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Fakulta Strojní (FS) – Faculty of Mechanical Engineering
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EQUIVALENT CIRCUIT OF THE THREE PHASE INDUCTION MOTOR

MASTER'S THESIS

Study program : **Master of Automotive Engineering**
Branch of study : **Advanced Powertrains**

Name and Workplace of Master's Thesis Supervisor: **doc. Ing. Pavel Mindl**, CSc., Department of Electric Drives and Traction, FEE

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Prague, 2018

Declaration

I hereby declare that I am the sole author of the thesis entitled "Equivalent circuit of the three-phase induction motor". I duly marked out all quotations. The used literature and sources are stated in the attached list of references.

In Prague on date 20/08/2018

Signature:
Rishabh Tathgir

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Abstract

The paper is about Modelling, Simulation and Verification (by way of practical testing) of 3-phase Induction Motor with Direct Torque Control and Inverter, for the purpose of vehicle propulsion. The purpose of my thesis is to simulate the outputs, for a given set of inputs being load torque and motor speed, of an Induction Motor performance, and outputs being motor torque, speed, power, 3 phase currents, AC voltage, power factor and DC current and voltage, and then compare those outputs to that obtained from practical testing of the motor in ČVUT Laboratory in Roztoky. This model, made using MATLAB/ Simulink, can then be used to see the performance of any motor at varying conditions, thus, basically simulating the working of an Induction Motor with Direct Torque Control. It is to replace practically testing a motor at every time and simply use the model to get the performance outputs and parameters, for different motor specifications.

Keywords

3-phase Induction Motor, Direct Torque Control, MATLAB/Simulink

CONTENT

1. Introduction

In today's world induction motor is vastly used in every industry. Therefore, it's performance characteristics development will prove to be very useful. The parameters, which were previously inter-dependent because of their coupling, can now be controlled, by carrying out Induction Motor (IM) Modelling. By completely controlling of these parameters, the current or voltage, frequency, output torque and speed can be monitored and checked. Therefore, Induction Motor Modelling is useful in monitoring the parameters which will achieve the desired results in the output.

The Direct Torque Control (DTC) is the crucial and the essential part of this project and it will be explained in the subsequent sections. However, a brief explanation of IM design and parameters, IM model and its guidance and controllability have to be mentioned first for better understanding of the project.

In further sections, there will also be a discussion concerning squirrel cage induction motor, which will be focused on the construction of squirrel cage induction motor, it's key features relating to speed, starting current, direction of rotation, slip, power factor and its upsides and downsides.

In general, induction motor can be controlled in two ways, they are referred to as the scalar and vector control ways. Using Vector Control, the magnitude and phase of the vector parameters of the motor can be modified. This estimation can be solved either by measurements or through calculations. On the other hand, using Scalar Control, also known as V/f control, the magnitude and frequency of either the voltage or current supplied to the stator can be modified.

The next section will be based on d-q analysis as the d-q transform which is often referred to as the Park transform. It is a space vector transformation of 3-Phase time-domain signals from a stationary phase coordinate system to a spinning coordinate system. This section will be followed by detailed computation of parameters and results achieved both from model and laboratory experiment. And finally, all the data will be summed up in conclusion part.

2. Three-phase Induction Machines

Electrical energy can be transformed into mechanical energy by way of an electromechanical device referred to as the electrical motor. 3-Phase Induction Motor is prominently applied motor because it starts to be operative by itself without any help of any other starting applications. This motor is composed of stator and rotor. As soon as the stator is successfully connected to the 3 phase AC source, it creates a rotating magnetic field that spins at the synchronous speed. Induction motors are so named because the rotating stator magnetic field induces currents in the short-circuited rotor, thus creating the rotor magnetic field. This rotor magnetic field interacting with the stator magnetic field, produces torque, which is the usable mechanical output of the machine. [1]

Furthermore, three phase induction motor provides advantages and disadvantages that are mentioned below.[2]

2.1. Construction of 3-phase induction motor

A 3-phase induction motor is based on 2 magnetic tools, stator and rotor. The stator and rotor are composed of electrically rotating circuit and magnetically spinning circuit. The stator is generally composed of aluminum and steel or laminated silicon steel, in a way to maintain current and magnetic flux. The rotor is generally composed of aluminum, brass or copper bars. These bars are called rotor conductors, placed in the peripheral slots of the rotor. The rotor conductors are then permanently shorted by the end rings, usually made of copper or aluminum.[3]

2.1.1. Stator frame

It is the external part of the three-phase induction motor. Its principle purpose is to support the stator core and the field windings, and functions as a housing, providing protection and mechanical strength to all the internal parts of the induction motor. The frame is made of die-cast or fabricated steel. Since the air gap between stator and rotor of a three phase induction motor is very small, the frame should be strong and rigid, so

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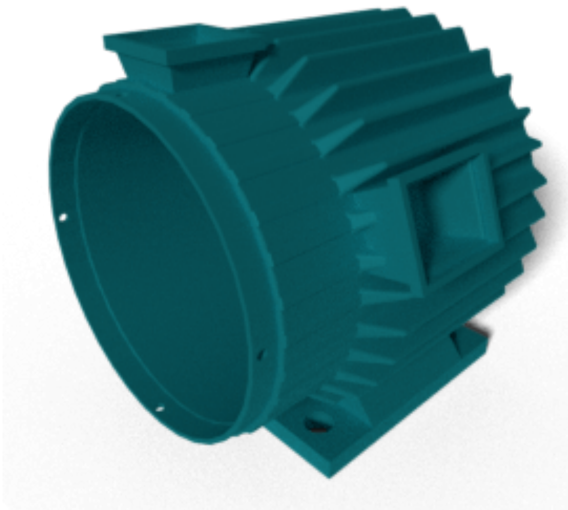
[1] *Www.ti.com: Three Phase Induction Motor* [online]. [cit. 2018-08-09]. Available at: http://www.ti.com/lit/an/sprabq8/sprabq8.pdf

[2] *Www.electrical4u.com: Explanation of three phase induction motor* [online]. [cit. 2018-07-11]. Available at: https://www.electrical4u.com/working-principle-of-three-phase-induction-motor/

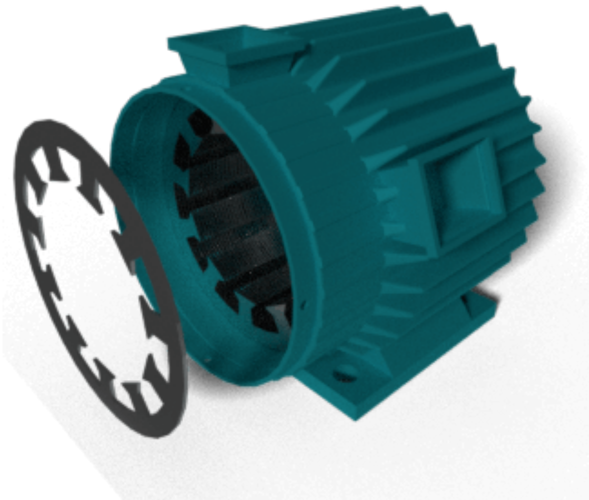
[3] *Www.electrcal4u.com: Construction of a squirrel cage induction motor* [online]. [cit. 2018-08-09]. Available at: https://www.electrical4u.com/construction-of-three-phase-induction-motor/

that the rotor remains concentric with the stator, else it will give rise to an unbalanced magnetic pull.



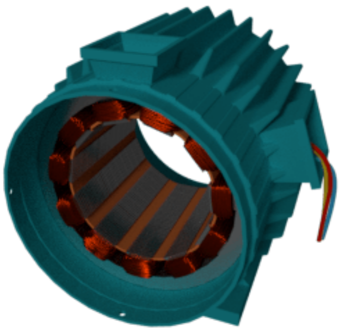
2.1.2. Stator Core

Its fundamental function is to carry the alternating magnetic flux. The stator core is laminated to reduce eddy current losses. These laminations are made of stampings which are approximately 400 to 500 μm thick. Such stampings are made of silicon steel, which reduce the hysteresis losses that occur in the motor. All these stampings, stamped together, form the stator core, which is housed in the stator frame.



2.1.3. Stator Winding or Field Winding

The peripheral slots of the stator core carry the three-phase windings, to which three-phase AC supply is applied. These windings are wound on the stator of three phase induction motor and are called field windings. When these windings are excited by three phase AC supply, a rotating magnetic field is produced. The three phases of the windings are connected in star or delta, based on type of starting method we use. In the case of squirrel cage three- phase induction motor, star-delta starter is commonly used. Thus, the stator of squirrel cage motor is connected in delta configuration. In the case of slip ring three-phase induction motor, resistances are inserted to start the motor. The stator windings of slip ring induction motor can be connected either in star or delta.[4]



2.2. Stator of three phase induction motor

There are many stampings in the creation of the stator in order to receive 3 phase winding circuit that is connected to the 3 phase AC supply. 3 phase windings are arranged in such a way that they lead to the creation of rotating magnetic field. Additionally, each winding is kept with 30% overlap to another winding.

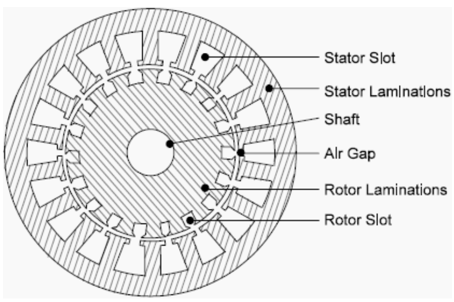


Figure 1. 1 Stator of three phase induction motor

[4] *Www.electrcal4u.com: Stator Winding or Field Winding*[online]. [cit. 2018-08-09]. Available at: https://www.electrical4u.com/construction-of-three-phase-induction-motor/)

The windings cannot operate without connecting to many devices that depend on the speed requirement and the formula provided for this operation is $N_s=120f/p$, where, N_s is a synchronous speed, *f* refers to the frequency of applied voltage and *p* is the number of poles.[5]

2.3. Rotor of three phase induction motor

The rotor of a 3-Phase induction motor can be of two types, squirrel cage rotor and phase wound rotor. Phase wound rotor refers to the 3 phase, double layer, distributed winding. The number of poles of rotor and the number of poles of the stator are the same. However, the rotor is always wound 3-phase, even if the stator is wound two-phase. This three-phase rotor winding is internally connected in star configuration. The three ends of the winding are then taken out via three insulated slip rings fitted on the shaft and connected through three carbon brushes, which are linked to an external star connected Rheostat. This arrangement is done to add an external resistance in rotor circuit for initial starting purpose and for varying the speed characteristics. When motor is running at its preferred speed, the slip rings are automatically short circuited, by means of a metal collar, and the brushes are disengaged from the slip rings, to reduce frictional losses.[6]

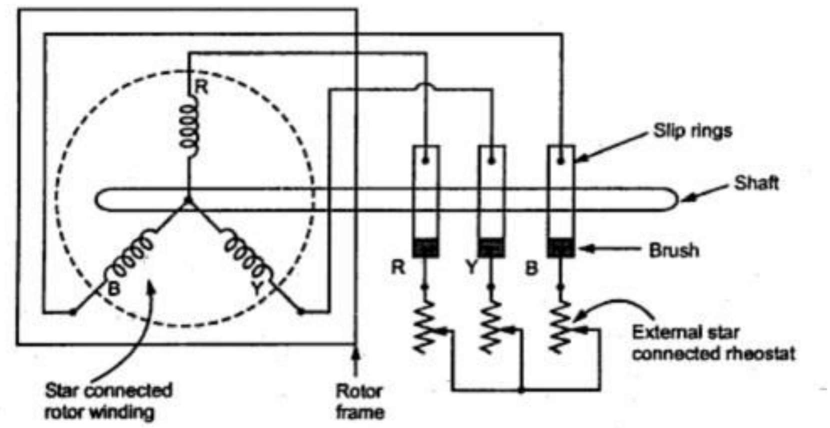


Figure 1. 2 Rotor of three phase induction motor

[5] *Www.marineinsight.com: Explanation stator of three phase induction motor* [online]. [cit. 2018-07-11]. Available at: https://www.marineinsight.com/marine-electrical/construction-and-working-of-3-phase-induction-motor-on-ship/

[6] *Www.electricaleasy.com: Rotor of three phase induction motor* [online]. [cit. 2018-07-11]. Available at: https://www.electricaleasy.com/2014/02/three-phase-induction-motor.html

2.4. Production of rotating magnetic field

When a 3-Phase voltage is applied to the 3-Phase stator winding of the induction motor, a rotating magnetic field is produced and, by transformer action, this causes a 'working' e.m.f. (Electro Motive Force) in the rotor winding. This e.m.f. is called an operating e.m.f., because it causes a current to flow via the armature winding conductors. This interacts with the revolving flux-density wave to produce torque. Thus, revolving field is essential to the working of the induction motor. When 3-Phase windings are displaced in space by 120^0 and fed by 3-Phase current displaced in time by 120^0, they produce a resultant magnetic flux that spins in space, emulating the mechanical spinning of actual magnetic poles.[7]

2.5. Production of magnetic flux

All magnets, irrespective of shape, have two regions, referred to as the magnetic poles, with magnetism both in and around a magnetic circuit. This produces a complete chain of cooperative and balanced pattern of invisible lines of flux all around it. These lines of flux are called the "magnetic field" of the magnet. The strength of this magnetic field is higher in some parts than in others, with the areas of the magnet that has the largest magnetism being referred to as "poles". There is a pole at each end. These lines of flux cannot be observed by the naked eye, but they can be noticed visually by using iron fillings sprinkled onto a sheet of paper or by using a small compass to follow them. Magnetic poles always exist in pairs. There is always a region of the magnet called the North-pole and an opposite region called the South-pole. Magnetic fields are always expressed visually as lines of power that give a magnetic pole at each end of the material, where the flux lines are tighter and more concentrated. The lines which indicate a magnetic field, as explained above, and their intensity, are referred to as the Lines of Force or more specifically, "Magnetic Flux", and are denoted by the Greek symbol, Phi (Φ), with the unit of flux being Weber, [Wb], that is named after Wilhelm Eduard Weber. The number of lines of power within a given unit area is referred to as the "Flux Density" and since flux (Φ) is estimated in Wb and area (A) in meters squared, [m^2], flux density is therefore expressed in Webers/Metre^2 or [Wb/m^2] and is depicted by the symbol B.

However, when referring to flux density in magnetism, it is denoted by the unit of Tesla, that is named after Nikola Tesla, and therefore, one Wb/m^2 is equal to one Tesla, $1\ Wb/m^2 = 1\ T$. Flux density is directly proportional to the lines of power and inversely proportional to area. Hence, we can explain Flux Density as:

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[7] *Www.electrical-engineering-assignment.com: Production of rotation magnetic field* [online]. [cit. 2018-07-11]. Available at: http://www.electrical-engineering-assignment.com/production-of-rotating-magnetic-field

Magnetic Flux Density [Tesla] = Magnetic Flux [Weber] / Area [m²]

By denoting magnetic flux density in B and the unit of magnetic flux density in the Tesla [T],

$$B = \Phi/A \text{ in Teslas}$$

It is crucial that all calculations for flux density be expressed in the same units, e.g., flux in Webers, area in m^2 and flux density in Teslas.[8]

2.6. Advantages and Disadvantages

Almost 70% of the machines used in industries, in today's world, are 3-Phase induction motors. As AC power source is commonly used in generation, transmission and distribution, induction motors have a significant place in industrial drive applications, thus, replacing the DC motors, which were formerly used for industrial applications. Induction motors are mainly of two types based on their construction - Squirrel cage induction motor and Slip ring induction motors. Squirrel cage induction motors are majorly used in motor and drive applications. Some of the advantages of induction motors, in contrast to DC motors and synchronous motors, and also, their disadvantages are given below:

- **Advantages:**

Induction motors have a simple and rugged construction, and are durable and robust, capable of working in any environmental condition. Due to the absence of brushes, commutators, and slip rings, Induction motors are cheaper in cost and are comparatively maintenance free motors, as against DC motors and synchronous motors. Induction motors can work in polluted and inflammable environments, as they do not have any brushes which can produce sparks. Three-Phase induction motors have self-starting torque, as against synchronous motors, hence no initiating systems are installed, unlike synchronous motor. However, single-phase induction motors do not have self-starting torque, and are designed to spin using some auxiliaries. These advantages of 3-Phase induction motors make them more prominent for industrial and domestic applications.

