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STEADY-STATE DETECTION TECHNIQUES

AC-drive-controlled motor systems

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ABSTRACT

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Modern AC-drives contain algorithms to optimize and improve the operation of electric motors. Some of these optimization algorithms are performed at steady-state operation of the AC-drive, and therefore, steady-state detection techniques are required. The steady-state operation can be determined from the measured values of the motor. For the motor to operate under steady-state, the output of the motor should be approximately constant. Due to electric motors behavior and the system conditions, determining the steady-state can be challenging.

This thesis examines the benefits of the steady-state detection. The challenges and difficulties of the steady-state detection will also be analyzed. To understand the methods, this thesis will review the basics of AC-drive-controlled motor systems.

In the beginning of this thesis, induction motor and its operating principles will be reviewed to understand the need for optimization algorithms. Then the thesis will examine AC-drives and the control of an induction motor. After that, the thesis will review and analyze different optimization algorithms which can be used to improve the control of an induction motor. These algorithms are identification run, flux optimization and condition monitoring.

The last part of this thesis will focus on steady-state detection. Definitions and basics will be introduced, and the difficulties of steady-state detection will be reviewed. Basic techniques for steady-state detection will be reviewed. These basic techniques are linear regression, t-test and f-test. The final chapter discusses steady-state detection in AC-drive systems.

In conclusion, steady-state detection is a difficult task due to its demands in computing power and need for user input. In AC-drive systems, same software is used in different application, causing different problems in steady-state detection. The benefits of using optimization algorithms can be found hugely beneficial for economic and technical standpoint.

Keywords: steady-state detection, identification run, flux optimization, condition monitoring, AC-drive, induction motor

TIIVISTELMÄ

Joonas Kaipainen: Tasapainotilan havainnointimenetelmät
Kandidaatintyö, 34 sivua
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Modernit taajuusmuuttajat sisältävät algoritmeja, jotka optimoivat ja parantavat sähkömoottoreiden toimintaa. Osa näistä algoritmeista tarvitsee järjestelmän tasapainotilan. Tämän vuoksi modernit taajuusmuuttajat tarvitsevat tasapainotilan havainnointia selvittääkseen moottorin toimintatilan. Systeemin tasapainotilan voi selvittää moottorin mittausarvoista. Jotta moottori toimii tasapainotilassa, tulee ulostulon olla keskimäärin muuttumaton. Johtuen sähkömoottorien käyttäytymisestä ja järjestelmien olosuhteista, voi havainnointi osoittautua ongelmalliseksi.

Tavoitteena kandidaatintyössä on tutkia eri mahdollisuuksia, joita tasapainotilan havainnointi mahdollistaa taajuusmuuttajakäytöissä. Työssä tutkitaan haasteita ja vaikeuksia, joita tasapainotilan havainnointiin liittyy. Ymmärtääkseen mitä mahdollisuuksia tasapainotilan havainnointi tuo, tullaan työssä käymään läpi taajuusmuuttajakäyttöisten moottorijärjestelmien perusasiat.

Työn alussa tullaan käymään läpi epätahtimoottori ja sen toiminta, jotta voidaan ymmärtää optimointialgoritmien tarkoitus. Tämän jälkeen työssä tullaan tutkimaan taajuusmuuttajia ja sähkömoottorin ohjaamista. Seuraavaksi työssä tullaan tutkimaan ja analysoimaan eri optimointialgoritmeja, joita voidaan käyttää epätahtimoottorin toiminnan parantamiseen. Analysoitavat optimointialgoritmit ovat tunnistuskäyttö, vuon optimointi ja kuntotarkkailu.

Työn loppuosa keskittyy tasapainotilan havainnointiin. Työssä tullaan esittelemään määritelmät ja perusasiat liittyen tasapainotilan havainnointiin. Tämän jälkeen tullaan tutkimaan tasapainotilan havainnointiin liittyviä haasteita. Työn lopussa tullaan tutkimaan perustekniikoita tasapainotilan havainnoinnille. Näitä perustekniikoita ovat lineaarinen regressio, t-testi ja f-testi. Viimeisessä kappaleessa keskustellaan tasapainotilan havainnoinnista taajuusmuuttajajärjestelmissä.

Yhteenvetona todetaan, että tasapainotilan havainnointi on ongelmallista, sillä tekniikat ovat laskentatehollisesti vaativia ja tarvitsevat palautetta käyttäjältä. Taajuusmuuttajajärjestelmissä samaa ohjelmistoa käytetään erilaisissa sovellutuksissa, ja se aiheuttaa ongelmia tasapainotilan havainnoinnissa. Optimointialgoritmien tuomat edut voidaan nähdä hyvin hyödyllisiksi tutkittaessa tilannetta ekonomisesta ja teknisestä näkökulmasta.

Avainsanat: Tasapainotilan havainnointi, tunnistuskäyttö, vuon optimointi, kuntotarkkailu, taajuusmuuttaja, epätahtimoottori

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1. INTRODUCTION

As the need for energy keeps growing in today's society and climate change is a scientifically proven fact, energy consumers must find ways to lower their energy consumption. The consumption can be lowered by many methods, but when looking at the energy consumption charts, approximately half of the electricity consumed in Finland goes to industries. [1] Out of that portion, 65% is used in electrical machinery. By optimizing and controlling those electrical machines as efficiently as possible, huge savings can be gained in electrical energy consumption.

Electric machines are the base of modern industry and infrastructure. They are used everywhere due to their ability to transform electricity into mechanical power. There is a huge variety of different types of electric machines whether it is the type of mechanical power they produce or the type of electricity it consumes to create that power. The most important type of electric motor is by far the induction motor. Its usage in industries is unrivaled due to easy controllability and low lifecycle costs. As a consequence, the AC-drive systems have become more popular compared to most DC-motor systems.

In this thesis, the goal is to review steady-state detection in AC-drive-controlled motor systems. Detecting a state of steadiness in a continuous process is useful if we use steady-state models to optimize the operation of the process. This thesis will consider the dynamic properties of electric motor operation, and different problems that occur that needs to be taken into consideration in steady-state detection. Different steady-state detection techniques will be reviewed.

Steady-state detection allows the use of optimization algorithms in AC-drive-controlled motor systems. To understand the optimization of electric motor operation, the structure and attributes of system components need to be reviewed. This thesis will consider what are the attributes of the electric motor that matter the most when it comes to optimizing the usage and power consumption. Some power is lost inside an electric motor due to the internal non-idealities. Knowing these non-idealities helps the AC-drive to control the motor more efficiently. When knowing these values, a steady-state model can be built, which can be used to control process variables to the advantage of the motor.

To understand the optimization algorithms, this thesis will consider the induction motors structure to understand what causes the internal non-idealities. The basic principles of how an induction motor creates mechanical power from electricity will be reviewed to fully understand the operation of the motor. AC-drives are reviewed, which control the motors. This thesis will then analyze the different optimization algorithms which use steady-state information. And finally, this thesis will look at steady-state detection techniques, their difficulties and how they can be approached.

This thesis aims to give the reader an insight into AC-drive-controlled induction motor systems and to enlighten the reader on different motor operation optimizing algorithms. The intention is to keep the thesis simple, as the subject can be quite challenging even for an experienced reader. The main questions which this thesis aims to answer are why steady-state detection is needed, and how reliable these techniques are. The topic of this thesis is provided by Danfoss Ltd., and the work is accomplished in collaboration with Danfoss and Tampere University.

The remainder of the work is organized as follows. Section 2 provides information on induction motors. The section goes through the structure and operation of an induction motor. Section 3 is about AC-drives, their operation, and structure. Section 4 presents different optimization algorithms used by AC-drives, which use steady-state information. In section 5 the steady-state concept is reviewed along with the difficulties of identifying steady-state in AC-drive applications. Section 6 goes through different techniques to detect steady-state and section 7 will provide the conclusion of this study along with discussion on the subject.

2. INDUCTION MOTOR

An induction motor is an asynchronous AC motor. Asynchronous means that the motor does not run with the frequency of the input current, unlike synchronous motors. An induction motor transforms electrical power into rotating torque. Due to its simple and relatively cheap build, it's the most common type of motor in industry-use. In addition, the technological advancement in AC-drives has made them easy to control and robust. [2]

Induction motors are typically run by three-phase AC-voltage. This voltage is transformed by the stator into a rotating magnetic flux, which will induce a current in the rotor of the motor. This current will create a force, which will create tangential momentum, ultimately creating torque to the axel of the motor. This torque can then be used to all sort of work that requires mechanical power, using mechanical solutions to transform the created power from the axel. [3]

In this chapter, this thesis will consider the physical phenomena behind the operation of the induction motor. Then the physical structure of the motor and the equivalent circuit of an induction motor will be considered.

