Reference frame	Rotor
Nominal power [kW]	150
Voltage line-line [V]	460
Base speed [rpm]	1785
Frequency [Hz]	60
Stator resistance [ohm]	0.01818
Stator leakage inductance [H]	0.00019
Rotor resistance [ohm]	0.009956
Rotor leakage inductance [H]	0.00019
Magnetizing(mutual) inductance [H]	0.009415
Inertia [kg.m^2]	8
Friction factor [N.m.s]	0.04789
Pole pairs	2

Table 52 – Parameters of the motor

Parameter	
Speed controller	
Regulation type	Torque
Controller output torque saturation [N.m] [negative, positive]	[-1200,1200]
Torque rate limit [N.m/s] [negative, positive]	[-5000,5000]
Flux controller	
Speed feedback – low-pass filter cut-off frequency [Hz]	100
Flux controller - flux estimation low-pass filter cut-off frequency [Hz]	16
Flux controller - proportional gain	100
Flux controller - integral gain	30
Flux controller - flux limit [Wb] [negative, positive]	[-2,2]
Nominal torque [Nm]	1200
Base speed [rpm]	1785
Initial flux [Wb]	0.73

[18] Model was discretized by GUI SimPowerToolbox

Nominal flux [Wb]	0.73
Rated line voltage [V]	500
Current controller	
Current controller - proportional gain	1
Current controller - integral gain	1
Current controller - phase limit [rad] [negative, positive]	[-1,1]
Relative current limit [negative, positive]	[-100,100]
Current rate limit [negative, positive]	[-1000,1000]
Current feedback – low-pass filter cutoff frequency [Hz]	100
Voltage feedback – low-pass filter cutoff frequency [Hz]	1
Phase feedback – low-pass filter cutoff frequency [Hz]	10
Phase controller - proportional gain	100
Phase controller - integral gain	100
Phase controller - phase limit [rad] [negative, positive]	[-10,10]
Alpha line [deg] [lower, upper]	[0.01,180]
Switching frequency of vector modulator [kHz]	50
Motor model	
Initial machine flux (Wb)	0.73
Line side converter gating and feedback	
Synchronizing frequency of rectifier [Hz]	60
Pulse width of rectifier [Deg]	10
Snubber resistance of thyristors [ohm]	500
Snubber capacitance of thyristors [F]	1e-6
On-state resistance of thyristors [ohm]	1e-9
Line side converter gating and feedback	
Snubber resistance [ohm]	1
Snubber capacitance [F]	1e-5
On-state resistance [ohm]	1e-9
AC Source	
Amplitude	500
Frequency	60
DC link	
Inductance [H]	0.25
Resistance [ohm]	0.5

Table 53 – Parameters of the frequency converter[19]

[19] Parameters regarding induction machine were set exactly the same as the induction machine