- **Disadvantages:**

3-Phase induction motors have low starting torque and have high in-rush currents. Inrush current is the instantaneous high input current drawn by the induction motor when turned-on, due to the high initial currents required to charge the capacitors and

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[8] *Www.electronics-tutorials.ws: Production of magnetic flux* [online]. [cit. 2018-07-13]. Available at: https://www.electronics-tutorials.ws/electromagnetism/magnetism.html

inductor.[9] Therefore, these motors are not majorly used for applications which require high starting torques, like traction systems. Squirrel cage induction motors have lower starting torques, compared to slip-ring induction motors, which have better starting torques, due to the presence of exterior resistor in the rotor. Other important disadvantage of Induction motor is that it drives high in-rush currents, resulting in high momentary voltage dip while starting of the machine. High in-rush currents can be decreased by using some starting methods in the induction motor. Induction motors always work under lagging power factor and with light load conditions they operate at very poor power factor. Some of the disadvantages of poor power factor are rise in I^2R losses in the system, which decreases the effectiveness of the system. Hence, a power factor correction equipment, such as static capacitor banks, should be connected to these motors to provide reactive power to them. The other main disadvantage of induction motors is that speed control of induction motors is difficult and troublesome. Hence, for fine speed control applications, DC motors are preferred in place of induction motors. However, with the advancements in power electronics, variable frequency drives (VFDs) with induction motors are used in industrial applications for speed control.[10]

[9] *www.sunpower-uk.com: What is Inrush Current [online].* [cit. 2018-07-15]. Available at: https://www.sunpower-uk.com/glossary/what-is-inrush-current/

[10] *Www.electricalquestionsguide.blogspot.com: Advantages and disadvantages of three phase induction motor* [online]. [cit. 2018-07-15]. Available at: http://electricalquestionsguide.blogspot.com/2011/12/induction-motor-advantages.html

3. Squirrel cage induction motor

The type of 3 phase induction motor with a squirrel cage rotor is called squirrel cage induction motor. The construction of squirrel cage induction motor is explained below. This is followed by its working principle and key features. Later, the equations of induction motor modelling are stated. Finally, some advantages and uses are explained.

3.1. Construction of Squirrel cage induction motor

Every induction motor has a rotor and a stator. It is the construction of rotor which makes Squirrel Cage Induction Motor distinctive from Wound Type Induction Motor. Stator construction is the same in these two kinds of motors.

- **Stator of squirrel cage induction motor**

Stator is the part of motor which is static. It is the external frame in which rotor is positioned. It has slots on internal circumference to carry the windings. This windings circuit is excited by 3-phase supply. This 3-phase winding circuit is then placed in the slots. These windings have 120 degrees of phase difference with each other and are connected in star or delta configuration.

- **Rotor of squirrel cage induction motor**

Rotor is the part of a motor which is rotating. It consists of a cylindrical core which is made of laminations to decrease eddy currents. The rotor and stator slots are not parallel to each other but are a bit skewed. This skewing avoids magnetic locking of stator and rotor teeth and makes the working of the motor smoother and quieter. Squirrel cage rotors consist of copper bars called conductors, which are longer than the rotor and are set in the rotor core slots. These extended conductors are short circuited with each other, by copper rings on each side. The rotor is also sometimes provided with fans on either side, for cooling purposes. Apart from the rotor and stator, an induction motor has other components, like bearings and casing, which help support, protect and ventilate the assembly.[11]

[11] *Www.theengineeringprojects.com: Construction of a squirrel cage induction motor* [online]. [cit. 2018-07-17]. Available at: https://www.theengineeringprojects.com/2016/10/squirrel-cage-induction-motor.html

3.2. Working of a squirrel cage induction motor

When AC power supply is applied to stator winding, the current flowing through the coil generates a magnetic flux in the coil. When the rotor windings are short circuited, the flux from the stator coils will cut the rotor coils, thus, according to the Faraday's law of electromagnetic induction, causing current to flow in the rotor coil due to short circuiting of the rotor coil. The stator and rotor currents, flowing in the coils, generate two fluxes, one being the stator flux and the other, the rotor flux. The rotor flux lags behind the stator flux. Therefore, the rotor acquires the torque that rotates it in the direction of the rotating magnetic flux.[12]

3.3. Key features

Some key features of Squirrel Cage Induction Motor are explained below.

3.3.1. Speed

A squirrel cage induction motor generally works at a constant speed. This speed is synchronous speed.

$$N = N_s \, (1 - S)$$

where,

N = speed of the rotor of an induction motor

N_s = synchronous speed

S = slip, at rotor standstill, slip is 1

3.3.2. Starting current

Induction motors require high starting currents, also called in-rush currents, which usually result in voltage fluctuations.

3.3.3. Direction of Rotation

The direction of rotation of Induction motor, and therefore the rotor, is always the same as the direction of the rotating magnetic field of stator. It is possible to reverse this direction of rotation, if two power lines out of three are inter-changed, thus reversing the direction of stator rotating magnetic field.

[12] *Www.hordu.com: How a squirrel cage induction motor works* [online]. [cit. 2018-07-18]. Available at: https://www.hordu.com/working-principle-of-3-phase-squirrel-cage-induction-motor/

3.3.4. Slip

The slip is the difference between the speed of rotating magnetic field of stator and rotating speed of rotor. Synchronous speed is the speed of rotation of magnetic field. Slip is defined as a ratio with synchronous speed or in percentage.

3.3.5. Power factor

Power factor is the ratio of real to apparent power. Real power is the actual power dissipated by an AC circuit. Apparent power is the product of the R.M.S. values of voltage and current. Power factor is a dimensionless number and is always less than unity, in the closed interval of -1 to 1. When the voltage and current waveforms are not in phase, the power factor is less than 1. The power factor is low while motor is running at no load and it is high while motor is working at full load. The difference between real and apparent power is caused due to reactance in the circuit and indicated as the amount of power that does not contribute to useful work. When the power flows back from device (generally the load) to the source, i.e., device generates power, a negative power factor is obtained. In this case, the device is considered a generator.[13][14]

3.4. Equations of Squirrel Cage Induction Motor Model

A dynamic model of the induction motor must be understood to design controllers for the motor. Even though this dynamic model could at best good approximation of the real system, the model should include all the essential dynamic effects that occur during both steady-state and transient operations. Additionally, it should be effective for any alterations in the inverter's supply such as voltages or currents. Such a model can be obtained by either the space vector phasor theory or two-axis theory of electrical machines. The two-axis theory of electrical machines will be used and explained.

The following assumptions about the induction motor are made:

- Symmetrical two-pole three phase windings
- Slotting effects and iron losses are neglected
- Iron parts have infinite permeability
- Flux density is radial in the air gap between stator and rotor

[13] *Www.theengineeringprojects.com: Key features of squirrel cage induction motor* [online]. [cit. 2018-07-18]. Available at https://www.theengineeringprojects.com/2016/10/squirrel-cage-induction-motor.html
[14] *https://en.wikipedia.org/: Power Factor* [online]. [cit. 2018-07-18]. Available at https://en.wikipedia.org/wiki/Power_factor

- Stator and the rotor windings are simplified as a single, multi-turn full pitch coil situated on the two sides of the air gap[15]

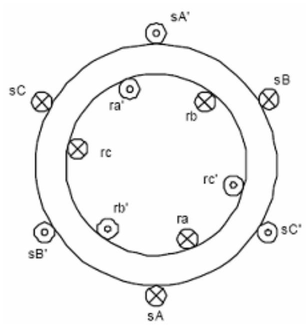

Figure 1. 3 Cross section of elementary symmetrical three phase induction motor

3.4.1. Voltage Equations

The stator voltages are expressed below, from the stationary reference frame fixed to the stator. Similarly, the rotor voltages are also expressed, from the rotating frame fixed to the rotor.

$$V_{sA} = R_s i_{sA}(t) + \frac{d\psi_{sA}(t)}{dt}$$ (Eq. 1.1)

$$V_{sB} = R_s i_{sB}(t) + \frac{d\psi_{sB}(t)}{dt}$$ (Eq. 1.2)

$$V_{sC} = R_s i_{sC}(t) + \frac{d\psi_{sC}(t)}{dt}$$ (Eq. 1.3)

$$V_{rA} = R_r i_{rA}(t) + \frac{d\psi_{rA}(t)}{dt}$$ (Eq. 1.4)

$$V_{rB} = R_r i_{rB}(t) + \frac{d\psi_{rB}(t)}{dt}$$ (Eq. 1.5)

$$V_{rC} = R_r i_{rC}(t) + \frac{d\psi_{rC}(t)}{dt}$$ (Eq. 1.6)

Now, the instantaneous stator flux linkage values per phase and roto flux linkages are expressed below.

[15] *https://pdfs.semanticscholar.org: Torque Ripple Reduction in Direct Torque Controlled Induction Motor drive by using Fuzzy Logic* [online]. [cit. 2018-07-18]. Available at https://pdfs.semanticscholar.org/bd5b/5b878aa358ed77d0794773f58c533dfd7dd3.pdf

$$\psi_{sA} = \overline{L}_s i_{sa} + \overline{M}_s i_{sB} + \overline{M}_s i_{sC} + \overline{M}_{sr} \cos\theta_m i_{ra} + \overline{M}_{sr} \cos(\theta_m + 2\pi/3) i_{rb} + \overline{M}_{sr} \cos(\theta_m + 4\pi/3) i_{rc}$$
$$\psi_{sA} = \overline{M}_s i_{sa} + \overline{L}_s i_{sB} + \overline{M}_s i_{sC} + \overline{M}_{sr} \cos(\theta_m + 4\pi/3) i_{ra} + \overline{M}_{sr} \cos\theta_m i_{rb} + \overline{M}_{sr} \cos(\theta_m + 2\pi/3) i_{rc}$$
$$\psi_{sA} = \overline{M}_s i_{sa} + \overline{M}_s i_{sB} + \overline{L}_s i_{sC} + \overline{M}_{sr} \cos(\theta_m + 2\pi/3) i_{ra} + \overline{M}_{sr} \cos(\theta_m + 4\pi/3) i_{rb} + \overline{M}_{sr} \cos\theta_m i_{rc}$$
$$\psi_{ra} = M_{sr} \cos(-\theta_m) i_{sA} + M_{sr} \cos(-\theta_m + 2\pi/3) i_{sB} + M_{sr} \cos(-\theta_m + 4\pi/3) i_{sC} + \overline{L}_r i_{ra} + \overline{M}_r i_{rb} + \overline{M}_r i_{rc}$$
$$\psi_{rb} = \overline{M}_{sr} \cos(-\theta_m + 4\pi/3) i_{sA} + \overline{M}_{sr} \cos(-\theta_m) i_{sB} + \overline{M}_{sr} \cos(-\theta_m + 2\pi/3) i_{sC} + \overline{M}_r i_{ra} + \overline{L}_r i_{rb} + \overline{M}_r i_{rc}$$
$$\psi_{rc} = \overline{M}_{sr} \cos(-\theta_m + 2\pi/3) i_{sA} + \overline{M}_{sr} \cos(-\theta_m + 4\pi/3) i_{sB} + \overline{M}_{sr} \cos(-\theta_m) i_{sC} + \overline{M}_r i_{ra} + \overline{M}_r i_{rb} + \overline{L}_r i_{rc}$$

(Eq. 1.7 & Eq. 1.8)

Using the matrix notation and considering all the above equations, the following expression is obtained.

$$\begin{bmatrix} V_{sA} \\ V_{sB} \\ V_{sC} \\ V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = \begin{bmatrix} R_s + p_{Ls} & pM_s & pM_s & pM_{sr}\cos\theta_m & pM_{sr}\cos\theta_{m1} & pM_{sr}\cos\theta_{m1} \\ pM_s & R_s + pL_s & pM_s & pM_{sr}\cos\theta_{m1} & pM_{sr}\cos\theta_m & pM_{sr}\cos\theta_{m1} \\ pM_s & pM_s & R_s + pL_s & pM_{sr}\cos\theta_{m1} & pM_{sr}\cos\theta_{m1} & pM_{sr}\cos\theta_m \\ pM_{sr}\cos\theta_m & pM_{sr}\cos\theta_{m1} & pM_{sr}\cos\theta_{m1} & R_r + pL_r & pM_r & pM_r \\ pM_{sr}\cos\theta_{m1} & pM_{sr}\cos\theta_m & pM_{sr}\cos\theta_{m1} & pM_r & R_r + pL_r & pM_r \\ pM_{sr}\cos\theta_m & pM_{sr}\cos\theta_{m1} & pM_{sr}\cos\theta_m & pM_r & pM_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{sA} \\ i_{sB} \\ i_{sC} \\ i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix}$$

(Eq. 1.9)

3.4.2. Applying Park's transform

Park's transform is applied to the above induction motor equation 1.1 to 1.9, to reduce the expressions and obtain constant coefficients in differential equations. Physically, it can be represented as transforming the three phase windings of the induction motor into two phase windings, as shown.

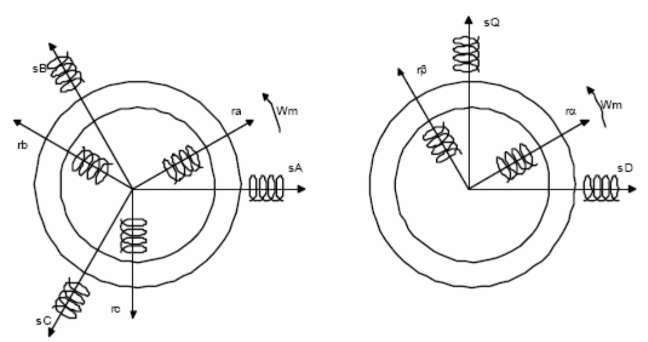

Figure 1. 4 Scheme of equivalent axis transformation

In case of a symmetrical three-phase induction motor, the direct and the quadrature axis of the stator magnitudes are fictional. The equivalencies for these direct (D) and quadrature (Q) magnitudes with the magnitudes per phase are as follows:

$$\begin{bmatrix} V_{sD} \\ V_{sQ} \\ V_{s0} \end{bmatrix} = c.\begin{bmatrix} \cos\theta & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ -\sin\theta & -\sin(\theta-2\pi/3) & -\sin(\theta+2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}.\begin{bmatrix} V_{sA} \\ V_{sB} \\ V_{sC} \end{bmatrix}$$

(Eq. 2.1)

$$\begin{bmatrix} V_{sA} \\ V_{sB} \\ V_{sC} \end{bmatrix} = c.\begin{bmatrix} \cos\theta & -\sin\theta & 1/\sqrt{2} \\ \cos(\theta-2\pi/3) & -\sin(\theta-2\pi/3) & 1/\sqrt{2} \\ \cos(\theta+2\pi/3) & -\sin(\theta+2\pi/3) & 1/\sqrt{2} \end{bmatrix}.\begin{bmatrix} V_{sD} \\ V_{sQ} \\ V_{s0} \end{bmatrix}$$

(Eq. 2.2)

where, c = constant, that can have value of 2/3 or 1 for the non-power invariant form or the value 2/3 for the power-invariant.