2.1 Electromagnetic forces

The basis of the operation of an induction motor is electromagnetic induction, which is used to create a rotating magnetic field from AC voltage [2]. This phenomenon is presented as Faraday's law of induction

$$\mathcal{E} = -\frac{d\Phi_B}{dt} \tag{2.1}$$

where $\mathcal{E}$ is the electromotive force (EMF) and Φ_B is the magnetic flux through a single loop of closed wire. EMF is a force, which moves electric charge to a higher potential, and it is measured in volts (V). Magnetic flux is the scalar product of the magnetic field and the area from which the flux is measured. [4] The magnetic flux can be presented as

$$\Phi_B = \int B \cdot dA \tag{2.2}$$

where B is the magnetic field and dA is the surface-vector. The magnetic flux is measured in webers (Wb). Faraday's law of induction states that an alternating flux induces an equal but inversed EMF into a closed wire loop. For a coil of wire, the induced EMF is

$$\mathcal{E} = -N\frac{d\Phi_B}{dt} \tag{2.3}$$

where N is the number of turns on the coil. [4]

When EMF is induced into a wire, and the wire is closed, it will create a current inside the wire. This current can be calculated with Ohm's law as

$$I = \frac{\mathcal{E}}{Z} = \frac{\mathcal{E}}{R + jX_R} \tag{2.4}$$

where $\mathcal{E}$ is the induced electromotive force, Z is the impedance of the wire loop, R is the resistance of the wire and jX_R is the reactance of the wire. When the current is flowing inside a closed wire loop, and the loop is affected by the variable magnetic field B, it will experience a Lorentz force (2.5) as

$$F = Il \times B \tag{2.5}$$

where I is the current flowing through the wire, l is a vector with the amplitude of the length of the wire and direction and B the vector for the magnetic field. [2] The direction of this force is best illustrated with the so-called "right-hand rule" in Figure 1.

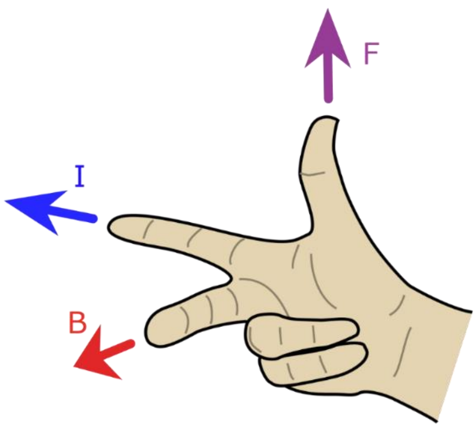

Figure 1: *Right-hand rule*

The right-hand rule is caused by the cross product of vectors, and it means that these three vectors will not be facing in the same direction. This Lorentz force is the basis of electric machinery operation.

2.2 Structure

The structure of the induction motor has been the main reason for its popularity. The simplicity and the paucity of mechanically unreliable parts are the advantages they present when comparing to other motor types. The induction motor has two main parts, stator and rotor. The stator is the stationary part which holds the primary side windings. The stator is usually constructed by welding steel or by casting, and it constitutes the frame of the motor. As the stator makes up the outer frame, it also has mountings and connections attached. [3] A disassembled induction motor is presented in Figure 2.

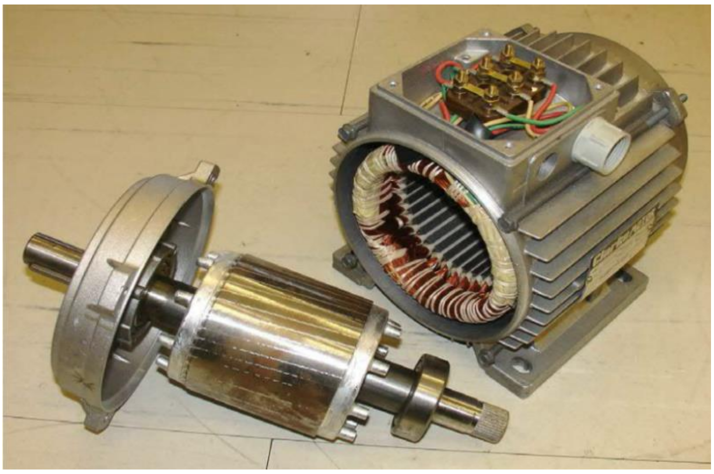

Figure 2: *Stator and rotor of an induction motor*

The rotor of an induction motor could be one of two types. The more common one is the squirrel-cage rotor. The squirrel-cage rotor consists of shorted conducting bars embedded into end rings on both ends. To reduce the effects of disturbances in inducted currents into the rotor, the rotor is then filled with thin sheets of lamination of magnetic material. The simplicity and ruggedness of this rotor type is the main advantage of this build, no-other motor type is as simple as this one. A squirrel-cage rotor of an induction motor is presented in Figure 3. The other type of rotor is called a wound-rotor or a slip ring-rotor, and it is based on slip rings that connect the rotor windings. [2]

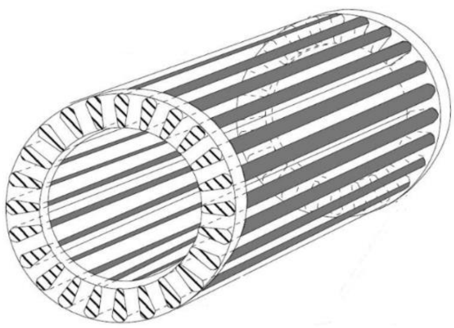

Figure 3: *Squirrel-cage rotor*

Between the stator and the rotor, there is a space called the air gap. In modern motors, the air gap between the stator and the rotor is reduced into small fractions of millimeters. The air gap is necessary to let the rotor rotate freely without contacting the stator. [3] Other parts of the physical structure of an induction motor are presented in Figure 4.

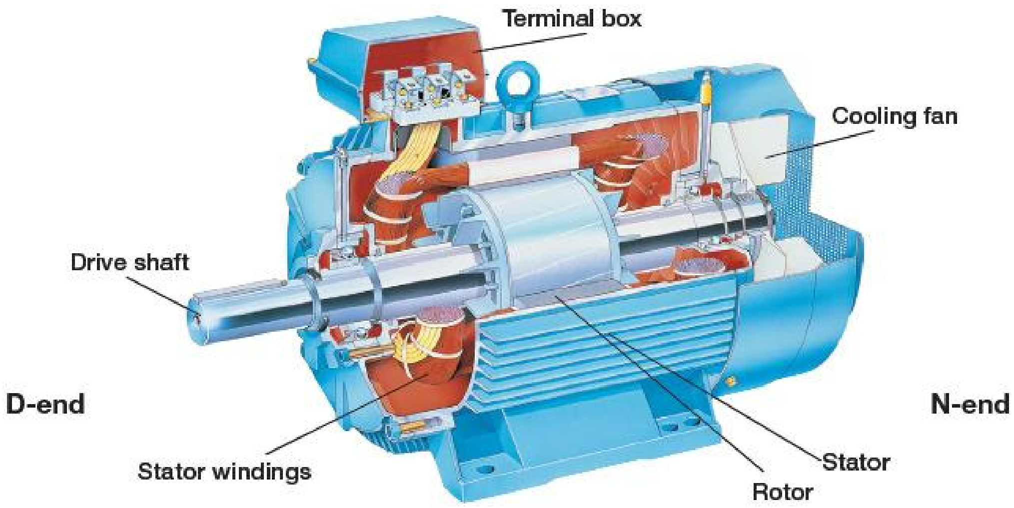

Figure 4: *Structure of an induction motor*

The terminal box is the connection module between the stator windings and the power input. Depending on the motor, it may contain other control equipment or depending on the phase count, more or less than three voltage inputs. The cooling fan is on the opposite side of where the motor shaft is. The fan is to cool down the motor during operation to prevent the thermal expansion of the motor steel structures. The motor shaft connects the rotor of the motor to the outside of the frame. The purpose of the shaft is to transfer the mechanical torque acquired by the rotor outside of the frame and into use. The bearings are to ensure free rotation of the shaft. [3]

2.3 Operation

The operation of an induction motor is based on the interaction of the magnetic field created by the stator windings, and the rotor windings in a rotating magnetic field. When the stator winding is excited with an alternating current, the stator winding will produce a rotating magnetic field according to Faraday's law (2.1). The magnetic field will rotate at synchronous speed (r/min) based upon the following equation

$$n_s = \frac{120 * f}{p} \tag{2.6}$$

where *f* is the electrical frequency and *p* is the number of stator poles. [2]