7.8.2. Results

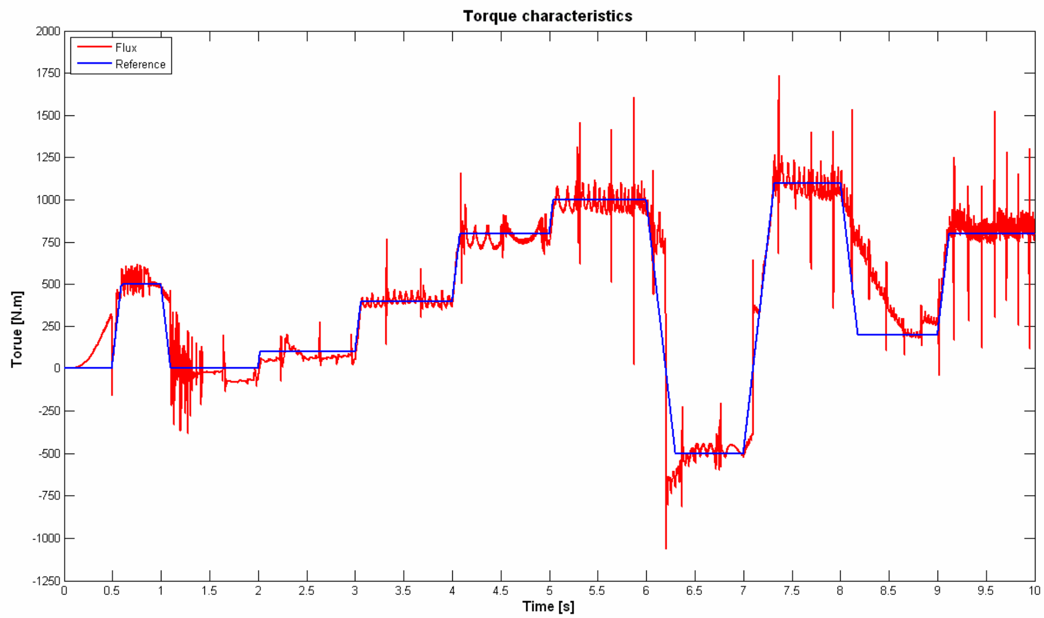

Figure 66 – Torque characteristics

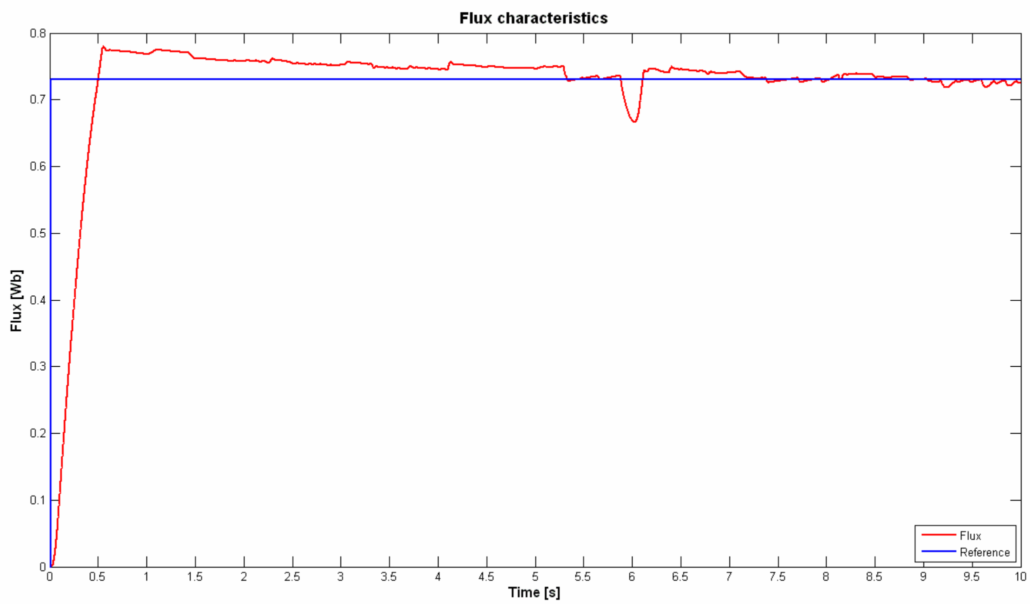

Figure 67 – Flux characteristics

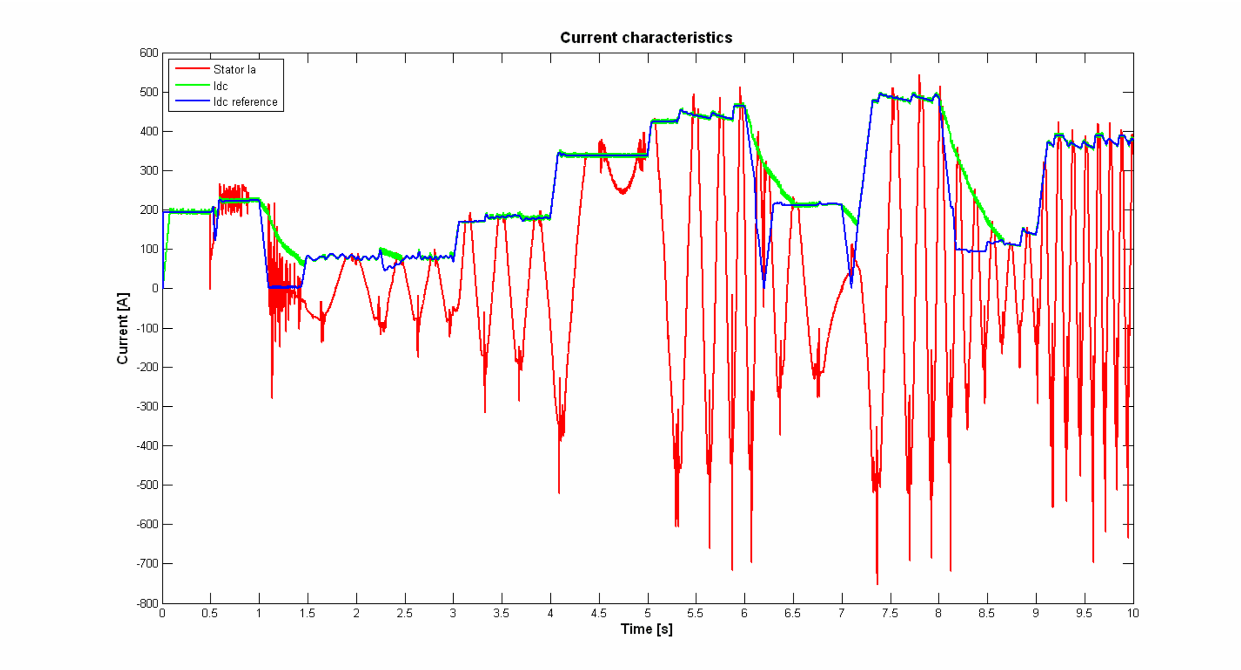

Figure 68 – Current characteristics

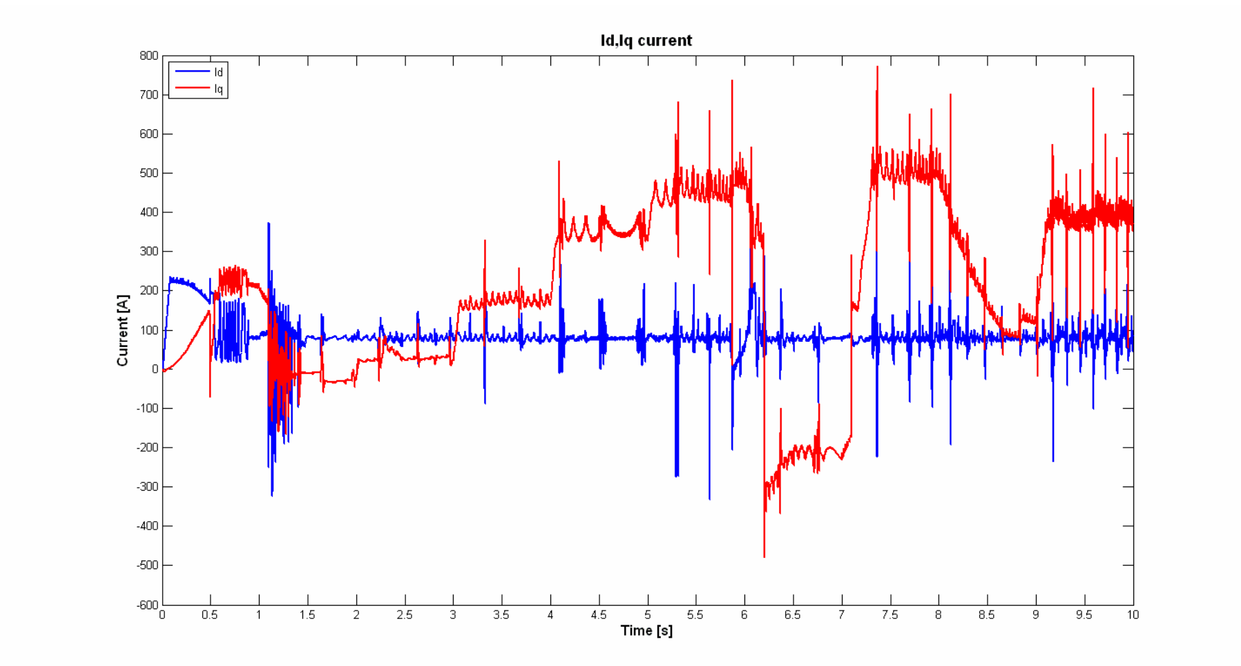

Figure 69 – I_d,I_q current

7.9. Induction machine 200HP: torque regulation, uncertainty in all parameters

This simulation and the following one should point out the disadvantage of vector converters – sensitiveness to uncertainties in motor parameters. Since during the operation the parameters of the motor could change, I will perform two simulations. In the first simulation I will set motor parameters used in the frequency converter to 150% of the nominal motor parameters. The others parameters of the simulation are exactly the same as in simulation 5.8.

Since it is more likely that only some parameters change (e.g. resistance varies with temperature), in second simulation I will set only motor resistances used in the frequency converter to 150% of the nominal motor resistance. The others parameters of the simulation are exactly the same as in simulation 5.8.