The equations 2.1 and 2.2 are applied for other magnitudes such as currents and fluxes, as well. The expression 1.9 can, therefore, be simplified into a much smaller expression in 2.3, after applying the Park's transform.

$$\begin{bmatrix} V_{sD} \\ V_{sQ} \\ V_{r\alpha} \\ V_{r\beta} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -L_s p\theta_s & pL_m & -L_m(P.w_m + p\theta_r \\ L_s p\theta_s & R_s + pL_s & L_m(P.w_m + p\theta_r) & pL_m \\ pL_m & -L_m(p\theta_s - P.w_m) & R_r + pL_r & -L_r p\theta_r \\ L_m(p\theta_s - P.w_m) & pL_m & L_r p\theta_r & R_r + pL_r \end{bmatrix}.\begin{bmatrix} i_{sD} \\ i_{sQ} \\ i_{r\alpha} \\ i_{r\beta} \end{bmatrix}$$

where $L_S = L_s - L_m$, $L_r = L_r - L_m$ and $L_m = \frac{3}{2}\overline{M}_{sr}$.

(Eq. 2.3)

3.4.3. Voltage Matrix Equations

The matrix expression 2.3 can be further simplified, based on certain initial conditions, as shown below.

- Fixed to stator: $w_s = 0$, $w_r = -w_m$

$$\begin{bmatrix} V_{sD} \\ V_{sQ} \\ V_{rd} \\ V_{rq} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & 0 & pL_m & 0 \\ 0 & R_s + pL_s & 0 & pL_m \\ pL_m & P.w_m L_m & R_r + pL_r & P.w_m L_r \\ -P.w_m L_m & pL_m & -P.w_m L_r & R_r + pL_r \end{bmatrix} . \begin{bmatrix} i_{sD} \\ i_{sQ} \\ i_{rd} \\ i_{rq} \end{bmatrix}$$ (Eq. 2.4)

- Fixed to rotor: $w_r = 0$, $w_s = w_m$

$$\begin{bmatrix} V_{sD} \\ V_{sQ} \\ V_{rd} \\ V_{rq} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -L_s P.w_m & pL_m & -L_m P.w_m \\ L_s P.w_m & R_s + pL_s & L_m P.w_m & pL_m \\ pL_m & 0 & R_r + pL_r & 0 \\ 0 & pL_m & 0 & R_r + pL_r \end{bmatrix} . \begin{bmatrix} i_{sD} \\ i_{sQ} \\ i_{rd} \\ i_{rq} \end{bmatrix}$$ (Eq. 2.5)

Fixed to synchronism: $w_r = s.w_s$[16]

$$\begin{bmatrix} V_{sD} \\ V_{sQ} \\ V_{rd} \\ V_{rq} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & -L_s w_s & pL_m & -L_m w_s \\ L_s w_s & R_s + pL_s & L_m P.w_s & pL_m \\ pL_m & -L_m S.w_s & R_r + pL_r & -L_r S w_s \\ L_m S.w_s & pL_m & L_r S w_s & R_r + pL_r \end{bmatrix} . \begin{bmatrix} i_{sD} \\ i_{sQ} \\ i_{rd} \\ i_{rq} \end{bmatrix}$$ (Eq. 2.6)

3.5. Advantages and Disadvantages

- Advantages

Very strong in construction and very economical. Can work in any working conditions. Cheaper in cost in contrast to Slip Ring Induction motors. Demands less maintenance because of the absence of Slip ring and Brushes and rugged construction. Maintenance time is less. No wear and tear of brushes. Higher efficiency in contrast to slip ring induction motor, due to less copper used, so less resistive loss. Explosions do not occur, due to the absence of slip rings and brushes, so no sparking. Squirrel Cage motors are better cooled in contrast to Slip ring induction

[16] *https://pdfs.semanticscholar.org: Torque Ripple Reduction in Direct Torque Controlled Induction Motor drive by using Fuzzy Logic* [online]. [cit. 2018-07-18]. Available at https://pdfs.semanticscholar.org/bd5b/5b878aa358ed77d0794773f58c533dfd7dd3.pdf

motors. Squirrel cage motors work at almost constant speed, have high over load capacity, and work at better power factor.

- Disadvantages

Main disadvantage of Squirrel cage induction motor (SCIM) is that they have low starting torque and high starting currents. As resistance cannot be added to rotor, speed control is not available. This is one of main drawbacks of SCIM. Starting torque is around 1.5 to 2 times the full load torque, in-rush current can be as high as 20 times as full load current and, after first half cycle, starting current is as high as 5 to 9 times the full load current. If we make a comparison to Slip ring induction motor (SRIM), the higher starting torque is achieved in SRIM as external resistance can be added to the rotor circuit while starting. This method also reduces the high in-rush currents while starting of induction motor.[17]

[17] *Www.gate2018online.in: Advantages and disadvantages of squirrel cage induction motor*[online]. [cit. 2018-07-19]. Available at: https://www.gate2018online.in/2017/06/squireel-cage-induction-motors-i.html

4. Direct torque control (DTC)

DTC was described first by Takahashi in 1984 in Japan and then it was presented to everyone in Germany by Depenbrock (1985). Unlike conventional vector control, Direct Torque Control doesn't demand coordinate transformation, PI regulators, PWM and position encoders, which makes DTC more suitable. Moreover, Both DTC and VC serve good dynamic response, but DTC is less sensitive to the motor parameter variations.

4.1. Principle of classical DTC strategy

Principally, the DTC strategy chooses one of the inverter's six voltage vectors and two zero vectors, as shown in Figure 1.5, to keep the stator flux and torque within a hysteresis band around the command or reference flux and torque magnitudes. In this figure, the inverter switching states are also indicated with the corresponding voltage vectors. The ON state of upper switches are signified by '1' and that of the lower switches are signified by '0'.

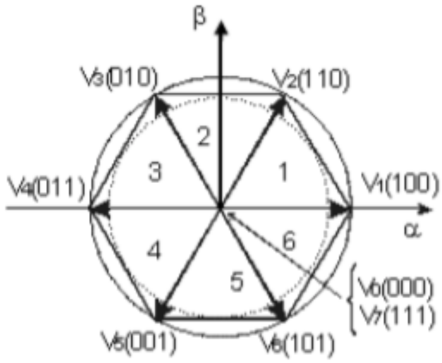

Figure 1. 5 Direct Torque Control Space Vectors

4.2. Methods of DTC

In the conventional DTC, there are numerous drawbacks. They are summed up as follows:

- Sluggish or not rapid torque and flux response during start-up.
- Large and small torque or flux mistakes are not distinguished
- The same vectors are applied during start-up, step changes and steady state conditions.

In order to overcome these drawbacks, the following methods are used:

- Modified switching table technique
- Deadbeat control technique
- Constant switching frequency technique

- Intelligent control techniques[18]

4.3. DTC motor drives

Variable-speed drives (VSDs) have allowed unprecedented fulfillment in electric motors and gave drastic energy savings by matching motor speed and torque to the driven load requirements. Most VSDs in the market employ a modulator stage that conditions voltage and frequency inputs to the motor, but results in inherent time delay in processing control signals. DTC technology also serves other benefits ranging up to system-level characteristics.[19]

4.4. Comparison of Field Oriented and DTC methods for IM used in electric vehicles

Field Oriented Control (FOC) and Direct Torque Control (DTC) are standard induction motor control techniques. The DTC technique is sensorless and is, thus, it is more convenient to consider a Direct Field Oriented Control (DFOC) scheme, instead of a general FOC scheme.

DTC scheme is characterized by the lack of:

- ✓ PI regulators;
- ✓ coordinate transformations;
- ✓ current regulators;
- ✓ PWM signals generators (no timers).

Thus, only the controlling schemes, which meet all these requirements, should be considered as real DTC schemes. A block diagram of a basic DFOC scheme is shown in Fig. 1.6.

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[18] *Www.shodhganga.inflibnet.ac.in: Methods of Direct Torque Control* [online]. [cit. 2018-07-21]. Available at: http://shodhganga.inflibnet.ac.in/bitstream/10603/27592/8/08_chapter%203.pdf

[19] *Www.new.abb.com: Direct Torque Control drives*[online]. [cit. 2018-07-21]. Available at: https://new.abb.com/drives/dtc

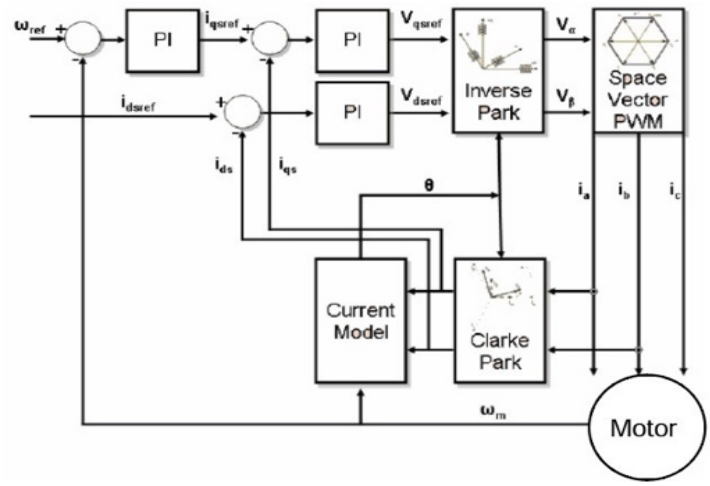


Figure 1. 6. Basic DFOC scheme.

FOC signifies induction motor operation in a synchronously rotating d-q reference frame that is aligned with one of the motor fluxes, typically the rotor flux. In this, control of torque and flux is independent, in such a way that the d-axis component of the stator current controls the rotor flux magnitude and the q-axis component controls the output torque. A proportional-integral (PI) controller regulates the stator voltage to attain the calculated stator current. The required voltage is then produced by the inverter using space vector modulation (SVM). However, during motor operation, the actual rotor resistance and inductance can fluctuate, for example with temperature, resulting in errors between the values used and the actual parameters, leading to an incomplete decoupling of torque and flux.[20]

4.5. DTC of IM using Fuzzy Logic

Direct torque control (DTC) method of induction motor control directly controls the electromagnetic torque and stator flux linkage. It has many advantages, such as simple implementation, insensitivity to motor parameters and quick torque response. However, high ripples in torque and flux linkages are the core problem associated with the conventional DTC method, because of the use of two-value (‘1’ and ‘0’) hysteretic controllers for the stator flux linkage. Here, the Fuzzy Logic (FL) method, based on the Fuzzy Logic language rules, is employed to solve this nonlinearity. The fuzzy controller has three fuzzy state variables and one control variable, for achieving DTC. There are three variables as input for the fuzzy logic controllers, which are the stator flux error,

[20] *Www.phad.cc.umanitoba.ca: Comparison of Field Oriented and DTC methods for IM used in electric vehicles* [online]. [cit. 2018-07-21]. Available at: http://phad.cc.umanitoba.ca/~bibeauel/research/papers/2006_PHEV_karlis.pdf

electromagnetic torque error, and angle of flux stator and the output is the voltage space vector.[21]

4.6. Comparison of scalar and vector control strategies of IM

Most existing variable speed drive systems with induction motors are low-performance drives, where variables to be adjusted are the magnitude and frequency of either the voltage or current supplied to the stator. Thus, controlling of the steady-state speed or torque of the motor is possible, while keeping the magnetic field in the motor at a constant, desired level. This type of control is called scalar control, since the controlled stator voltage or current are assumed sinusoidal and only the magnitude and frequency are adjusted, with no regard to the phase of the vector quantities. On the other hand, vector control method, based on the Field Orientation Principle, allows adjustment of both the magnitude and phase of the vector quantities of the motor. In vector controlled high performance drive systems, the instantaneous torque and magnetic field of the motor are controlled, both in the steady-state and transient operating conditions. Clearly, scalar control systems are simpler than those using vector control. Possibly the most common scalar technique used in practice is that of Constant Volts/Hertz (CVH), so named because the magnitude of stator voltage is adjusted in proportion to the frequency, in order to maintain an approximately constant stator flux in the motor. The CHV method consists, in essence, of controlling the speed of the rotating magnetic field of the stator by changing the supply frequency. The torque developed in the motor depends only on the slip speed, i.e., the difference in speeds between the field and the rotor. The control system is simple, since only speed feedback is required. [22]

Initially, I chose vector control and modelled a system based on it, but I faced problems with control and getting the required output, as it is based on sector selection and corresponding voltage intensity control with PI controller, all of which required a specialized knowledge and were difficult to tune and manipulate to get the required output. That is why I chose scalar control, since in this case, controlling was comparatively easier.

[21] *Www.ijettjournal.org: DTC of IM using fuzzy logic*[online]. [cit. 2018-07-27].Available at: http://ijettjournal.org/volume-6/number-3/IJETT-V6N3P129.pdf

[22] *Www.link.springer.com: Comparison of scalar and vector control strategies of IM* [online]. [cit. 2018-08-10]. Available at: https://link.springer.com/chapter/10.1007/978-1-4615-2730-5_2)

4.6.1. Basics of scalar control

The scalar control method is applied by varying two parameters simultaneously. The speed is varied by increasing or decreasing the supply frequency, which results in change of impedance. This change of impedance leads to the increase or decrease in current. If the current is small, the torque of motor reduced. If the frequency reduces or the voltage rises too much, the coils can be burned or saturation can occur in the iron of coils. To overcome these obstacles, it is essential to change the frequency and the voltage simultaneously. In this way, the occurring drawbacks of varying frequency and voltage can be compensated. Thus, as can be seen from the equation of induced voltage, the V/Hz constant control gives constant flux in the stator. (Eq. 2.7)

$$\frac{V_{e,RMS}}{f} = 4.44 \cdot N \cdot \psi_s \cdot \xi \quad \text{(Eq. 2.7)}$$

where,

$V_{e,RMS}$	= induced voltage in the stator
f	= frequency of the supplied voltage
N	= number of turns
Ψ_S	= magnetic flux-linkage in the stator
ξ	= constant of coil

The torque–speed equation of induction motors (Eq. 2.8) is then applied to find the voltage–torque and frequency–torque functions.

$$T_{air-gap} = \frac{3}{2\omega_m} I_r^2 \frac{R_r}{s} \quad \text{(Eq. 2.8)}$$

where,

$T_{air\text{-}gap}$	= torque of the motor in the air-gap
ω_m	= mechanical angular speed
I_r	= rotor current
R_r	= resistance of rotor
s	= slip

From these equations, we can see that the relation between torque and frequency is inverse, while voltage is directly proportional to torque. Torque–speed control is solved by the linear variation of the two parameters (Eq. 2.9).

$$\frac{T}{\omega} \sim \frac{V^2}{2\pi \cdot f^2} \sim \frac{V}{f} \quad \text{(Eq. 2.9)}$$

It can be seen from the above equations that, if the ratio V/ƒ remains constant for any change in ƒ, then flux remains constant and the torque becomes independent of the supply frequency. With increase in speed, the stator voltages must, therefore, be proportionally increased to keep the constant ratio of V/f.[23]

4.6.2. Open-loop scalar control

The open-loop Volts/Hertz control of induction motors is widely applied in industry *(Fig. 1.7)*. For this strategy, feedback signals are not demanded. This type of motor control has some upsides:

- ✓ low cost,
- ✓ simplicity
- ✓ immunity to errors of feedback signals.