When the magnetic field rotates inside the stator, it induces a current into the rotor windings following Faraday's law (2.1). Because the rotor windings are shorted, a current is flowing through it, creating a loop. A closed wire loop with a current in an alternating magnetic field is subject to Lorentz's force (2.4). [4] This will create tangential momentum to the rotor, effectively making it rotate along with the magnetic field. As the name states, the asynchronous motor will not run in synchronized speed. This difference between synchronous speed and the rotor speed is called slip. [3] Slip can be calculated as

$$s = \frac{n_s - n}{n_s} \tag{2.7}$$

Where n_s is the synchronous speed of the magnetic field and n is the speed of the rotor. Slip is necessary for an induction motor because EMF needs a changing magnetic field to be induced. If the rotor speed was equal to the stator field, the rotor windings would be stationary in respect of the magnetic field. Thus, no EMF would be induced. Likewise, if the rotor is locked, the slip would equal to one as there would be no rotation in the rotor. [3]

The produced torque of the motor can be calculated when dividing the electrical power with the angular velocity of the rotor

$$T = \frac{P_{em}}{\omega} \tag{2.8}$$

where P_{em} is electromechanical power and ω is the angular velocity of the rotor. Electromechanical power for a three-phase induction motor's shaft can be presented as the following equation.

$$P_{em} = 3 * I_r^2 * \frac{1 - s}{s} * R_r \tag{2.9}$$

where I_r is the rotor current, s is the slip and R_r is the rotor resistance. The relation between the output torque and the rotor current can be seen from the equation. The slip and its impact can also be seen from (2.9). [3]

2.4 Equivalent circuit

To operate induction motors according to today's standards, a steady-state model of the induction motor must be constructed. This equivalent circuit can be used to create that model, to simulate different values from the system, and to calculate currents and voltages in the motor. [3] A single-phase equivalent circuit of an induction motor is presented in Figure 5.

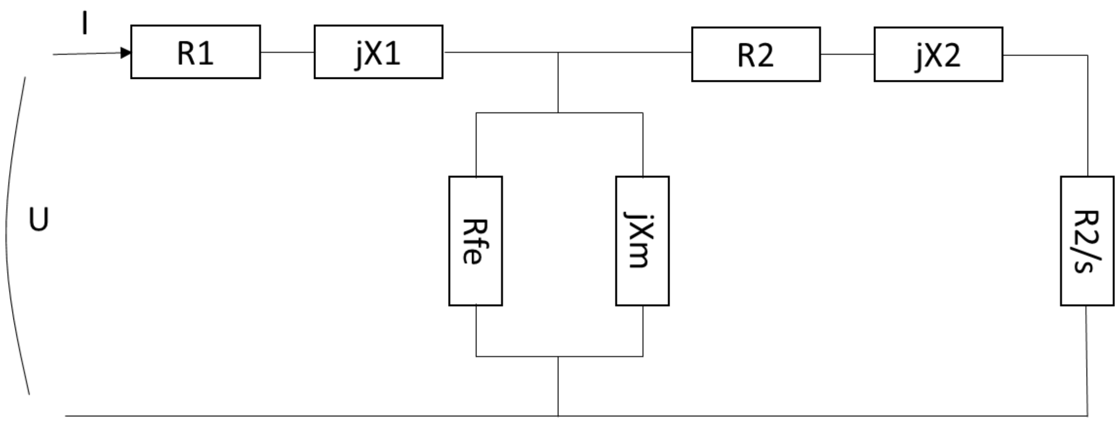

Figure 5: *Equivalent circuit of a single-phase induction motor*

In the equivalent circuit, the parameters go as follows: U represents the input voltage, R1 is the stator resistance, jX1 stator reactance, Rfe iron losses, jXm magnetization reactance, jX2 rotor reactance, R2 rotor resistance, and R2/s represents the equivalent electromechanical power resistance. The effect of the slip on the motor can be seen from the electromechanical power resistance of the rotor. Electrical power losses inside an induction motor are caused by internal resistance and reactance of the motor. Resistance causes active power loss and reactance causes reactive power loss. [3]

These parameters in Figure 5 can be affected by non-idealities that are hard to model. Resistances inside the electric motor can be affected by changing temperatures, which cause a change in parameter values. Saturation of the magnetic circuit is also a difficult non-ideality, which affects the parameters presented above. [2] These non-idealities are hard to model because their behavior is non-linear. That is why they are nearly impossible to predict but can be detected.

With the circuit presented in Figure 5, AC-drive’s full potential can be used by taking these parameters into account. This way, the input power and the operation of the motor can be controlled as efficiently as possible. Modern AC-drives can use various control methods, and the key for some of these control methods is to create a model of the motor. [5]

3. AC-DRIVE

AC-drives are an important part of induction motor systems, as they control and optimize the use of the motor. AC-drive takes the input power from the grid or other source of electrical power and transforms it into a right frequency and voltage for the motor. Simplified operation of an AC-drive can be described as an AC to DC to AC conversion. The main objectives for an AC-drive are energy efficiency optimization, enabling a higher level of factory automation, process control, and optimization and hybridization. [5] In this chapter this thesis will go through the structure of the AC-drive, the control of the induction motor and the benefits of using AC-drives to control motors.

3.1 Structure

Today's AC-drives consist of integrated circuits, sensors, and complex control systems. Here, this thesis will look at the basic structure of an AC-drive, without looking too deeply into the circuitry. When analyzing the block diagram of an AC-drive in Figure 6, it consists of four different parts; rectifier, intermediate circuit, inverter and control circuit. [5]

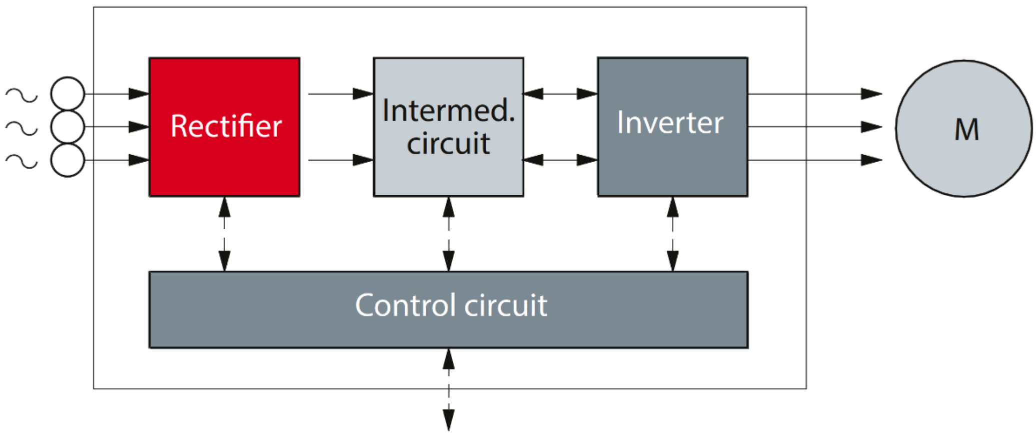

Figure 6: *Block diagram of an AC-drive [5]*

3.1.1 Rectifier

The objective of a rectifier is to produce a constant DC voltage from an AC voltage. When the AC-drive is connected to the grid, the first task is to take the input voltage and modify it into a constant DC voltage that can then be used for the latter parts of the AC-drive. [5]

The base model for a single-phase full-wave rectifier consists of diodes. The diode is a basic electronic component that allows current to flow in only one direction. As the AC voltage is typically a sine wave changing between positive and negative peaks, the diode prevents current to flow while the voltage is below zero. [6] In Figure 7, a basic topology of a full-wave single-phase rectifier is presented.