7.9.1. Results

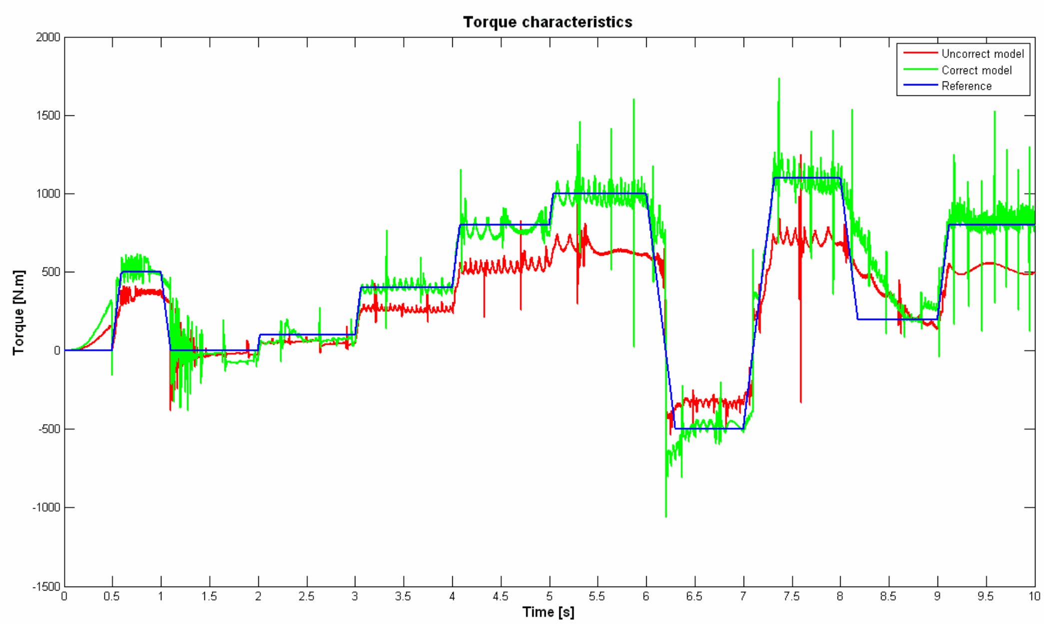

Figure 70 – Torque characteristics

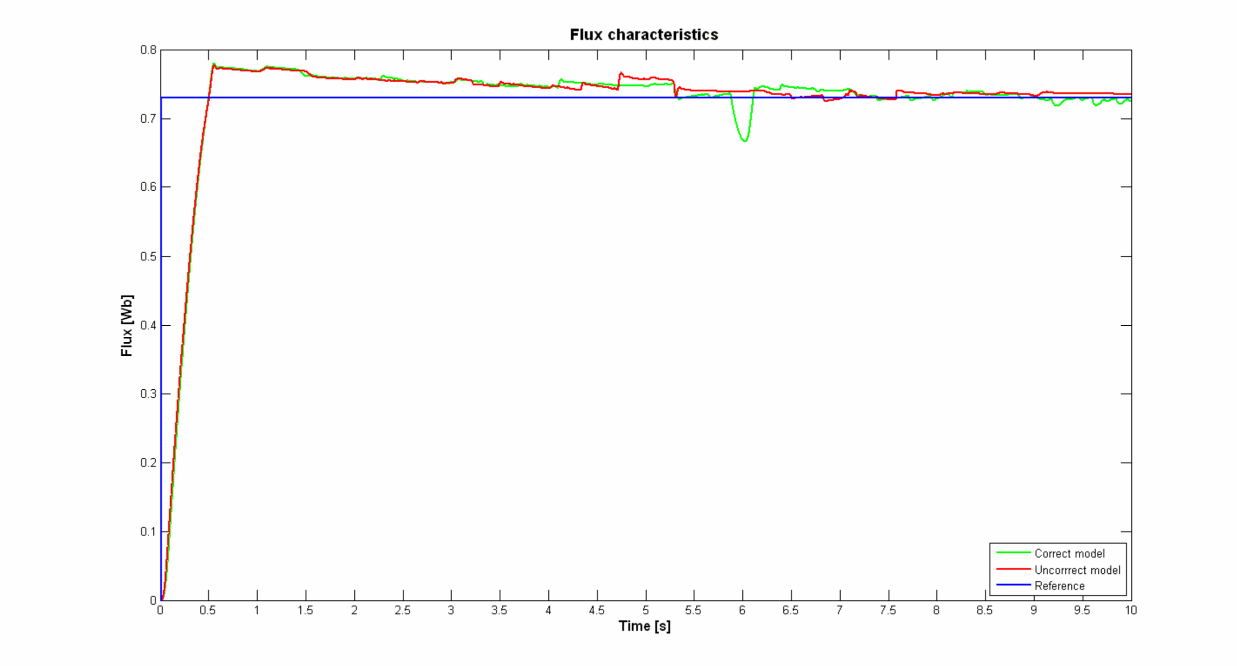

Figure 71 – Flux characteristics

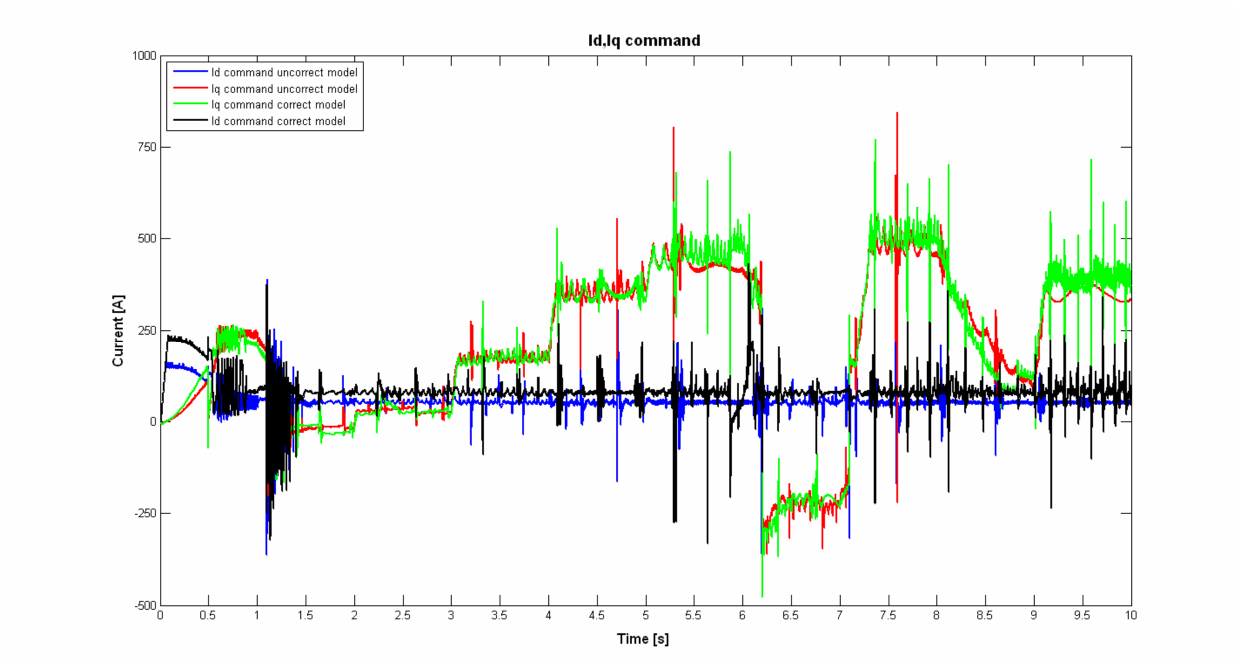

Figure 72 – I_d,I_q current

7.10. Induction machine 200HP: torque regulation, uncertainty in one parameter

7.10.1. Results

APPENDIXES

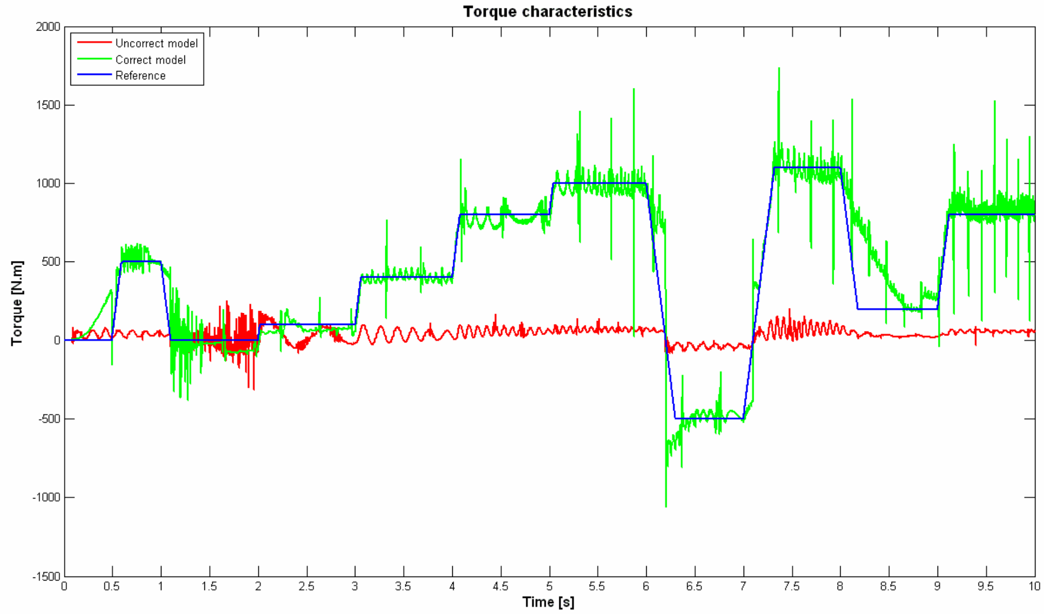

Figure 73 – Torque characteristics

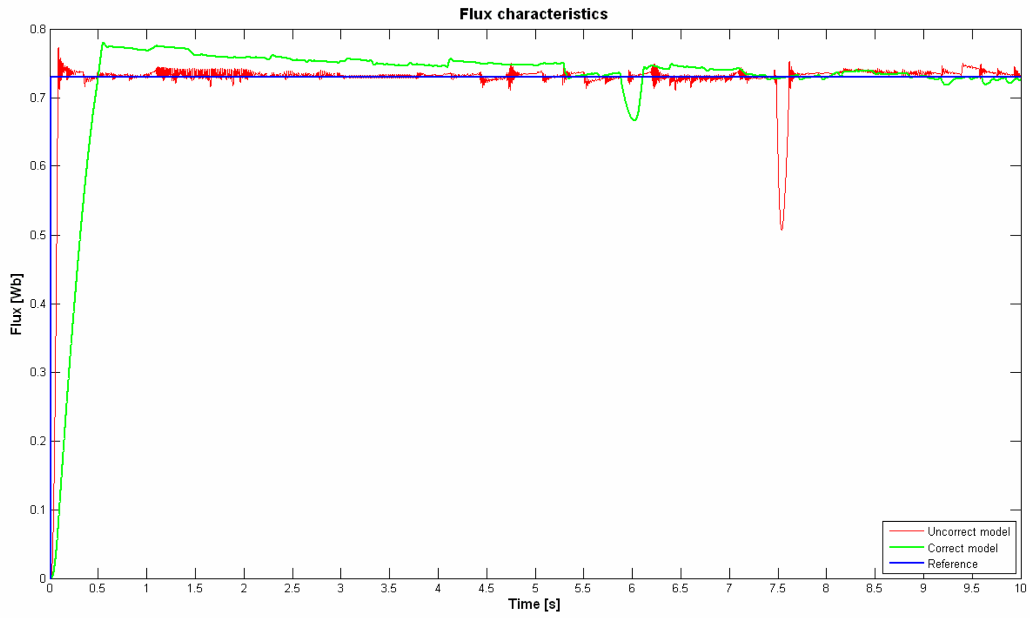

Figure 74 – Flux characteristics

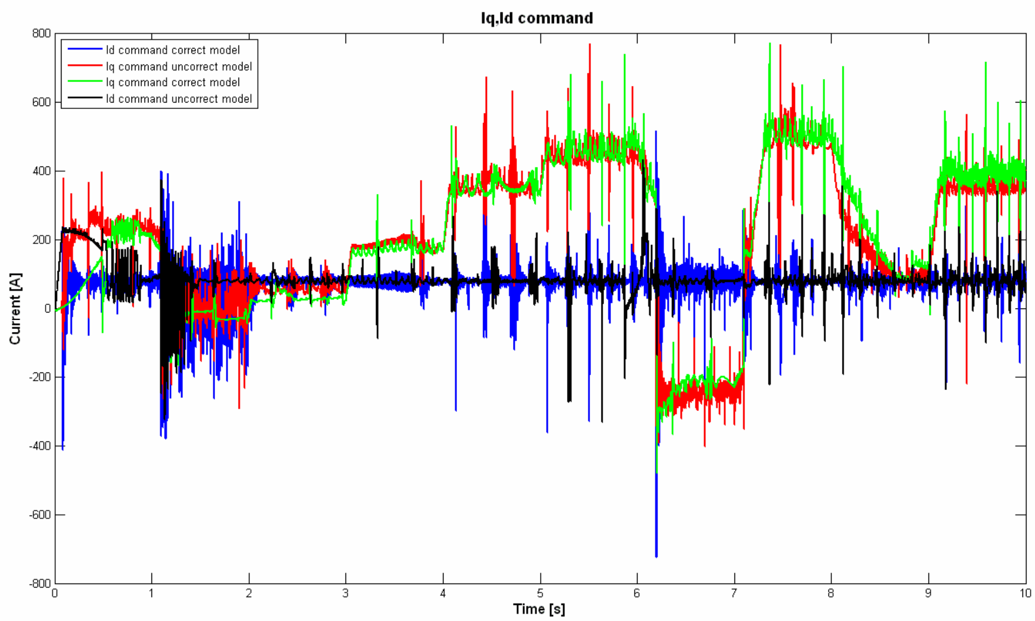

Figure 75 – I_d,I_q current

7.11. Robustness of Vector control

Simulations 5.9 and 5.10 have shown one significant drawback of Vector control – sensitiveness to uncertainties in parameters of the motor. In order to compare results from such simulations, it is important to realize that Vector control is based on equation (31), (32), (33) and (34):