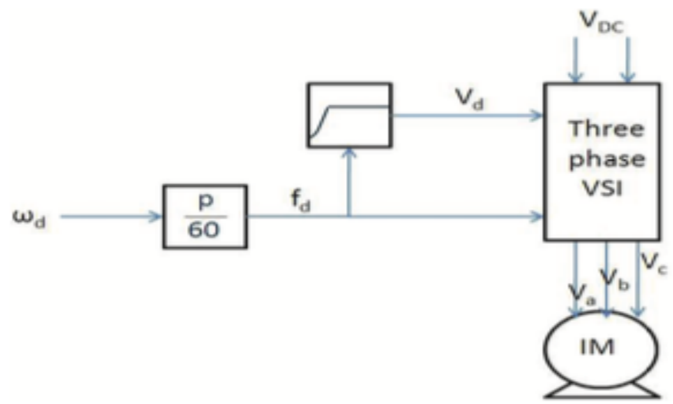


Figure 1. 7. Open-loop scalar control

4.6.3. Closed-loop scalar control

The closed-loop control method provides a more accurate solution to observing the speed than the open-loop method. In addition, the closed-loop technique monitors the torque, as well. The main disadvantage of the open-loop control method is that it does not observe and control the torque, so the required torque is only accessible at the nominal working point. If the load torque varies, the speed of the motor will vary. The closed-loop method contains a slip control loop, since to slip being proportional to the torque. The feedback signal of speed from the tachogenerator is compared to the required speed value. The difference is reduced to zero by a PI controller, so the motor will attain the desired speed.

[23] *Www.ti.com: Comparison of scalar and vector control strategies of IM* [online]. [cit. 2018-08-10]. Available at: http://www.ti.com/lit/an/sprabq8/sprabq8.pdf

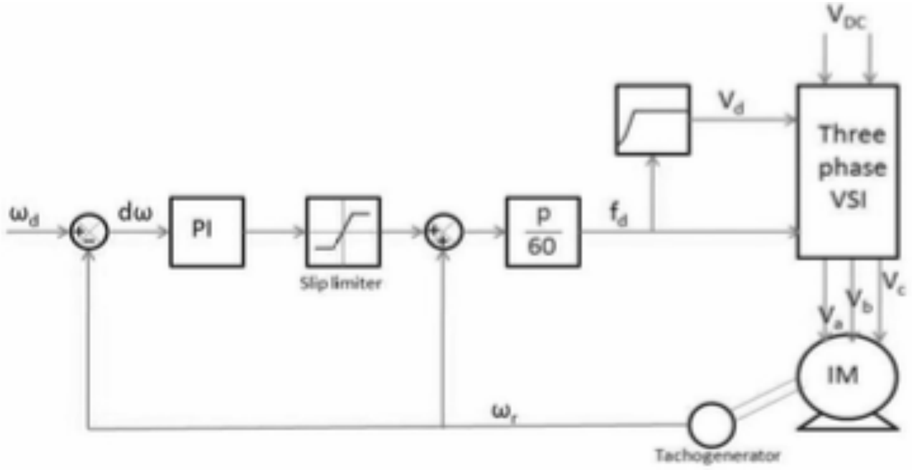


Figure 1. 8 Closed-loop scalar control

4.6.4. Vector control method

Field oriented control is considered one of the vector control methods. The other prominent ways are direct torque control and direct self control, that work with vectors, as well. The field oriented control method ensures good and firm control in case of transients. The principle of operation of field oriented control is rotating vectors in a different coordinate system. Both the magnitude and the phase of the controlled current varies. With this method, it is possible to isolate the field components, which creates two independent and single controlled currents: the flux-producing current and the torque-producing current. Using these currents, the flux and torque can be independently and completely controlled and observed. Moreover, a 90° phase angle is ensured between the isolated controlled currents. Field oriented control can be assigned by system and coordinate transformations of the basic equations of the induction motor. After using the transformations, the alternating and sinusoidal outputs become non-alternating quantities. Due to isolation, the currents can be monitored, and then, after back-transformation it is possible to correct the 3-phase quantities of the inverter. Thus, the magnitude and phase of supplied voltage or current can be corrected. The valid equations can be expressed by the general voltage and flux phasors of the motor (Eqs. 3.1, 3.2, 3.3, 3.4). It is possible to separate the equations into two parts. The stator equations are valid in the coordinate system stationary to the stator, and the rotor equations are valid in the coordinate system stationary to the rotor.

$$\bar{v}_s = \bar{i}_s \cdot R + \frac{d\bar{\psi}_s}{dt}$$

$$\bar{v}_r = \bar{i}_r \cdot R + \frac{d\bar{\psi}_r}{dt}$$

$$\bar{\psi}_s = \bar{i}_s \cdot L_s + \bar{i}_r \cdot e^{j\theta} \cdot L_m$$

$$\bar{\psi}_r = \bar{i}_r \cdot L_r + \bar{i}_s \cdot e^{-j\theta} \cdot L_m$$

(Eqs. 3.1, 3.2, 3.3, 3.4)

where,

v_r, v_s	= supplied voltage in rotor and in stator
i_r, i_s	= current in rotor and in stator
R	= resistance of stator and rotor coils
Ψ_r, Ψ_s	= magnetic flux-linkage in rotor and in stator
L_r, L_s, L_m	= inductance of stator coil, of rotor coil and of the air-gap

It is important to identify the electromagnetic torque to get the equation of motion of the motor (Eq. 3.5).

$$\bar{T}_e = \frac{3}{2}\bar{\psi}_r \bar{i}_r \sin\varphi = -\frac{3}{2}\bar{\psi}_r \times \bar{i}_r \qquad \text{(Eq. 3.5)}$$

Where,

T_e	= electromagnetic torque of motor
Ψ_r	= magnetic flux-linkage in rotor
I_r	= current in rotor[24]

[24] *Www.mk.uni-pannon.hu: Comparison of scalar and vector controls and brief introduction to them* [online]. [cit. 2018-07-28]. Available at: http://mk.uni-pannon.hu/hjic/index.php/hjic/article/download/422/390

5. Equivalent circuit of squirrel cage induction motor

This paragraph introduces an equivalent circuit, description of Power System Block set, determination of equivalent circuit parameters, calculations by experiment and verification of parameters on real induction motor.

5.1. Equivalent circuit

Direct Quadrature (d-q) transformation is mathematically transformed in order to make the analysis of 3-Phase circuit simpler. In the case of balanced three phase circuits, application of d-q transformation decreases the 3 AC quantities to 2 quantities. Simplified estimations can then be assigned on these imaginary quantities before operating the inverse transformation to treat the actual 3-Phase AC results.

5.1.1. Stator reference

Stator and rotor fluxes:

$$\psi_{sD} = \frac{1}{s}\left(V_{sD} - R_s i_{sD}\right)$$

$$\psi_{sQ} = \frac{1}{s}\left(V_{sQ} - R_s i_{sQ}\right)$$

$$\psi'_{rd} = \frac{1}{s}\left(V_{rd}' - R_r I_{rd}' - P.w_m \psi_{rq}'\right) = \frac{1}{s}\left(-R_r i_{rd}' - P.w_m \psi_{rq}'\right)$$

$$\psi_{rq} = \frac{1}{s}\left(V_{rq}' - R_r i_{rq}' + P.w_m \psi_{rd}'\right) = \frac{1}{s}\left(-R_r i_{rq}' + P.w_m \psi_{rd}'\right)$$

(Eq. 3.7)

Stator and rotor currents:

$$i_{sD} = \psi_{sD}\frac{L_r}{L_x} - \psi_{rd}'\frac{L_m}{L_x}$$

$$i_{sQ} = \psi_{sQ}\frac{L_r}{L_x} - \psi_{rq}'\frac{L_m}{L_x}$$

$$i_{rd} = \psi'_{rd}\frac{L_s}{L_x} - \psi_{sD}\frac{L_m}{L_x}$$

$$i_{rq} = \psi'_{rq}\frac{L_s}{L_x} - \psi_{sQ}\frac{L_m}{L_x}$$

$$\text{Where } L_x = L_s L_r - L_m^{\,2}$$

(Eq. 3.8)

5.1.2. Rotor reference

Stator and rotor fluxes:

$$\psi_{rd} = \frac{1}{s}\left(V_{rd} - R_r i_{rd}\right) = 0$$

$$\psi_{rq} = \frac{1}{s}\left(V_{rq} - R_r i_{rq}\right) = 0$$

(Eq. 3.9)

$$\psi'_{sd} = \frac{1}{s}\left(V_{sd}' - R_s I_{sd}' + P.w_m \psi_{sq}'\right) = \frac{1}{s}\left(-R_r i_{rd}' - P.w_m \psi_{rq}'\right)$$

$$\psi'_{sq} = \frac{1}{s}\left(V_{sq}' - R_r i_{sq}' - P.w_m \psi_{sd}'\right) = \frac{1}{s}\left(-R_r i_{rq}' + P.w_m \psi_{rd}'\right)$$

(Eq. 4.1)

Stator and rotor currents:

$$i_{sD} = \psi'_{sD}\frac{L_r}{L_x} - \psi_{rd}'\frac{L_m}{L_x}$$

$$i_{sQ} = \psi'_{sQ}\frac{L_r}{L_x} - \psi_{rq}'\frac{L_m}{L_x}$$

$$i_{rd} = \psi_{rd}\frac{L_s}{L_x} - \psi'_{sD}\frac{L_m}{L_x}$$

$$i_{rq} = \psi_{rq}\frac{L_s}{L_x} - \psi'_{sQ}\frac{L_m}{L_x}$$

$$\text{Where } L_x = L_s L_r - L_m^2$$

(Eq. 4.2)

5.1.3. Motion equation

The motion equation is expressed as follows:

$$t_e - t_L = J\frac{dw_m}{dt} + Dw_m$$

(Eq. 4.3)

where,

t_e = electromagnetic torque

t_L = load torque

J = inertia of the rotor

D = damping constant

Using the torque expressions eq. , the motion equation (Eq. 4.3) can be expressed as follows:

$$P.c.\left(\psi_{sD}.i_{sQ} - \psi_{sQ}.i_{sD}\right) = t_L + w_m\left(D + Js\right)$$

$$w_r = \frac{P.c.\left(\psi_{sD}.i_{sQ} - \psi_{sQ}.i_{sD}\right) - t_L}{D + Js}$$ (Eq. 4.4)

Where,

P	= number of pair of poles
c	= torque constant, takes the values 1 or 2/3.[25]
d	= direct axis
q	= quadrature axis
s	= stator variable
r	= rotor variable
ψ	= flux linkage
V_{sq}, V_{sd}	= q and d – axis stator voltages
V_{rq}, V_{rd}	= q and d – axis rotor voltages
ψ_{sd}, ψ_{sq}, ψ_{rd}, ψ_{rq}	= q and d axis magnetizing stator and rotor flux linkages
R_s	= stator resistance
R_r	= rotor resistance
L_s	= stator leakage inductance
L_r	= rotor leakage inductance
L_m	= self-magnetizing inductance
i_{sd}, i_{sq}	= q and d – axis stator currents
i_{rD}, i_{rQ}	= q and d – axis rotor currents

5.2. Description of Power System Block set

MATLAB/Simulink is a systems simulator and it cannot manage to directly simulate electrical circuits. That’s why, when simulating electric circuits, a power system block set is utilized, which incorporates libraries of electrical blocks and analysis tools which are applied to transform electrical circuits into Simulink diagrams. The electrical blocks or electrical models such as electrical machines, current and voltage sources, power electronics switches, conductors and sensors for estimations purpose. When the simulation begins, Simulink especially use the PM block set and transform the electrical circuit into a state space depiction with the conditions of state variables. The real

25 *https://pdfs.semanticscholar.org: Torque Ripple Reduction in Direct Torque Controlled Induction Motor drive by using Fuzzy Logic* [online]. [cit. 2018-07-18]. Available at https://pdfs.semanticscholar.org/bd5b/5b878aa358ed77d0794773f58c533dfd7dd3.pdf

simulation begins after this recent conversion. This lets us use the wide variety of fixed step and variable step algorithms that is free in Simulink. As variable time step algorithms are quicker than fixed time step way, since the number of steps are less, these algorithms are applied for small and medium size systems, and for large systems consisting of a greater number of stages, a fixed time step algorithm is applied. A Simulink scope can be applied to present the simulation outputs or these quantities can be delivered to workspace while the simulation is on. The variety of MATLAB functions and tool boxes are present for operating and plotting of wave forms from store data.

5.3. Determination of Equivalent circuit parameters by experiment

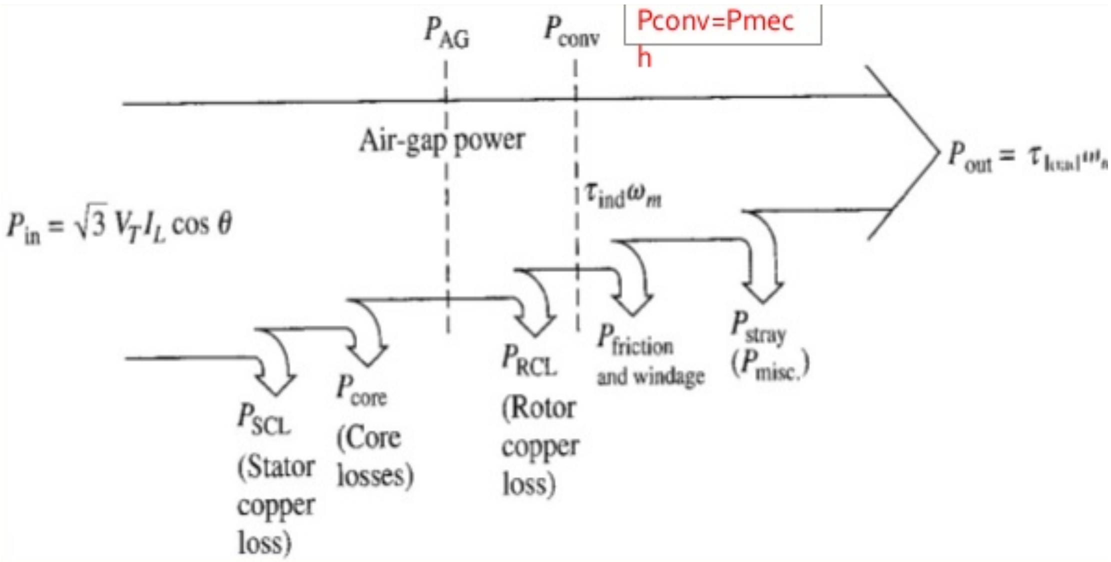
Induction motor efficiency (η) is the degree of the ability of an induction motor to convert electrical power to mechanical power; kilowatts (kW) of electric power supplied to the motor at its electrical terminals and kW of mechanical power measured at the motor rotating shaft. Thus, the power absorbed by the electric motor, during this conversion from electrical to mechanical power, is the losses incurred in making the conversion. To reduce the electric power consumption of an induction motor, for a given mechanical energy out, the motor losses must be reduced and the electric motor efficiency will be increased. To accomplish this, it is necessary to understand the types of losses that occur in an electric motor.