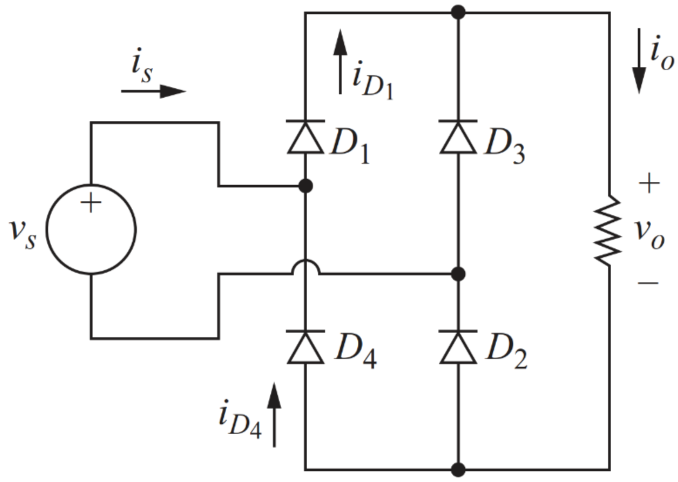

Figure 7: *Single-phase full-wave rectifier [6]*

When the AC supply voltage is on the positive half-period, diodes D1 and D2 are conducting, supplying a positive voltage waveform for the load. In the negative half-period, diodes D3 and D4 are conducting, inverting the supply voltages negative half-period to positive in aspect to the load, creating a pulsating DC voltage. In Figure 8, this can be seen from the waveforms of the supply voltage and the load voltage. [6]

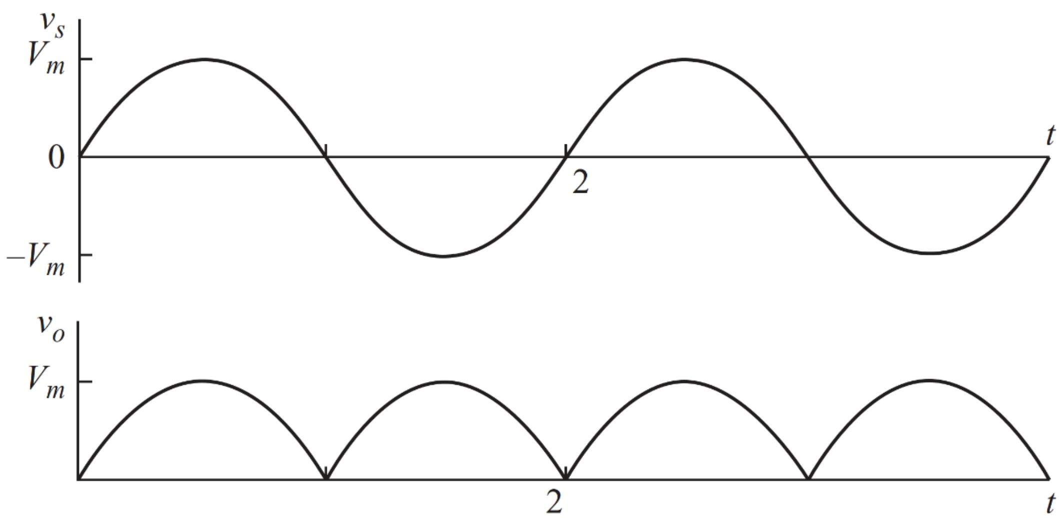

Figure 8: *Single-phase full-wave rectifier waveform [6]*

The basic topology can be further modified by using different components to add controllability to the rectifier. There are four different kinds of controlled rectifiers, un-controlled, semi-controlled, fully controlled and active front end rectifiers, presented in Figure

9. In semi-controlled and fully controlled rectifiers the diodes are partly or fully replaced with silicon-controlled rectifiers (SCR), also known as thyristors, whereas active front end rectifier works with insulated-gate bipolar transistors (IGBT). [5]

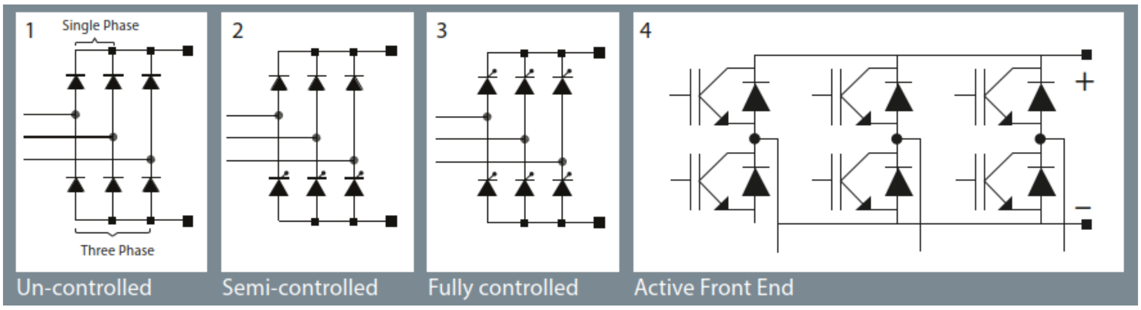

Figure 9: *Rectifier types [5]*

SCR is essentially the same component as the diode because it prevents negative current flow. The difference comes that it starts conducting after it has a gate current applied, and the thyristor is forward-biased. After the current becomes negative, it stops conducting and prevents current flow, and it needs a gate current to start conducting again. [6] By controlling the thyristors firing times, the current into the circuit can be limited and soft charging of the intermediate circuit can be achieved. Thyristor firing angle control allows inverting the waveform if it is chosen to be activated during the negative half period. Power losses in controlled rectifiers are substantial compared to uncontrolled because of the reactive current they draw when they start conducting. [5]

IGBT is a transistor that starts to conduct when a positive voltage is applied for the gate and stops conducting when that voltage is cut off. IGBTs unlike thyristors, allow current to flow both ways. [6] This controllability and flexibility allow the use in applications where the motor could also be used as a generator. These active rectifier topologies are called Active Front End or Active Infeed Converters. Losses in these rectifiers are greater than in the previous, but they allow a completely different operation. IGBTs are also used in rectifier topologies because they reduce harmonics and reduce costs in doing that effectively. [5]

3.1.2 Intermediate circuit

Intermediate circuit, also known as DC-link or DC-bus, is the middle piece between the rectifier and the inverter. The main objectives of an intermediate circuit are the conversion of the rectifier voltage into a DC voltage and stabilization or smoothing of the inverter voltage. [5] As seen from Figure 8, the inverter DC voltage is far from perfect when it comes to the smoothness of the voltage. The objective of the intermediate circuit is to smooth out the voltage so that power losses can be minimized.

A constant DC intermediate circuit consists of a capacitor and/or an inductor. These constant intermediate circuits are not controllable, and they rely on passive component abilities. The capacitor stores energy and smoothens out the DC voltage. It acts as a buffer that stores overload energy and reserves it when the voltage drops. The inductor smoothens the current ripple and reduces harmonics. [5] A constant intermediate circuit is presented in Figure 10.

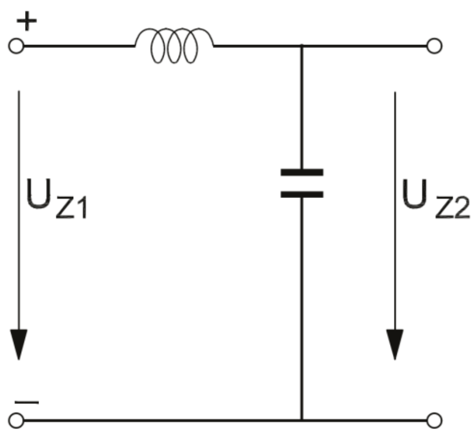

Figure 10: *Constant intermediate circuit [5]*

A variable intermediate circuit can be used to control the DC voltage by using a transistor to change the conduction time of the intermediate circuit. Thus, the average voltage waveforms can be manipulated by chopping the voltage. [5] A variable intermediate circuit is presented in Figure 11.

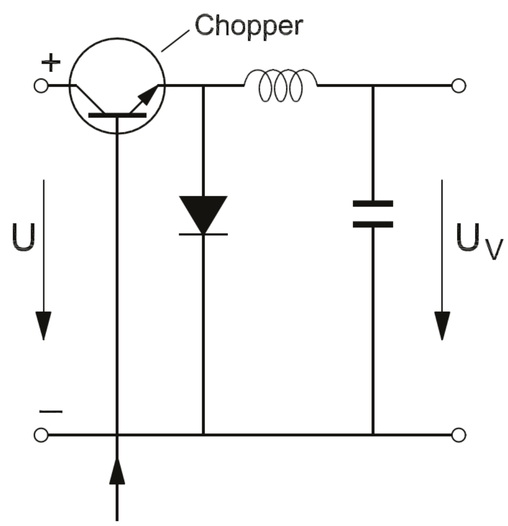

Figure 11: *Variable intermediate circuit [5]*

3.1.3 Inverter

The objective of an inverter is to convert DC to AC. The inverter takes the DC voltage created by the rectifier and smoothened by the intermediate circuit and transforms it into AC voltage with the amplitude and the frequency that is necessary to power the electric motor. The basic topology of an inverter is quite general, and with different control principles, the operation of the inverter can be changed. [6] This basic topology is presented in Figure 12.