$$|\overline{\psi}_r|(s) = \frac{L_m}{1 + s\tau_r} i_{sd}(s)$$

$$\omega_\psi = R_r \frac{L_m}{L_r} \frac{1}{|\overline{\psi}_r|} i_{sq} + p\omega_m$$

$$i_{sd} = \frac{\psi}{L_m}$$

$$i_{sq} = \frac{2}{3} \frac{1}{p} \frac{L_r}{L_m} \frac{M}{\psi}$$

It is obvious that (34) is not affected by the change in all parameters, as long as the change is proportional. Therefore, I_q command is the same (Figure 72). Equation (32) (position of the flux) is also not affected by the proportional change in all parameters, since the magnitude of the flux $\overline{\psi}_r$ changed according to (31). So the only equations which are affected by the change in all parameters are (31) and (33). Hence, the flux shown in Figure 71 has been calculated wrongly and, therefore, the flux profile in the motor is not 0.73Wb but lower resulting in field- weakening mode (see section 5.3) and, therefore, electromagnetic torque of the motor is also lower (Figure 70).

If only one parameter is changed, all equations are affected and the motor cannot be controlled (see Figure 73).

7.12. Comparison between 3HP, 200HP induction machine and PowerFlex7000

I will compare performance of the frequency converter with 3HP motor and 220HP motor at the speed set point of 1700rpm.

7.12.1. Comparison between 3HP and 200HP induction machine

Model	**3HP**	**200HP**
T_r [s]	2.374	1.69
T_s [s]	2.548	1.83
OS [%]	0.18	3
Steady-state error [rpm]	2	2
Steady-state error [%]	0.11	0.11
$\frac{T_n}{J}$ [N.kg^{-1}m^{-1}]	75	150
Range of current [A]	15	300
$\frac{T_n}{T_{l1700}}$	2.6	2.6

Table 54 – Comparison between 3HP and 200HP at 1700rpm

The reason why 200HP motor accelerates quicker than 3HP is that $\frac{T_{n200}}{J_{200}} > \frac{T_{n3}}{J_3}$. Since it is more difficult to control wider range of current 200HP motor has bigger overshot. However, both motors maintained the same steady-state error.

7.12.2. Comparison between the model and PowerFlex7000

According to [1] Rockwell Automation guarantees following speed regulations:

Frequency [Hz]	Below 6	Above 6
PowerFlex7000 [%][20]	0.02	0.01
Equivalent speed [rpm]	Below 360	Above 900
Model-3HP [%]	-	0.11
Model-200HP [%]	-	0.11

Table 55 – Comparison between the model and PowerFlex7000 at 1700rpm

As far as a steady-state error is concerned I have not managed to obtain similar accuracy as PowerFlex7000. This was probably caused by the phase shift.

[20] Error related to the base speed