$$Efficiency = \frac{Mechanical\ Power\ out}{Electrical\ Power\ in}\ x\ 100\%$$

$$Here, Mechanical\ Power\ out = Electrical\ Power\ in - Motor\ losses$$
$$or, Electrical\ Power\ in = Mechanical\ Power\ out + Motor\ Losses$$

(Eq. 4.5)

The power losses of a motor consist of stator power losses and rotor power losses. Stator power loss depends on the current flowing in the stator winding and the stator winding resistance. It's important to note the interdependence of efficiency and power factor of a motor; with increase in efficiency, the power factor tends to decrease. To maintain a constant power factor, the stator current must be decreased in proportion to the increase in efficiency. To increase the power factor, the stator current must be decreased more than the increase in efficiency. From a design perspective, however, this is difficult to accomplish, while still maintaining other performance requirements such as breakdown torque. But the stator losses are also inversely proportional to the square of the efficiency and the power factor. Additionally, the stator loss is dependent on stator winding resistance, which is inversely proportional to the weight conductors in the stator winding. Thus, more conductor material in the stator winding results in lower losses. Rotor power loss is usually expressed as slip loss. Rotor slip can be reduced in two way: by increasing the amount of conductor material in the rotor or by increasing the total flux across the air gap into the rotor. However, the extent of these changes is limited by the minimum starting torque required, the maximum starting current and the minimum power factor required.[26]



I would, now, like to kindly introduce the working system in our Roztoky laboratory:

- Motor: 28 kW, 100 Hz, 125 A, 180 V star connection of windings (Y). 230 V to 300 V, Frequency controlled. We use braking for idle or no load conditions, since, even if the torque is ideally 0 at these conditions, there may be some small revolutions, which are avoided by braking. Revolution sensor in motor is magnetic.
- Inverter used is 100 kW at 400 V.
- Dynamometer used to measure torque output and apply load torque is 85kW, 0.5 to 197 Hz, 400 V (3 phase), 147 A (3 phase), 0 to 6000 rpm, power factor 0.78, insulation class F (Motor winding insulation max temperature of 155 degree C), 750 kg.
- Torque and speed are controlled by frequency. Frequency is varied depending on required torque, which determines the speed based on load. Weight, inclination and speed will determine load and load torque.
- Operational algorithm:

DTC → Inverter (DC from accumulator to AC) → Motor → Feedback loop from motor output to DTC.

- The motor is water cooled, to reduce heat losses and keep the mechanism cooled during operation (especially during heavy loading or long running

[26] *http://what-when-how.com: What is Efficiency? (Electric Motor) [online].* [cit. 2018-07-20]. Available at http://what-when-how.com/electric-motors/what-is-efficiency-electric-motor/

duration). The temperature of the cooling water is maintained at around 10 deg C.

- 1200 rpm is resonance, which is critical resolution of test bench.

The test conducted at Laboratory was to simulate variation in load torque at constant speeds, i.e., to simulate change in load conditions like incline, decline and loaded weight. The test bench at the lab was used.

To simulate these conditions, I maintained the speed at a certain value and then gradually increased load torque, to measure the corresponding values of Frequency, AC and AC currents and voltages, Mechanical Power, Electrical Power, DC Input Power, Electromagnetic Torque, Motor Speed, Power Factor (cosϕ) and Motor Efficiency (η).

The values of speed and torque were chosen around their rated values (rated speed 2900 rpm and rated torque 90 Nm, from specification sheet of motor provided by manufacturer). Speeds were set at 2900 rpm, 2500 rpm and 3400 rpm for each test variation, and the value of load torque was gradually increased from 7 Nm to 90/ 100 Nm (approximately). At each of these initial conditions set, the test bench measured the other required values which were then saved in a table format in an excel sheet, for ease of review and converting into graphical form, to make it understandable. Unwanted values and columns were removed, and the important values were kept, for graphical representation.

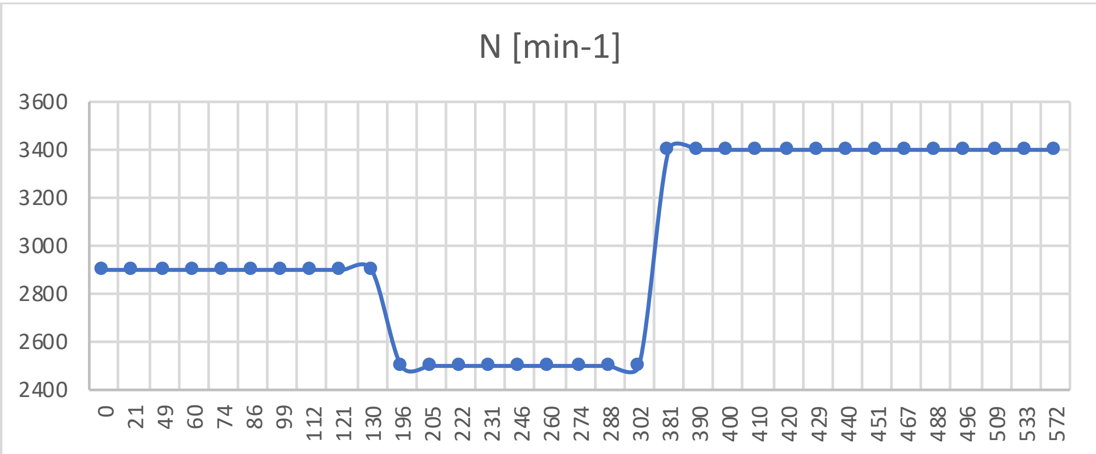


Figure 1. 9 Speed, N[min-1]

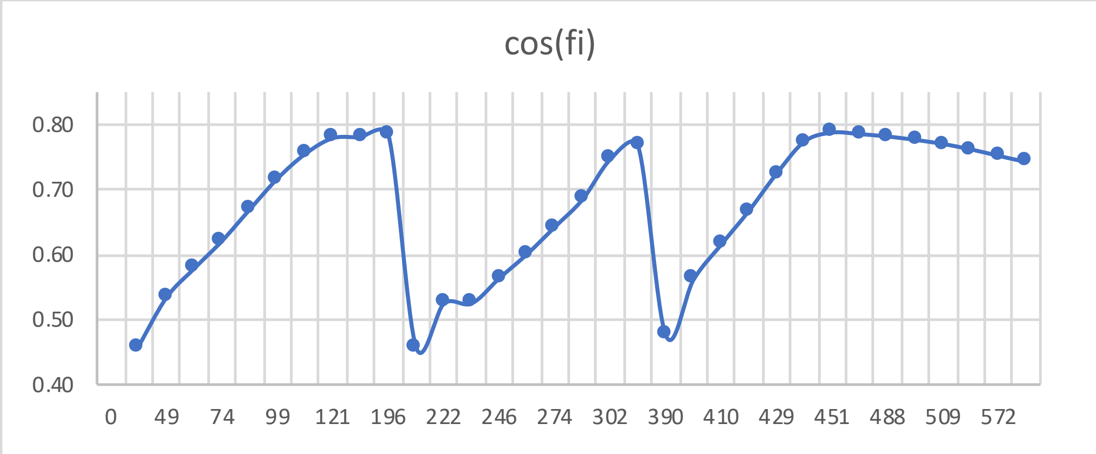


Figure 2. 1 Power Factor, cos[fi]

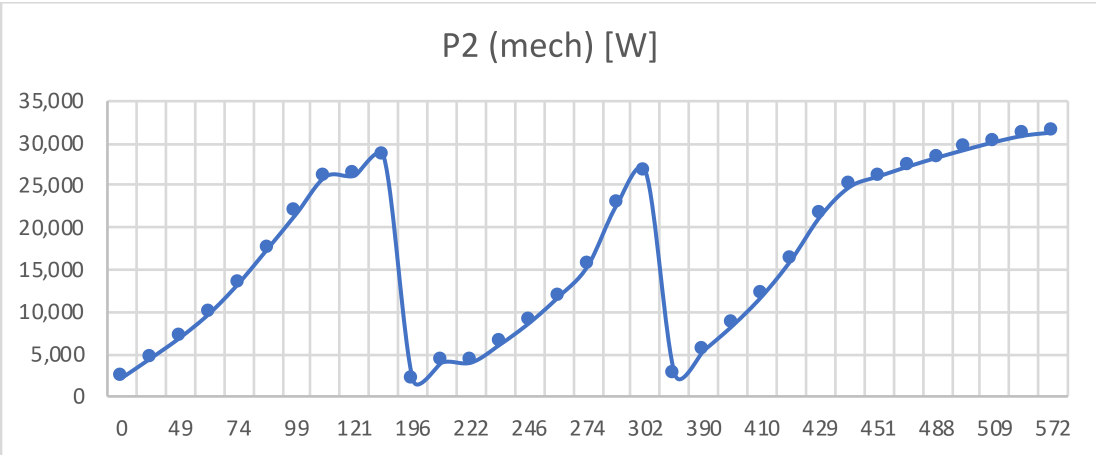


Figure 2. 2 Mechanical Power, P2 (mech) [W]

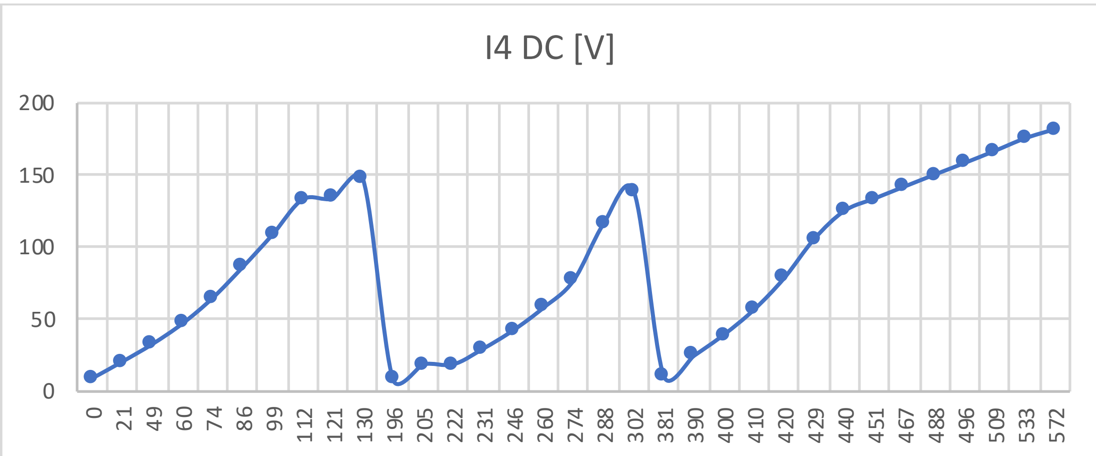


Figure 2. 3 DC, I4 DC [V]

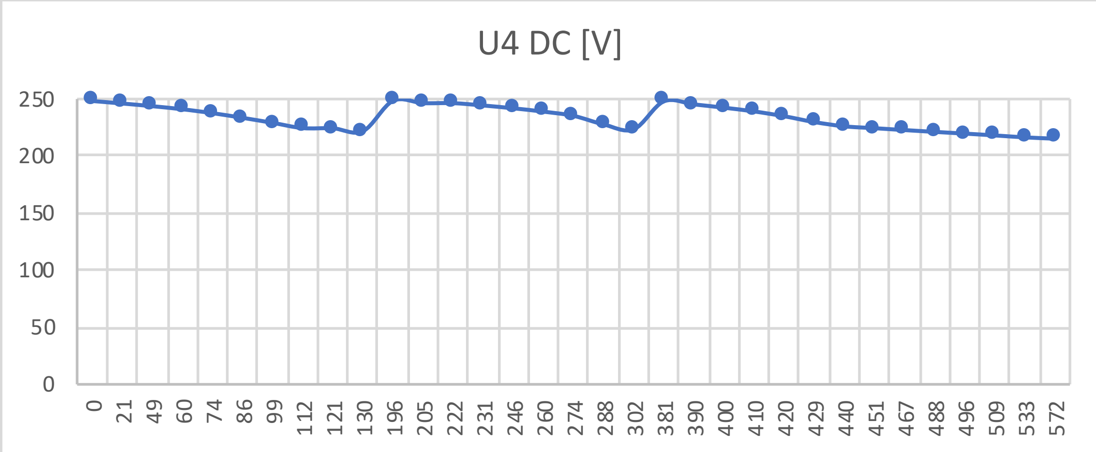


Figure 2. 4 DC Voltage, U4 DC [V]

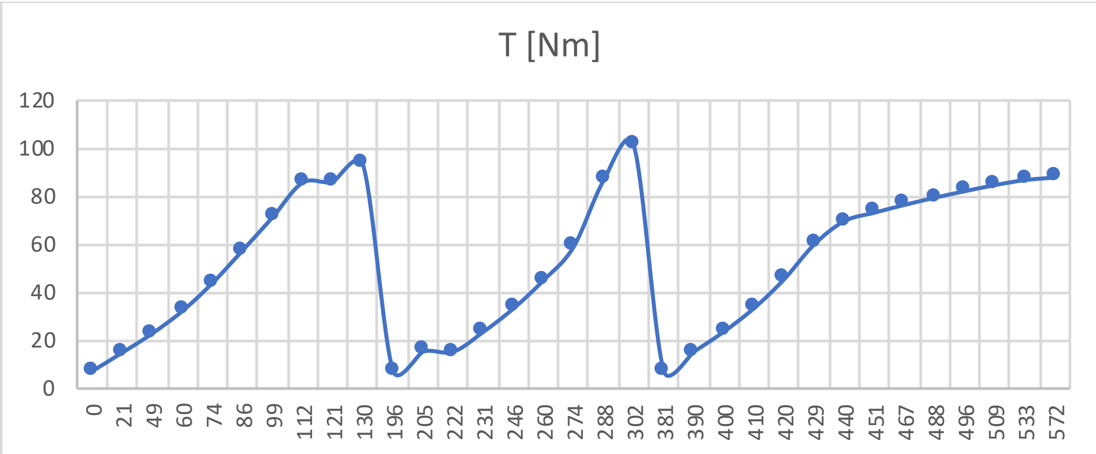


Figure 2. 5 Electromagnetic Torque, T [Nm]

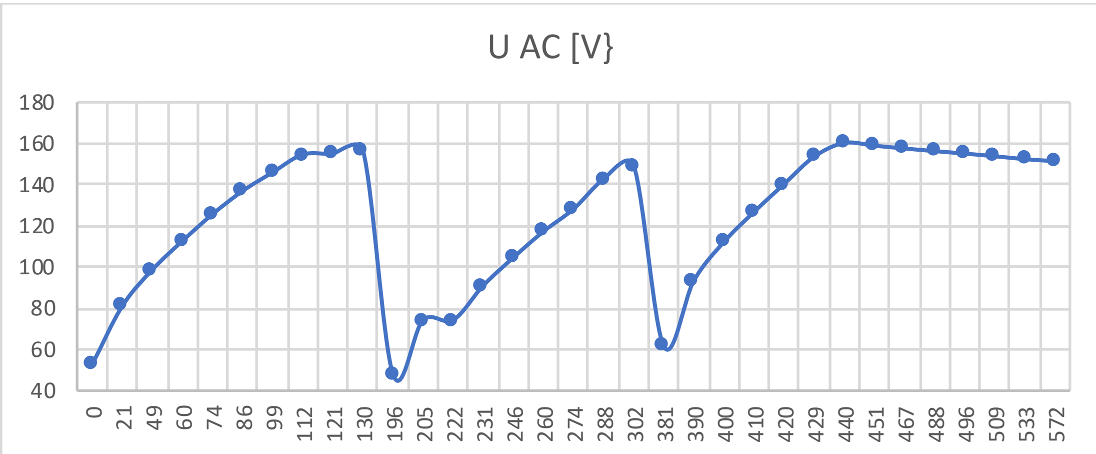


Figure 2. 6 AC Voltage, U AC [V]