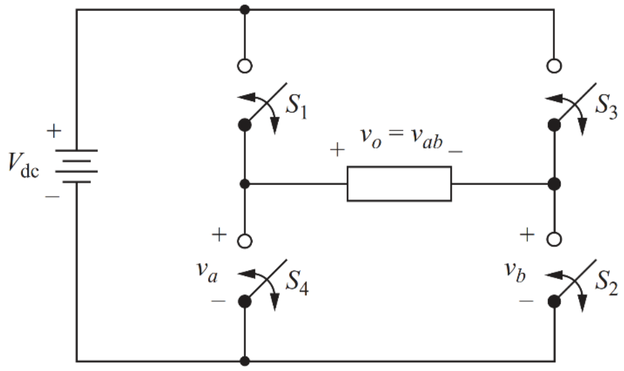

Figure 12: *Single-phase inverter topology [6]*

With four switches, there are four different conduction modes, S_1 and S_2 closed, S_3 and S_4 closed, S_1 and S_3 closed and S_2 and S_4 closed. S_1 and S_4 and S_2 and S_3 should not be closed at the same time as it would short circuit the DC source. With these conduction modes, three different voltages over the load are acquired; V_{DC}, $-V_{DC}$ and 0. Switching between these voltages, the waveform presented in Figure 13 is gained. [6]

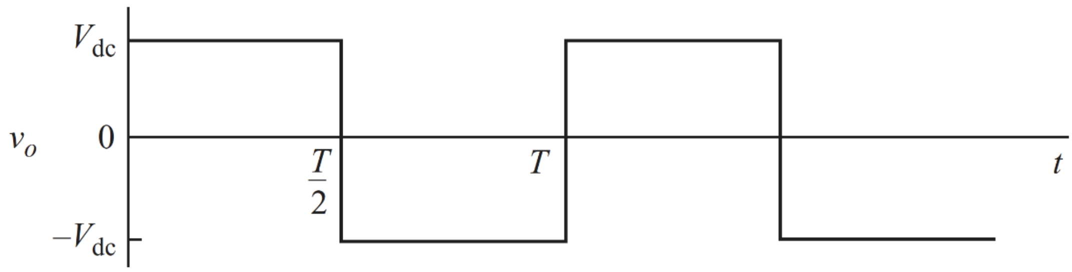

Figure 13: *Single-phase square wave inverter [6]*

As the waveform acquired with the following specs is a square waveform, it is still switching between 0 and with equal and opposite peaks. With different control of the inverter, a more sinusoidal waveform can be gained. The most used control method for an inverter is Pulse Width Modulation or PWM. The PWM varies the duty cycle of the switches to achieve a target average voltage, duty cycle being the conducting time compared to the whole cycle. The objective of inverter PWM is to chop the DC voltage into pulses with a certain width to gain a sinusoidal average AC voltage. [7] In Figure 14 an exemplary signal created by a PWM signal is presented.

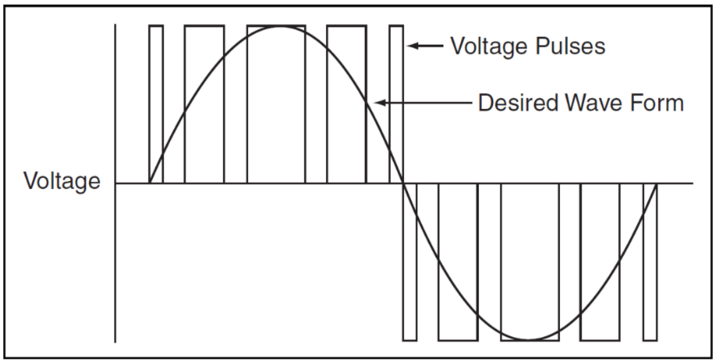

Figure 14: *Pulse width modulation in single-phase inverter [8]*

There is a huge variety of different methods to create the PWM signal. The important part regarding the PWM modulation is to understand, that the control circuit controls the inverter by creating a suited PWM signal. By controlling the inverter waveform, the control circuit controls the motor. [5]

3.2 Control of an induction motor

The fourth part of the AC-drive is the control circuit which, as the name states, controls the AC-drives operation. The control circuit is an embedded system with a microprocessor, and it is programmed to control the AC-drive according to peripherals. The four main tasks of the control circuit are to control the semiconductors, exchange data with the larger system, measure, detect and display system information and perform protective functions for the system. [5]

In electric motor applications, the feedback is usually gained from the current response. When the control circuit gains the current response of the motor, it can use it to estimate the required voltage for the input. Speed and torque can also be measured using an encoder, which converts mechanical speed or position to electrical quantity. [9]

The main objective of an AC-drive is to feed the required voltage and frequency to the motor. The control circuit enables the automation of this process. Because of the built-in features of the drive, the operation can be determined from different control methods. The level of control can be divided into three different methods; open-loop, closed-loop and cascade closed-loop control. These levels of control can then be applied to three different control methods: scalar control, space vector control, and flux vector control. [9]

3.2.1 Open-loop control

In open-loop control, the output torque or speed is not to be measured, and therefore the input voltage or frequency cannot accommodate changes in load or slip. This results in a simple block diagram, where input into the controller is given and it creates an input into the motor based on that input. This control level is best for applications that do not require complex dynamic control, such as pumps or conveyors. [9] Figure 15 presents a basic block diagram of an open-loop controlled system.

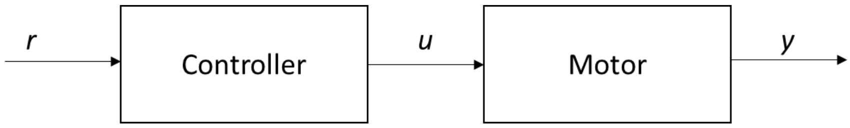

Figure 15: *Open-loop control*

Depending on the use of the motor, open-loop control can be determined to control the speed, the torque or the position of the motor. Because the effects of the load or other conditions on the output are not known, the system might be inaccurate. [5]

3.2.2 Closed-loop control

Closed-loop control takes advantage of the measurements that the use of an AC-drive gives and uses that information to give a correct input into the motor. Closed-loop control takes feedback from the output that is controlled and uses that information to adjust the input. This is vital for applications that require precision and dynamic from the system. A closed-loop feedback control system is presented in Figure 16. Setpoint *r* is the control signal from the user or from other parts of the system, where the desired output of the system is determined. The controller then takes the difference of the setpoint and the process variable *y*, which determines the error *e* between the desired output and the real output and forms an input *u* to the process based on that error. [9]

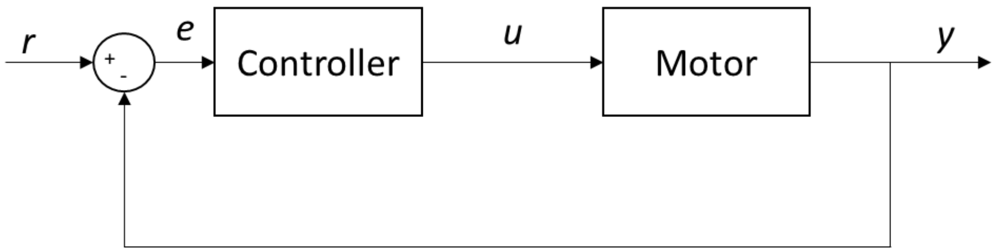

Figure 16: *Closed-loop control*

Closed-loop control can be used to control the speed, torque or the position of the motor, as with the open-loop control, but with the difference being enhanced precision in output accuracy. Feedback helps the system to recover from alternating load or other disturbances. [5]

3.2.3 Cascade closed-loop control

In applications that require more efficient speed and torque control, cascade closed-loop control can be used. The controller design holds feedback from the system as it is a closed-loop control but has more than one control loop. In the case of AC-drives, usually, the control loops are for the speed and the torque, and the output is measured by current or speed. [9] In Figure 17, a basic cascade control loop is presented.

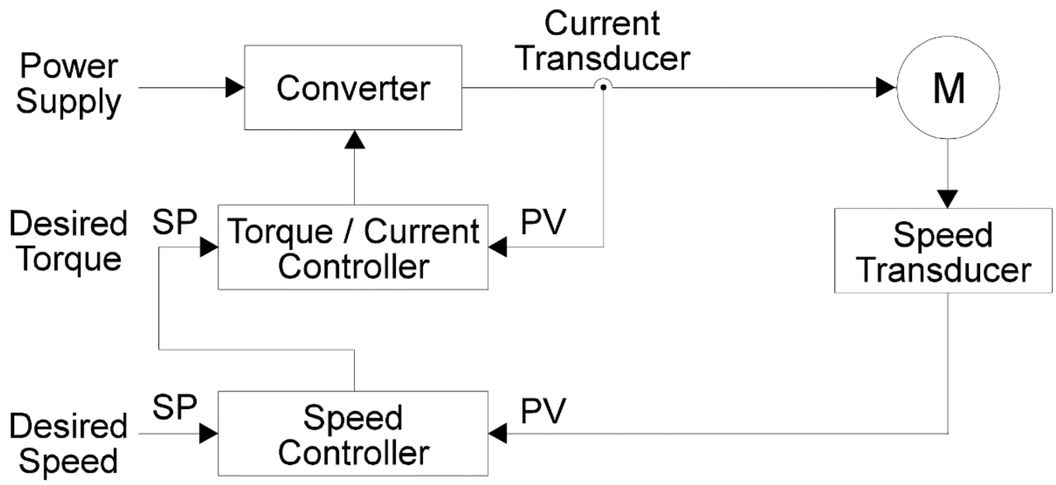

Figure 17: *Cascade closed-loop control [9]*

When analyzing Figure 17, the system uses two different controllers to control the motor, both of which in relation to different values. This enhances the precision of a controlled system because it follows the setpoint of two different variables.

3.2.4 Scalar control

The scalar control method of an AC-drive is essentially open-loop control as presented in Figure 15. Setpoint is taken from the user or other system and it controls the voltage and the frequency applied to the motor. This setpoint signal is passed to the control circuit which sets the magnitude of voltage and frequency for the motor input. [9] This ratio between the voltage and the frequency (U/f) is kept constant and is determined by the plate values of the motor. The ratio determines the magnetic flux density of the motor, which when staying constant, ensures optimum torque to the shaft. If the motor is rated at 400 V and 50 Hz, the U/f ratio is 8 V/Hz. That means that when the output frequency is changed by 1 Hz, the output voltage will rise 8 V. [5] An ideal U/f curve is presented in Figure 18.

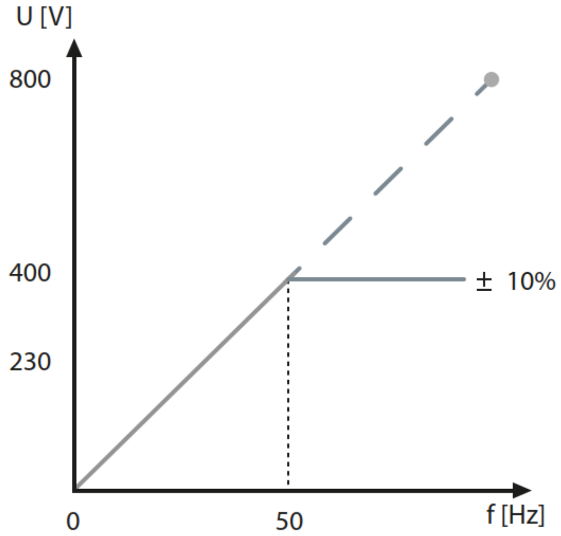

Figure 18: *Ideal U/f curve [5]*

The feedback from the motor is gathered as the output current, but primarily for safety reasons, to ensure that there is no overload for the motor. Some U/f-controlled AC-drives have slip compensation to improve the output speed/torque. This type of control is usually suited for low-level applications that do not require dynamic abilities, such as pumps or conveyors. [9]

3.2.5 Space vector control

Space vector control is a control method that is hugely popular in AC-drives due to the method's higher level of performance compared to fixed U/f control methods. In space vector control, the amplitude and the phase angle of the voltage waveform are controlled along with the frequency. As stated in (2.9), the rotor current is directly proportional to the output torque. And when examining the steady-state model of an induction motor (Figure 5), the stator current is the sum of the magnetizing current and the torque producing current. The objective in vector control of an induction motor is to calculate the individual current vectors in order to control them separately by varying the voltage amplitude and angle. That way, the stator flux and the torque producing current can be controlled as efficiently as possible. To calculate the individual currents, the measurement of system variables is needed along with the steady-state parameters of the induction motor. As seen from the steady-state motor model, there are a lot of variables that affect these currents and therefore a lot of computing power is needed to provide these calculations. [9]

Space vector control is available with open-loop or closed-loop control. In open-loop control of an induction motor, the speed and torque of the motor can be calculated based on the steady-state model of the motor. This model in open-loop control is based on the static model and is entirely relied on the given parameters and their accuracy. Measurements of motor current and frequency are used to calculate the speed of the motor, which might cause inaccuracy. [5]

Closed-loop space vector control is used in situations where high dynamics and accurate control is needed. An encoder is used to measure output speed which gives feedback to the control circuit. This feedback is used to improve accuracy. [9]

3.2.6 Flux vector control

Flux vector control, also known as field-oriented control, controls the magnetic flux in the rotor. In relation to the space vector control, flux vector control controls the rotor flux directly. Speed and torque of the motor can be controlled with this type of control, as with the space vector control. A strength for flux vector control is that it can control the motor during transient state. [5] The use of flux vector control is based on modeling the motor and using the model to solve for the correct control. Without the model, flux vector control cannot be used.

Open-loop flux vector control is essentially a fixed U/f ratio control method, but with more control components. Compared to the U/f control method, the open-loop flux vector control solves the currents as in the space vector control from the mathematical model of the motor. It uses the currents to solve for the magnetic flux and regulates it according to the U/f ratio. Essentially, the open-loop flux vector control is best suited in applications that need improved dynamics and torque compared to what the U/f-controlled systems can. This method is a speed control method and does not provide torque control. [9]

Closed-loop flux vector control is the best control method when it comes to the dynamics, controllability and all in all higher levels of performance. This method is usually cascaded closed-loop level of control, with separate control loops for speed and torque. The control itself is being made as it is with the open-loop control, but with the speed being measured and not calculated or estimated. This provides an inferior dynamic response compared to sensorless open-loop flux vector-controlled systems. [9]

3.3 Current measurement

AC-drive systems utilize current measurement from the motor to protect, control and meter the system. The most important of which, in the premises of this thesis, is its utilization for control purposes. Current measurement allows feedback from the motor, which is an integral part of vector-controlled motor systems. [5]

As can be seen from Figure 5, the stator current of the motor is the vector sum of the magnetizing current and the load producing current. This enables the use of the stator current to indicate load if information on the magnetizing current can be acquired. This information can be gathered through modeling of the motor. [9] With the current response of the motor, the effects of electrical features of the motor and the inertia of the system can be seen, along with many other features. When a load is applied on the shaft, the slip increases and more current is induced to the rotor. [10] Non-load related current alterations can be traced to malfunctions of the motor’s electrical features.

While current measurement is an integral part of vector-controlled AC-drive systems, the measurements can be used in lower-level applications as well. AC-drive control methods provide compensations and estimations that can be done using the current measurement from the motor. The current from the motor can be measured to compensate for operational losses, such as slip or load related losses. The current can be used to estimate the slip in the operation and the AC-drive can apply positive feedback to compensate for the effects of the slip. [5]

When the current response of the system is analyzed, difficulties need to be taken into consideration. The reviewed magnetic and thermal non-idealities in Chapter 2.4 can be detected from the current response of the system. Due to IGBT switching and other structure-related effects, AC-drive itself might cause effects on the current response. Wiring losses to the motor causes current response corruption, which might go unnoticed. [2]

4. OPTIMIZATION ALGORITHMS

In this chapter, this thesis will go through optimization algorithms that utilize the steady-state characteristics of an electric motor. Measurements and calculations are used to create models that can be used to optimize and better the control of an induction motor system. These algorithms are vital in precise and efficient modern motor control. [5]

4.1 Identification run

Identification run is the type of algorithm which can be used to determine the inner parameters of an induction motor. In Figure 5, the equivalent circuit of an induction motor is presented. Essentially, the identification run uses measurements to calculate the values for resistance and reactance, which can be used to create a steady-state model of the motor. This model allows the use of model-based control methods presented in Chapters 3.2.5 and 3.2.6. [9]

In order to figure out the parameters of an induction motor model, presented in Figure 5, multiple different methods can be used. These methods can be either dynamic or static, which means that it can be either determined by accelerating the motor or at standstill. [5] Next, one way to determine the parameters is described. Two tests need to be used; blocked-rotor and no-load test. These tests allow measurements of the current response of the motor for examining the leakage impedances. [3]

The no-load test is performed by unmounting the motor from the shaft load and letting it run freely. The motor is fed with a constant rated voltage and frequency, and the current and power are measured, and how it is affected by the motor’s impedance. Due to the rotor rotating freely and without a load, it can be assumed to run without any slip. Because there is no slip, the rotor is not affected by a varying magnetic field and no EMF is induced (2.1). Therefore, the rotor side of the model can be deducted. [3] The resulting model is presented in Figure 19.