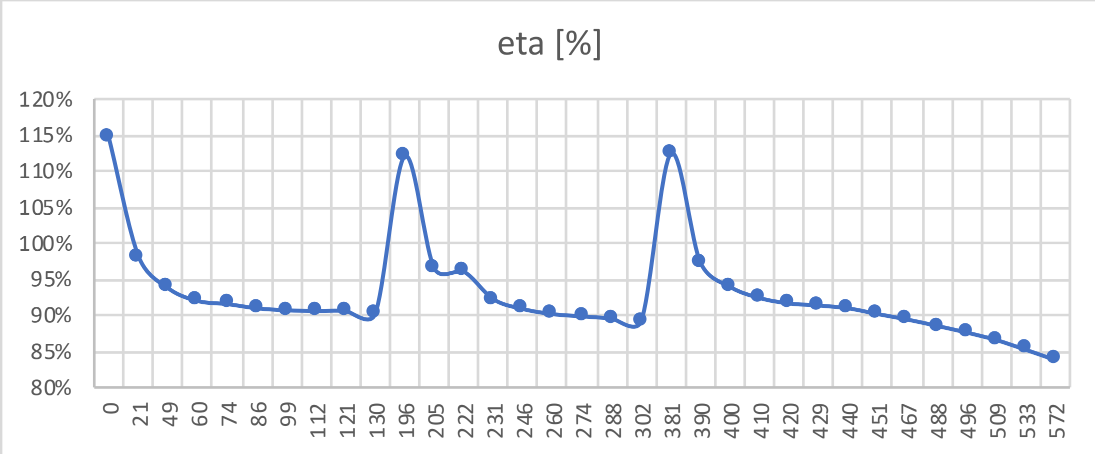


Figure 2. 7 Efficiency, eta [%]

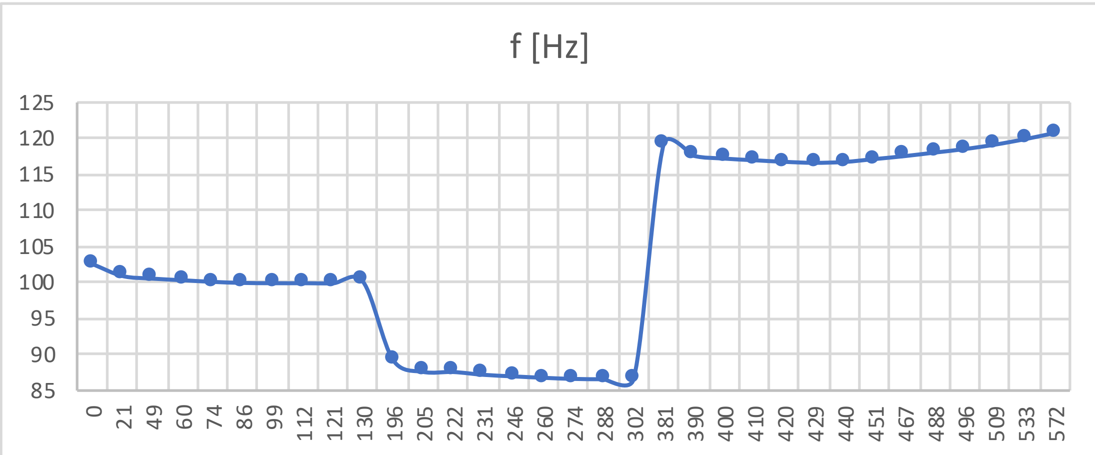


Figure 2. 8 Frequency, f [Hz]

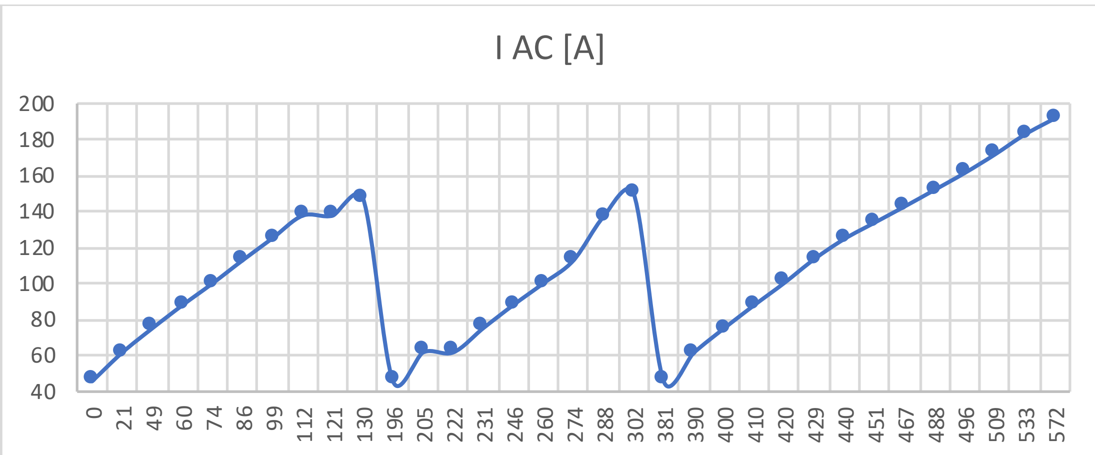


Figure 2. 9 AC, I AC [A]

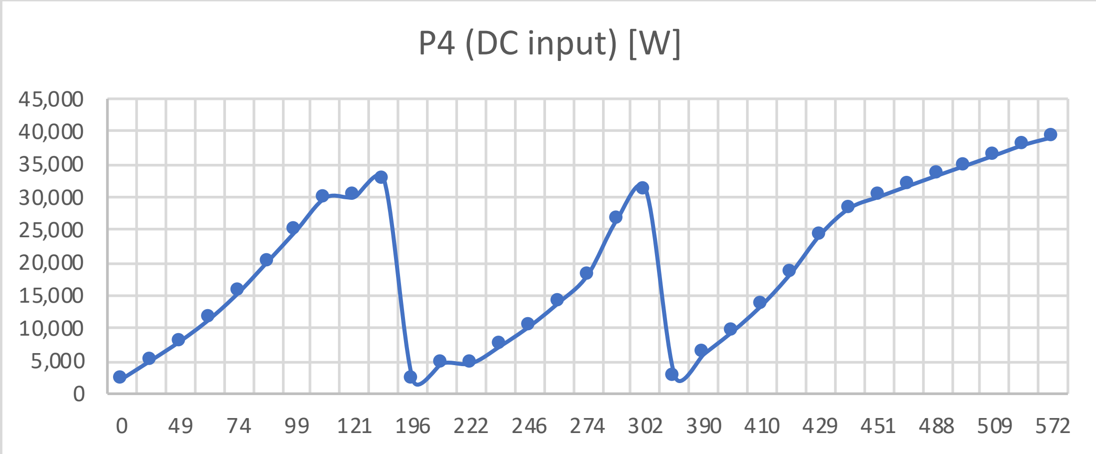


Figure 3. 1 DC Input Power, P4 (DC input) [W]

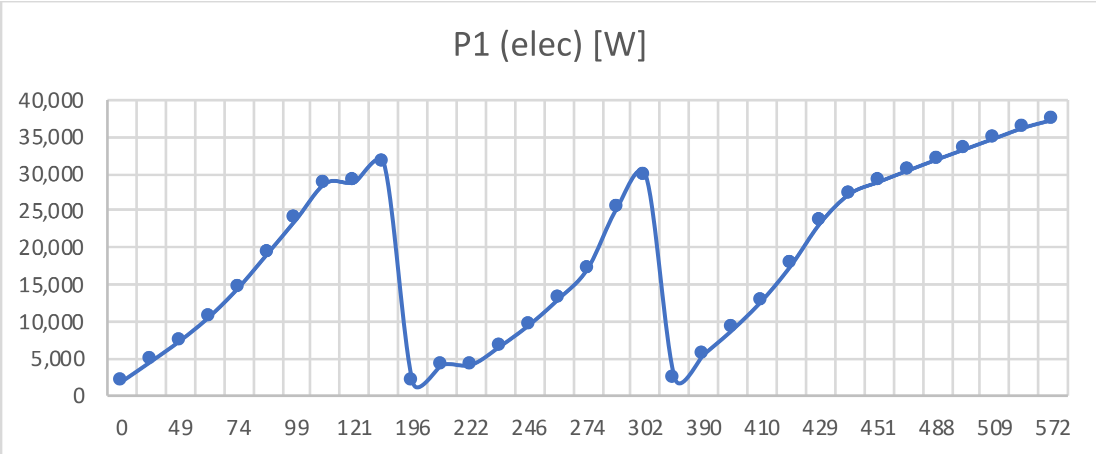


Figure 3. 2 Electrical Power, P1 (elec) [W]

The graphs show that for a constant value of speed:

- The slope of torque curve up to or around rated value is higher when speed is below rated value, this increase in torque is much slower towards rated value when operating speed is above rated value.
- Speed is dependent on frequency. For a constant speed frequency is also constant, consequently frequency is lower for lower speed and higher for higher speed.
- With increase in torque, value of AC and DC currents also increases, thus increasing electrical, dc input (source) and mechanical power.
- From the DC input which is usually the battery, energy is being consumed, resulting in a decrease in output voltage from the DC source. This decrease in voltage is however usually around 35 to 50 V.
- AC voltage however increases with increase in torque

- Efficiency (eta) reduces with increase in load torque. It is highest at the lowest load torque and reduces rapidly at fist (exponentially) after which this reduction is very slow.
- Power factor (cosfi) increases with increase in load torque. Then the explanation about this increase can be based on the definition of power factor.
- When load torque is around rated/ nominal value of torque, with increase in speed, torque value increases to rated value at rated speed and then decreases.
- When load torque is higher than rated/ nominal value of torque, with increase in speed, torque value increases to rated value before rated speed and then decreases.
- When load torque is below rated/ nominal value of torque, with increase in speed, torque value remains almost constant throughout range of operation of variable speed.

Full load Induction Motor Efficiency usually ranges from about 85% to 97%, where the related motor losses can be divided as follows: Friction and winding losses = 5–15%, Iron or core losses = 15–25%.

Temperature was also an option while conducting the measurements, but during my testing of the motor, reading from the temperature sensors could not be obtained since it had to be properly calibrated and, therefore, gave no readings. This posed a problem for modelling as well, since adding temperature dependence on motor operation in mathematical modelling of the motor, with its controllers, was complicated. I chose that for the purpose of this project, being the simulation and verification of induction motor with DTC to replicate functioning of the motor and allied controllers in our Roztoky test laboratory (thus the equivalent circuit of induction motor), it was not necessary to test or model temperature dependence.

5.4. Verification of parameters on real induction motor

Generally, it is impossible to get everything perfectly in the simulation and that's why I adjusted the voltage and current.

5.5. Induction Motor model in MATLAB/Simulink

Using all the equations mentioned previously, a dynamic model of the induction motor with Direct Torque Control (Scalar Control, V/f control) was created in MATLAB/ Simulink, composed of an electrical sub-model for the three-axis to two-axis (3/2) change of stator voltage and current estimation, a torque sum-model to estimate the developed electromagnetic torque (T_{em}) and mechanical sub-model to concede the rotor speed (ω).

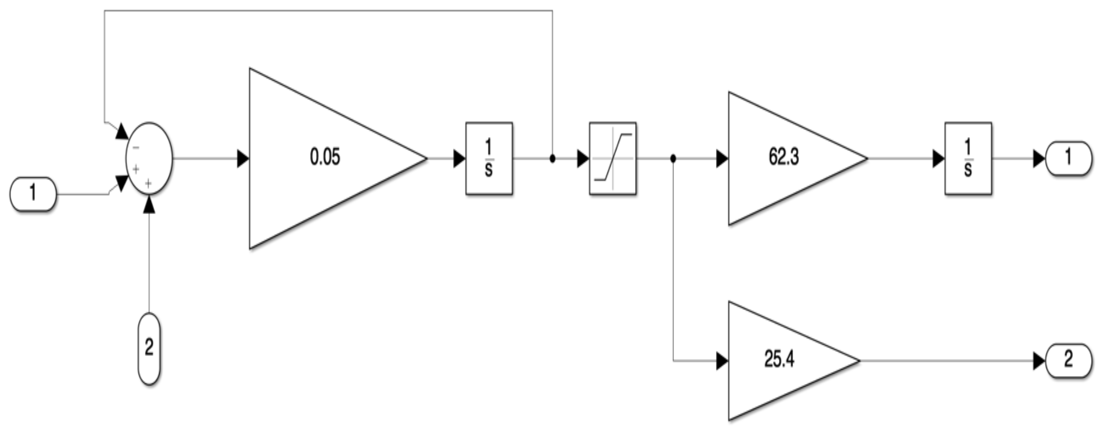


Figure 3. 3. Intensity adjuster for V/f

I modelled an Intensity adjuster for V/f (Figure 3.3) that performs frequency control and acts as a frequency regulator, fed to 3-phase sinus inverter that is depicted below (Figure 3.4):

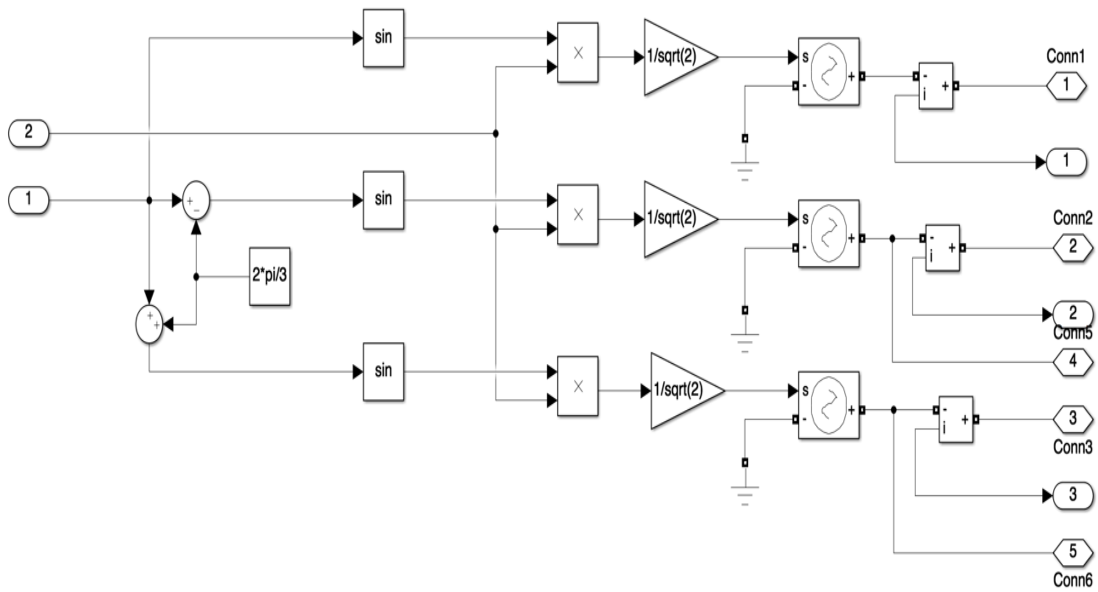


Figure 3. 4. 3-phase sinus inverter

The generalized load model of induction motor created in MATLAB/ Simulink is depicted below:

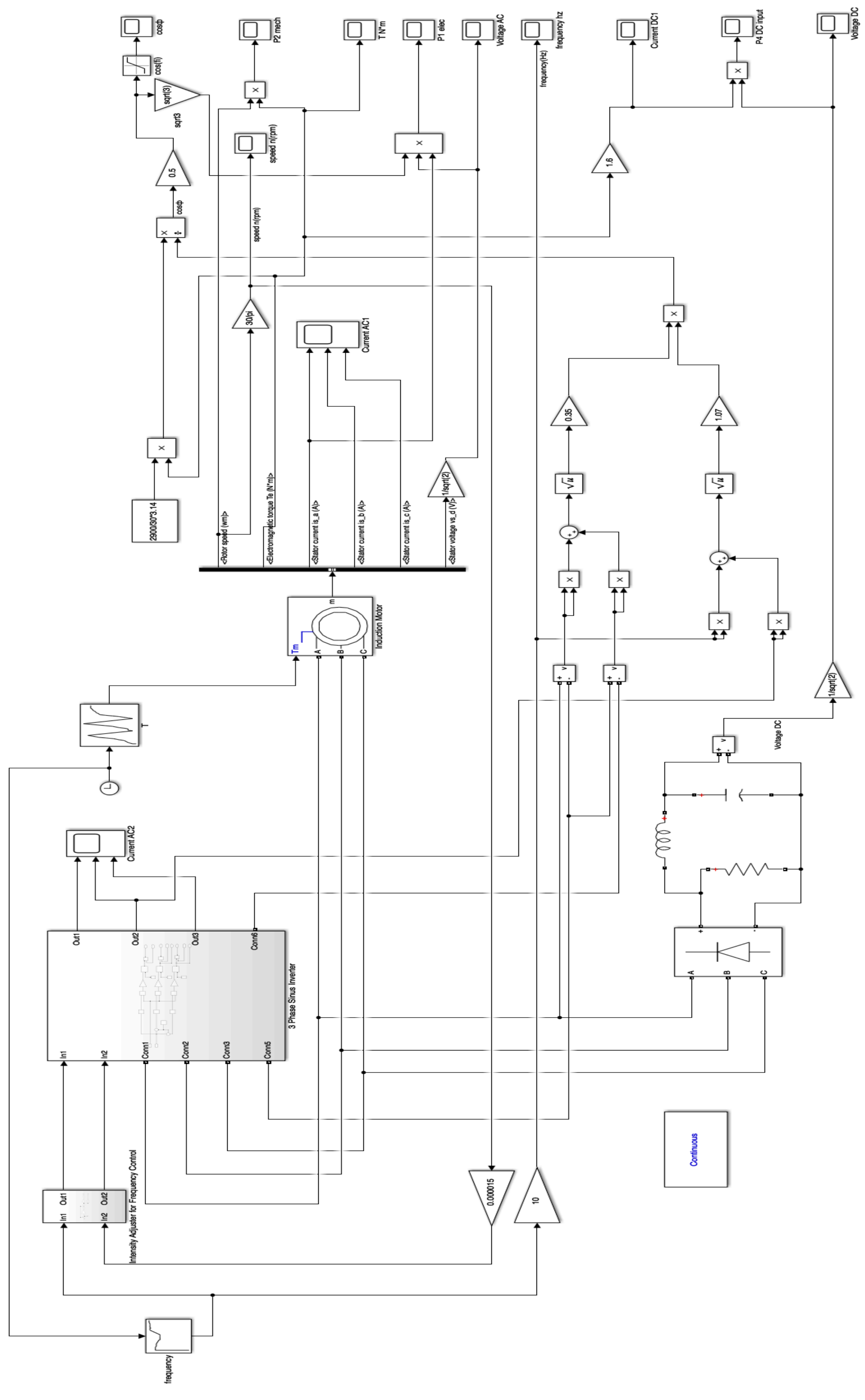
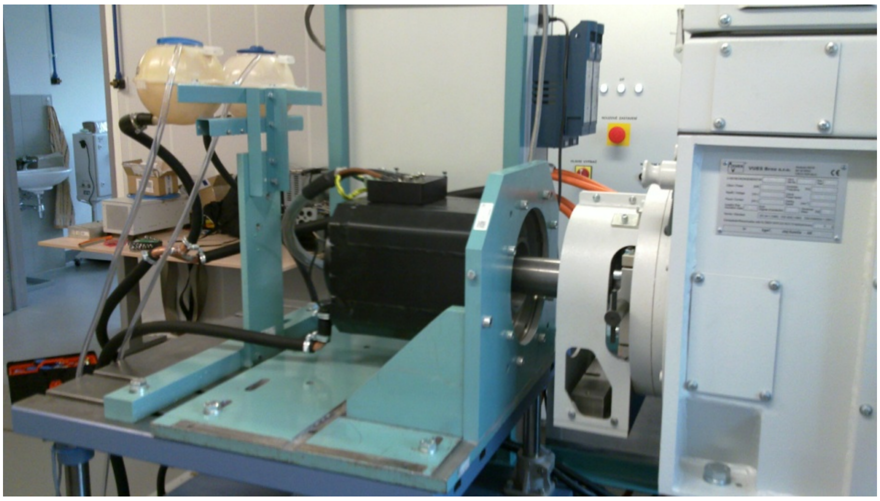
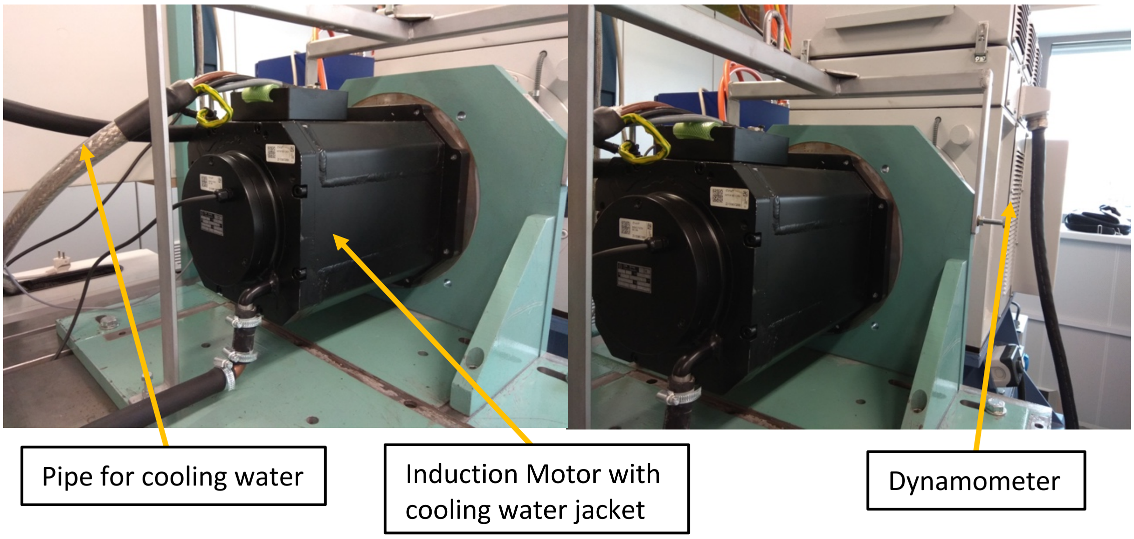


Figure 3. 5. SIMULINK Model of IM

During testing, some pictures were taken in the laboratory of the test bench and equipment, which are attached here for future reference.



Tested Induction Motor connected to the Dynamometer



Measuring and controlling part of testing system

5.6. Simulation and results

Here are the input parameters of the motor, as provided by the manufacturer and verified by tests. The motor specifications are as follows:

- Phase to Phase voltage = 180 V
- Frequency = 100 Hz
- Stator Resistance = 0.016 Ohm
- Rotor Resistance = 0.018 Ohm
- Stator Leakage Inductance = 0.00014 H
- Rotor Leakage Inductance = 0.0002 H
- Magnetizing Inductance = 0.0029 H
- Number of Poles = 4
- Moment of Inertia = 0.04 kg/m^2
- Rated Speed = 2900 rpm
- Rated Torque = 90 Nm
- Rated Power = 28 kW

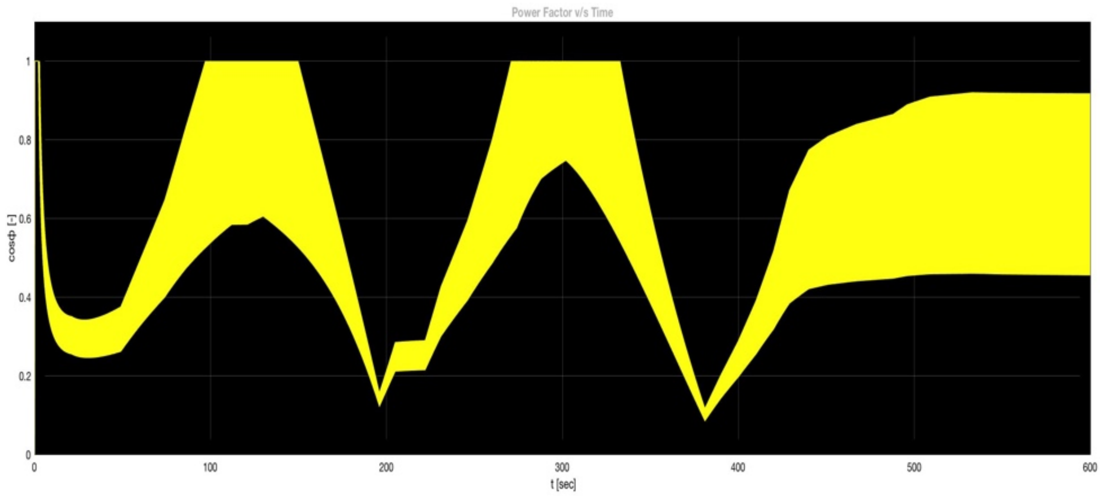


Figure 3. 6 Power Factor, cosφ [-]

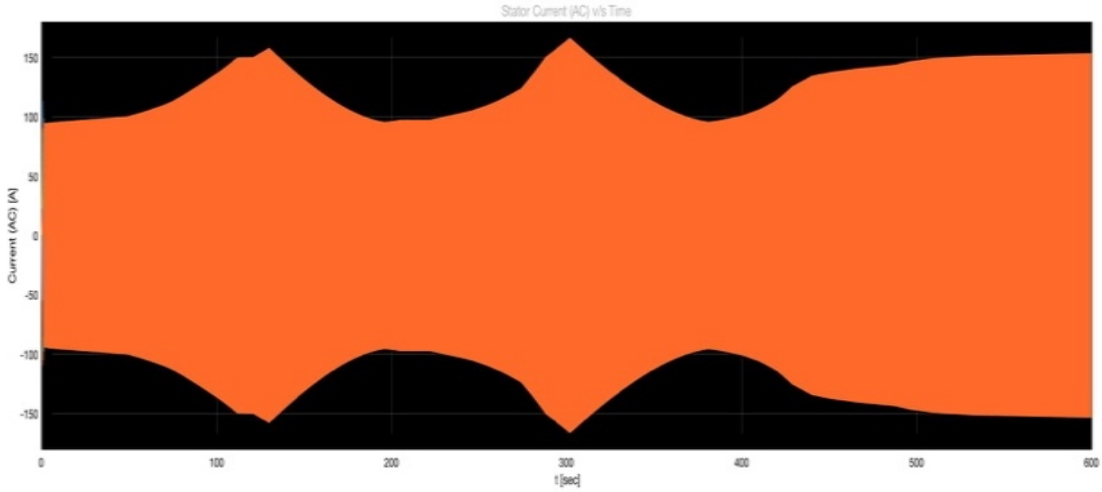


Figure 3. 7 Current AC [A]

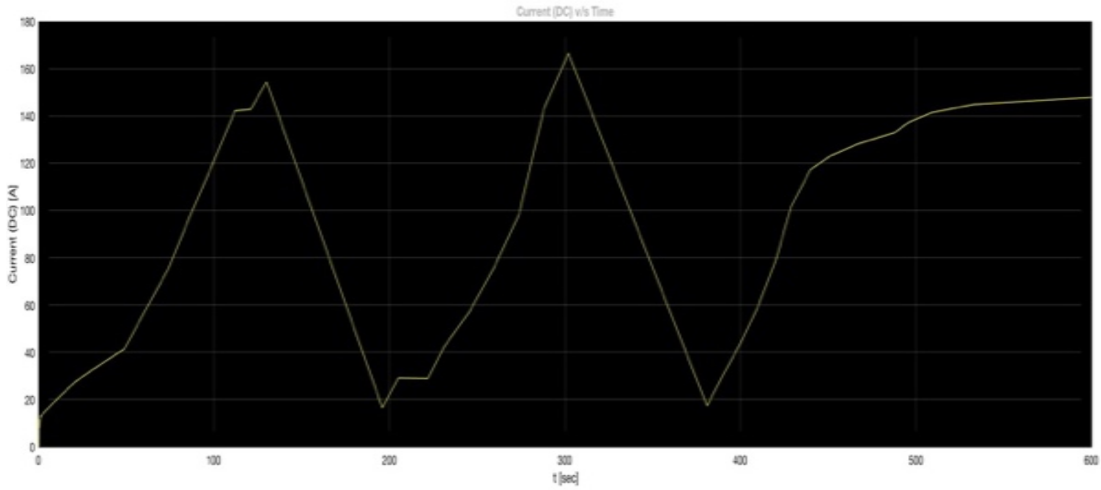


Figure 3. 8 Current DC [A]

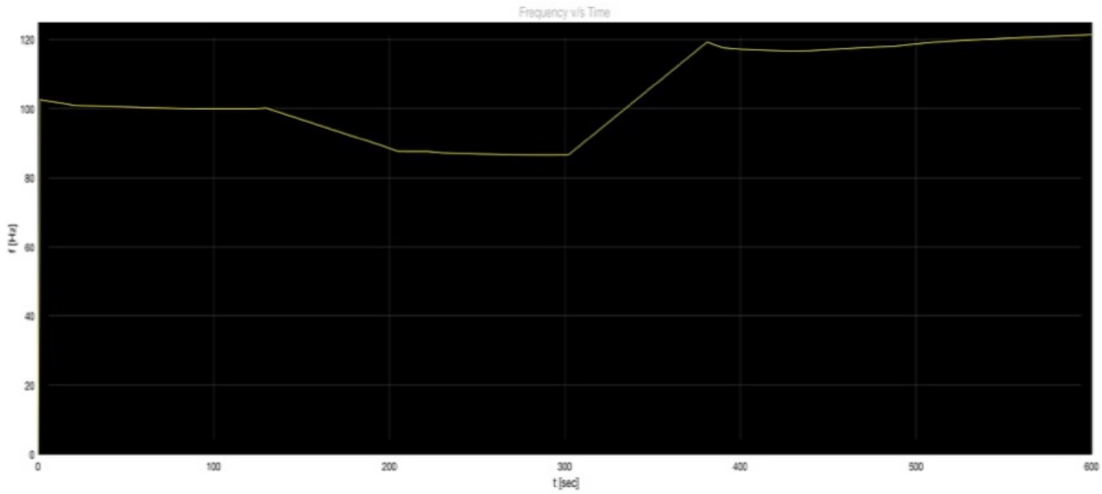


Figure 3. 9 Frequency, f[Hz]