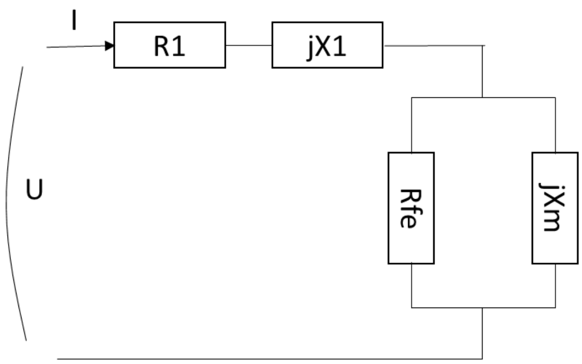

Figure 19: *No-load test steady-state model*

From this model, using the measured values of the current and power, the total impedance of the stator side circuit can be determined.

The blocked-rotor test is performed by locking the rotor to a certain position, essentially making the slip equal to 1. The blocked rotor test is done using the rated frequency and voltage, which the motor is designed to operate. The purpose is to simulate the starting conditions of a motor. This way, the leakage impedances of the motor at the starting point can be acquired, which can be used to build the model for the induction motor. [3]

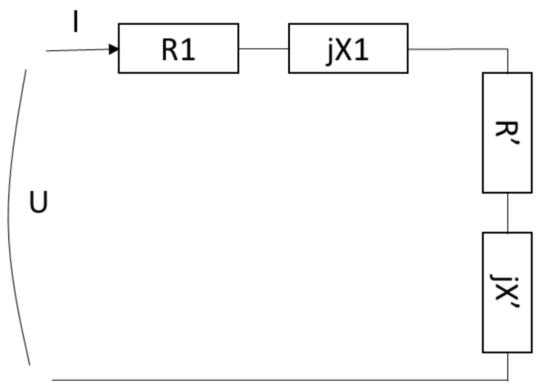

Figure 20: *Blocked-rotor test steady-state model*

The blocked-rotor test equivalent circuit is presented in Figure 20. The parallel connection between the magnetizing branch and the rotor branch is presented with R' and jX'.

The benefits of using identification run depend on the control method being used to control the system. In methods that use a model of the motor to determine control, identification run is essential to make the control precise. Using the shield values of the motor in the model might cause the system to be inaccurate. This precision of control can be seen from the output speed/torque precision. Then again, in functions that do not use models of the motor to determine control, identification run can be used to help other optimization algorithms to work and gain better efficiency. [5]

4.2 Flux optimization

Flux optimization is used to optimize the required magnetic field while the motor is operating in a steady-state. The algorithm detects steady-state characteristics and uses the information to optimize energy usage. This results in better efficiency, as the magnetizing current is reduced, and reactive power is drawn less. [11]

When operating in steady-state, and the motor is creating a constant torque, this information of the torque can be used to determine, whether the magnetic field is fully optimized. The excessive magnetic field can be reduced to ensure better efficiency of the operation. Better efficiency comes from lower current being drawn for magnetizing, but also from lowering the magnetizing/torque producing current ratio. This effectively makes the drawn current contain less reactive current and therefore giving the operation a better power factor. [5]

The featured scalar control method of the U/f ratio is an easy control method for simple applications, as examined in Chapter 3.2.4. However, its efficiency is compromised when the motor is operating at a low torque, as the required magnetic field is excessive. Modern AC-drives offer multiple different U/f ratio profiles which are not linear and try to improve the curve to be more precise. These, however, need manual changing and knowledge from the end-user. [11]

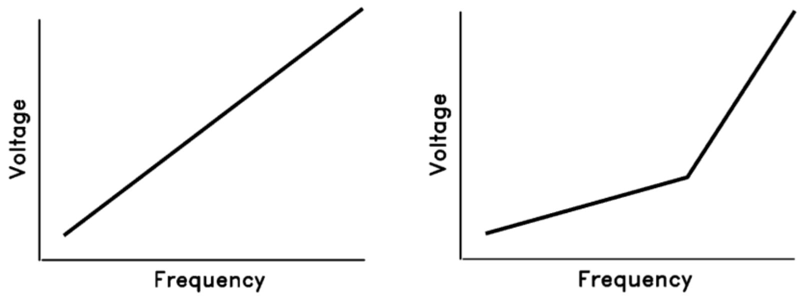

Figure 21: *U/f ratio, linear versus fixed [11]*

Flux optimization builds a mathematical model of the motor to regulate the input voltage as a function of the magnetizing current. The needed magnetizing current is estimated based on the steady-state model. The algorithm changes the ratio automatically, which needs no user assistance. This gains a huge advantage, as low-speed operating motors are typically very inefficient. The automatic algorithm enables the ratio to change in case there happens to be variance on the load of the motor. [11]

4.3 Condition monitoring

An electric motor is a machine that requires less maintenance than combustion engines due to only having a single moving part, the rotor. However, this does not liberate the system from maintenance needs. As the motor system has a lot of measurements, it is useful to use these measurements to the advantage of the system and to monitor the physical condition of the system. AC-drive manufacturers have created multiple different algorithms to detect issues regarding the condition of the system. This helps the operator to act before problems occur and that way avoid collateral damage to other parts of the system. [5]

An example drive from Danfoss is reviewed, the VLT® AutomationDrive FC 302. It features condition-based monitoring embedded into the drives control circuit. It includes three different functions as a part of its condition monitoring. Motor-stator-winding monitoring detects and reacts to early faults in the motor stator windings. As winding faults develop slowly over time, this function measures current and compares it to previous values to detect faults. Mechanical-vibration monitoring is used to detect faults in the mechanical side of the motor. It measures vibrations in different stages of motor use and compares them to standard operating conditions. The function can detect mechanical misalignment, wear-out and looseness in real-time, and act according to the level of risk. Load-envelope monitoring compares the load curve history to detect performance losses. This function can detect power losses, no matter what part of the system it is originated, as it monitors the change of load curve. [12]

These condition monitoring functions are useful when it comes to long time use of a certain system, as it prevents big breakdowns by detecting smaller faults which can cause bigger problems in the long run. These functions can be modified by giving the control system instructions on what to do in case the functions detect a fault. These instructions can be limits to current, frequency or torque, or different operational instructions. Operational instructions can be such as a warning signal, motor speed decreasing or total shutdown of the motor. [5] Fault instructions need to be thought carefully, as it should depend on the process that the motor is used in. If the motor is used in a simple one-motor-system, it might be best to shut down the whole system if there is a critical fault detected. If the motor is part of a larger system, for example a paper machine, a sudden shutdown might cause huge problems to other parts of the system, which can turn out to be quite expensive.

5. STEADY-STATE DETECTION

An induction motor in a motor system is a dynamic part of the system. It means that it has its own dynamics, which cause different effects. This has various effects that need to be taken into consideration when figuring out a control strategy for a motor system. [11] A key part of modern AC-drive control is steady-state detection. In modern AC-drives, some features require steady-state operation. If a process signal is noiseless, steady-state detection would be trivial, as there would not be a change in the signal. Due to electric motor operation, these processes contain a lot of unwanted components in the signal, and therefore steady-state detection is needed. [13]

In this chapter, this thesis will look at the motor as a part of the system, and how does it present itself when it is operating. Different problems of electric motor steady-state detection are reviewed, and solutions for these problems are presented.

5.1 Transient vs. steady-state

To understand what steady-state operation means, the definitions of transient and steady-state concepts need to be reviewed. According to IEV 113-04-07 standard, steady-state is a macrostate which does not change spontaneously with time and is stable against small perturbations. This means that the system has reached a state where its output is unchanged in time. In electric motor applications, reaching a steady-state is essential, as it allows precise control of the motor. If the motor would not reach a steady-state, the output would vary, and it would be good-for-nothing. [9]

The transient phase in system operation is the opposite of steady-state. According to IEV 161-02-01 standard, transient means pertaining to or designating a phenomenon or a quantity that varies between two consecutive steady states during a time interval short compared with the timescale of interest. In other words, transient means the phase of operation, in which the system is changing. These phases in electric motor applications are starting and stopping the motor and changing the speed of the motor. [9]

While a system is in steady-state, it can be assumed that the behavior of the system will continue until there is a change in system variables, for example, input change, disturbances or other malfunctions. The state of a dynamic system is the information on the variables that characterize the system for the purpose of predicting the future. When the state of a system is known, the system can be controlled as desired, because the behavior can be solved. [14]

The difference between transient and steady-state is vague because it depends on how it is determined. The easiest way to demonstrate this is by presenting a step response of a simple system. Step response means that the input changes from 0 to 1, and the output of the system is presented in Figure 22.