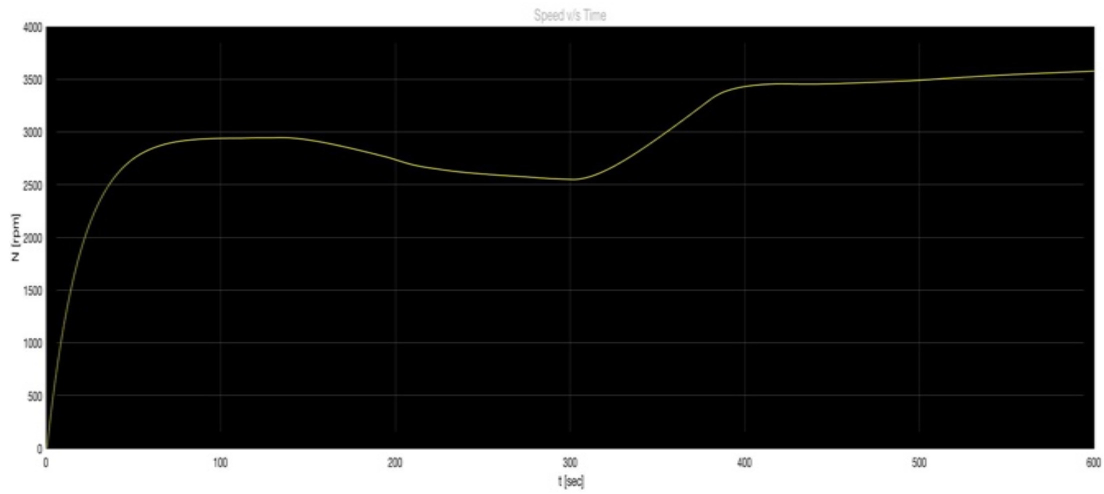


Figure 4. 1 Speed, N[rpm]

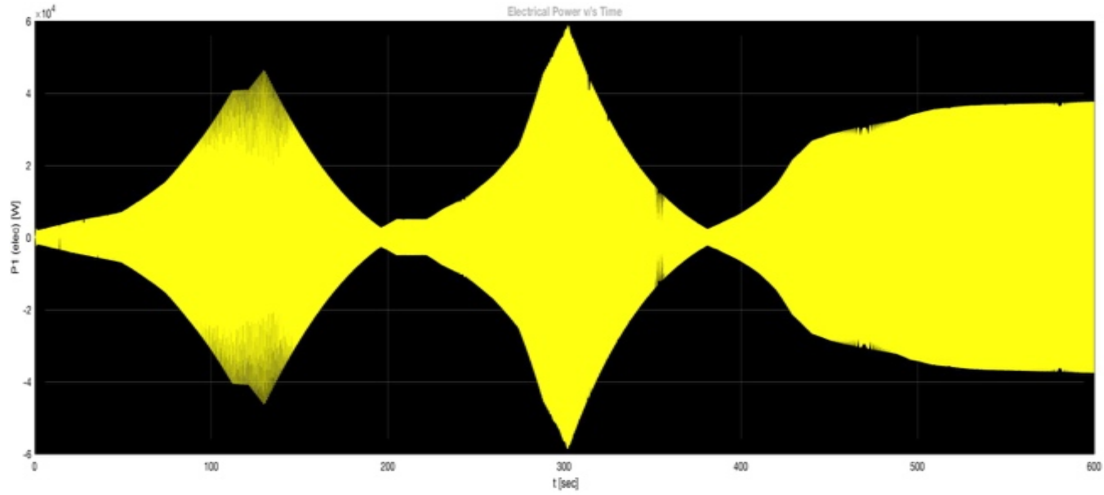


Figure 4. 2 Electrical Power, P1 (elec) [W]

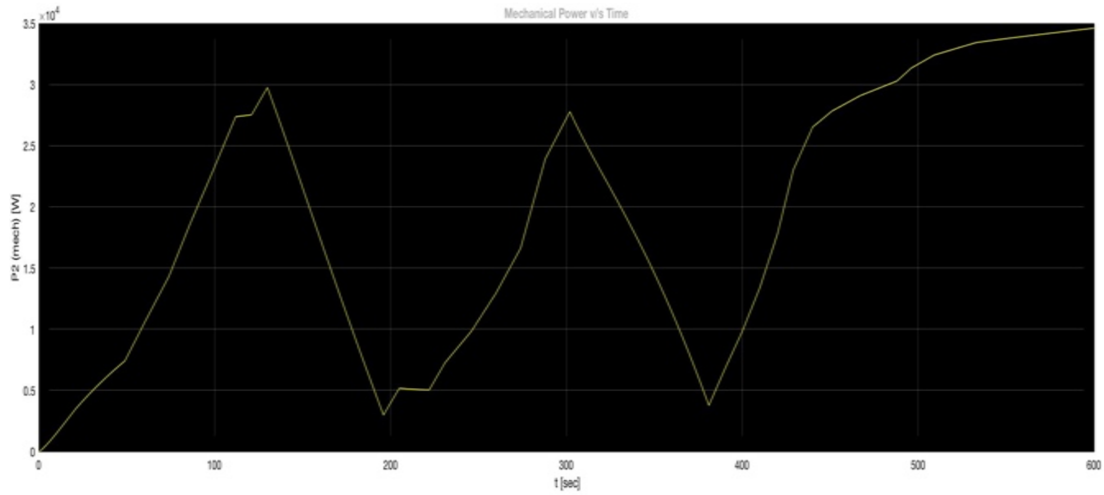


Figure 4. 3 Mechanical Power, P2 (mech) [W]

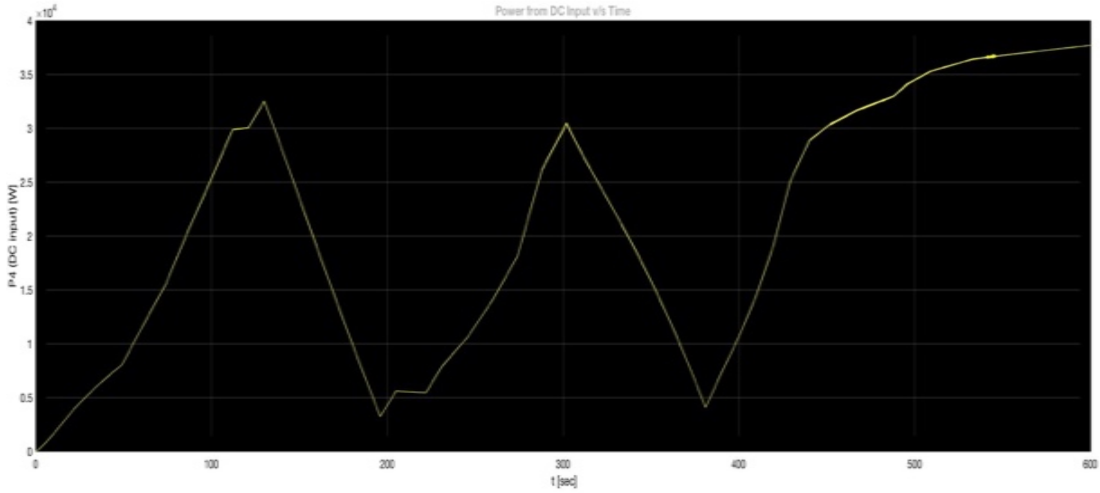


Figure 4. 4 DC Input Power, P4 (DC input) [W]

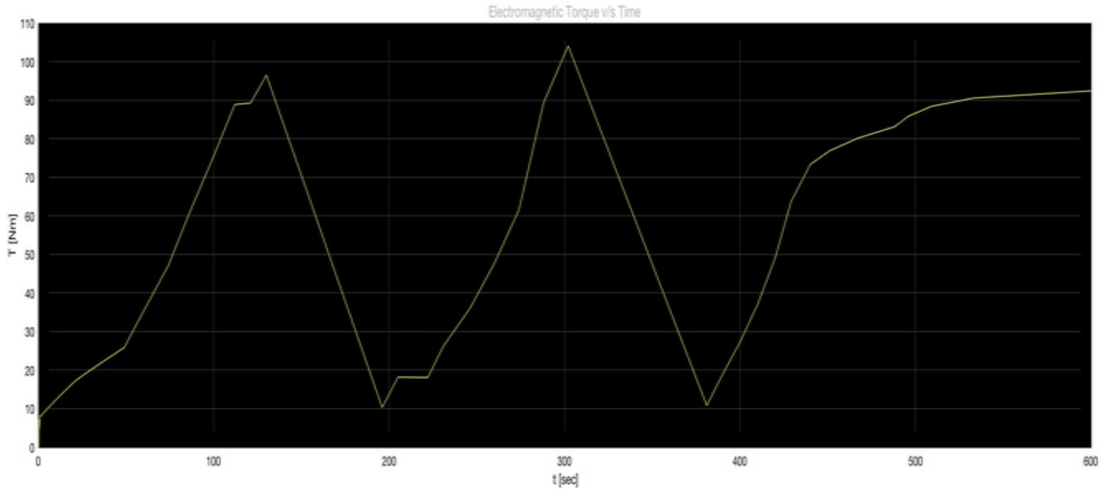


Figure 4. 5 Electromagnetic Torque, T [Nm]

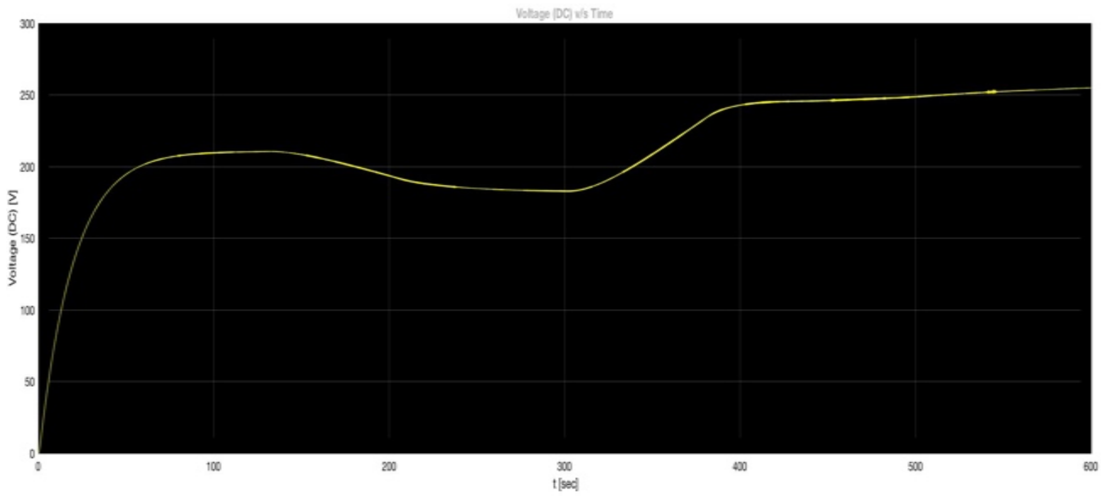


Figure 4. 6 Voltage (DC) [V]

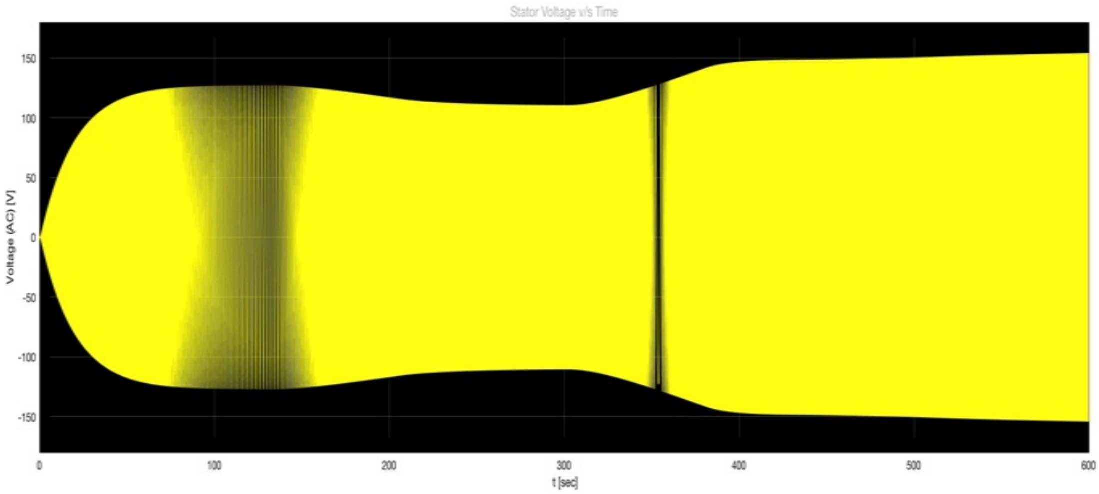


Figure 4. 7 Voltage (AC) [V]

6. Conclusion

To sum up, an induction motor model has been created and its control, monitoring and stability have been shown. Thereafter, Simulink sub-models have been created for different components of DTC. The proposed DTC model has been experimented and assessed on induction machine. The outputs of simulation have shown a high accuracy in torque independent control. In addition, a high stator starting current is seen because of small changes in the stator flux. Thus, further work is demanded to restrict this stator starting current in a way to secure the machine and power electronics devices.

Direct Torque Control is considered to be one of the best and outstanding controllers for induction motor control. Its main principles have been shown, explained and proved. Also, it is shown in this thesis that scalar control method of DTC allows the independent and decoupled control of motor torque and motor stator flux. A MATALB/ Simulink model has been created based on the equation governing the performance and control of Induction Motors with Direct Torque Control. From the results, it is obvious that DTC strategy is simpler to process and operate than flux vector control method, since voltage modulators and co-ordinate transformations are not required. However, it presents some disadvantages, like the torque ripple. Another disadvantage is that there is no control on voltage independently from frequency, as high voltage values at low load torque leads to high power losses. Model individually prepared has proved that the results received at the end successfully match the results obtained from Roztoky laboratory test results.

Keeping the future work in mind, it can be seen that use of fuzzy logic control can gave relative results and decrease the computation burden by escaping unnecessary difficult mathematical modeling of the nonlinear systems. It could be recommended that, to be more successful, there must be the development of new fuzzy controllers and they can work completely on automatic controllers, that easily adapt, even to any other motor. Lastly, I would recommend a deep study on Fuzzy logic DTCs, and this study can be not only applied to induction motors but also any other electrical motors. For this purpose, I believe that the Simulink is an irreplaceable tool for the learning and research of electrical machine drives.

7. List of Figures

List of symbols

IM	Induction motor
DTC	Direct torque control
Hz	Hertz
Ω	Ohm
Wb	Weber
kW	Kilo-Watt
Nm	Newtown-meter
P	Number of pair poles
Te	Electromagnetic Torque
d,q	Direct and quadrature axes
Ψ	Flux linkage
rpm	Revolutions per time
V	Voltage
A	Ampere
H	Henry
f	Frequency
R	Resistance
L	Inductance
s	Slip
J	Inertia

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