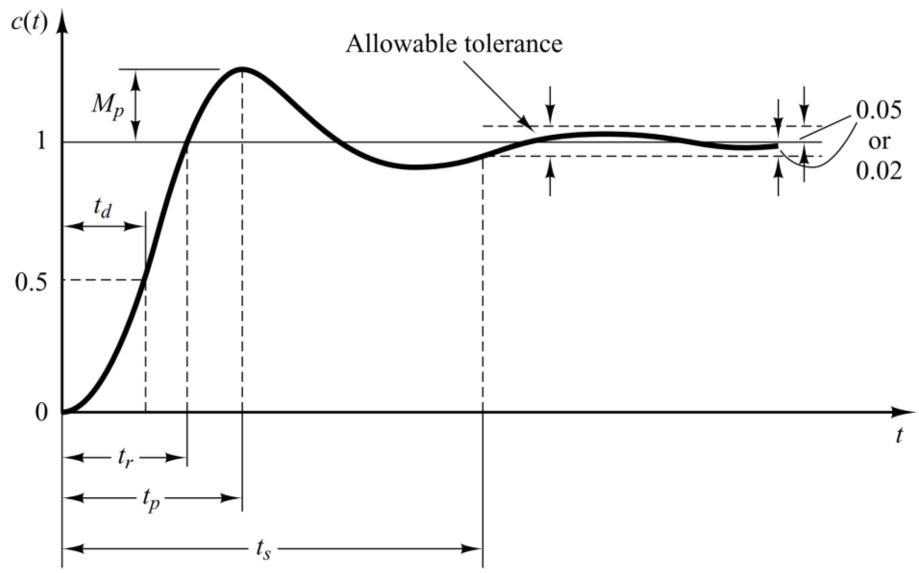

Figure 22: *Step response example*

As seen from the step response the system output does not instantaneously step to the desired output. Instead, the output contains a lot of unwanted dynamic effects. First, the output starts to rise to the desired output. The time that it takes to reach the desired value is called rise time (t_r). Then the output overshoots the desired output value, and the peak time (t_p) is presented. After that, the system starts to settle into the desired value. The desired value can be determined to meet the requirements in a certain range, and the error is shown in the figure as allowable tolerance. This means that the system has reached the output value at settling time and thus, has reached a steady-state. [15]

5.2 Motor operation states

As mentioned previously, an electric motor has its own dynamics. These dynamics emerge when the motor shifts to the transient phase. For the motor to shift to the transient phase, there needs to be a state change in the operation.

During the start-up of an electric motor, energy is consumed to accelerate the load and the motor to the required speed. This acceleration period consumes more energy than the steady-state operation, as the slip is initially higher, and the rotor current is high to create enough torque to overcome the inertia of the shaft. [5] There are multiple different ways to start up an electric motor, star-delta starting, solid-state soft-starting and series inductance starting to name a few. Even though each way is highly optimized to require as low energy as possible, they still end up drawing between 3 to 8 times the current compared to the full load current. [9]

While the induction motor operates in steady-state, the equivalent circuit presented in Figure 5 can be applied to create a model of the motor. During the steady-state operation, the values of the motor can be calculated, and the operation is predictable. This enables the use of optimization algorithms because the outcome of made decisions can be predicted in the control of the motor. [3]

Other transient phases include output regulations in applications that require variable load control. As the descriptions state, transient phase information cannot be used to control the motor, because the outcome is unpredictable. That is why information on the state of the system needs to be known, and steady-state or transient-state needs to be detected. [5]

5.3 Difficulties of steady-state detection

As explained in Chapter 5.2, electric motor operation contains different transient and steady-state phases. The difficulty for the steady-state detection is to find out where the transient ends and the steady-state begins. This can be quite a demanding task, especially in variable load systems, where the output is constantly changed. In these applications, steady-state operation periods can be so volatile that the control circuit cannot detect the steady-state, or the output never settles to steady-state. In some industrial applications, steady-state metering might be prevented because of bad control or operating circumstances. It is challenging to find out the right timescale for steady-state detection because it depends solely on the application. For some applications, a steady-state is achieved a lot faster than others. A big megawatt-scale motor has a larger settling time than a small kilowatt motor. This difference in settling times can be huge, and it needs to be taken into consideration when making steady-state assumptions. [13]

Another problem in steady-state detection is noise in signals. Filters are used to filter disturbances from the measured signal, whether they are caused for example by the measuring sensors or switching disturbances. When trying to measure steady-state characteristics or steady-state output of a motor, filtering the signal is essential, as it gives more precise information. If the signal is affected by a significant disturbance, steady-state detection techniques might give a false reading and say that the system is not in fact in steady-state. The control circuit has its own parameters, and if the steady-state error allowable tolerance (Figure 22) is too small, the signal does not meet the requirements for the control circuit to regard it operating in a steady-state. [9]

Figure 23 presents an example of how disturbance causes distortion in comparison to the real signal. In this figure, a constant signal is being affected by a minor noise component. This noise component could in real-life applications come from anywhere, and if steady-state detection is wrongly adjusted, it can cause huge detecting errors.

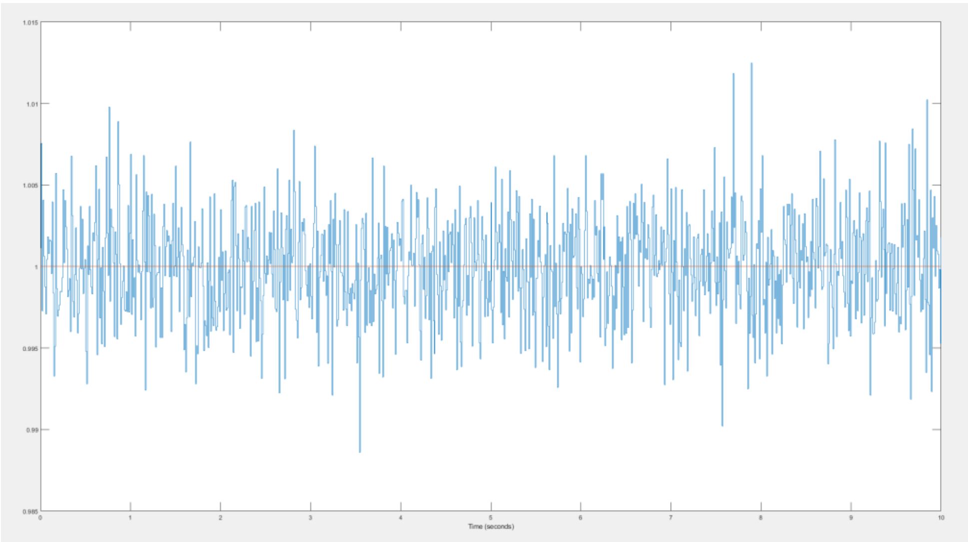

Figure 23: *Noise in a constant signal*

Steady-state operation is compromised in electric motor applications if the inner properties of the motor are changed. These properties can be changed due to mechanical-, thermal- or magnetizing-related issues. Mechanical issues are the result of varying load, whether it is due to a variable load, or mechanical wear of the motor. Thermal properties inside an electric motor can vary. This variance can cause effects in the resistance of the motor, as resistance changes due to thermal effects. This effect is known as the temperature coefficient of resistance. [4] Magnetizing issues in electric motors are caused by two phenomena of magnetization: saturation and hysteresis. Saturation means that the magnetic material has reached a large enough value of the magnetic field, that the magnetization becomes constant, and cannot be increased. Hysteresis is the result of saturation and means that the decrease of the magnetic field contains lag and might not be decreased to zero. Both phenomena are nonlinear and difficult to model. [17]

6. STEADY-STATE DETECTION TECHNIQUES

When talking about steady-state detection techniques it needs to be specified that steady-state detection techniques are not for acquiring steady-state values. Instead, the purpose of steady-state detection techniques is merely to define whether the system is in steady-state or transient. [18] In this chapter, this thesis will review the basic concepts behind steady-state detection.

6.1 Linear regression

A straightforward implementation of steady-state detection would be linear regression. Acquiring the process variable values during the operation and creating a linear trend line for the variable during a timescale. While the process is in steady-state, the trend-line would remain unchanged, and the slope of the trend would be zero. Therefore, by definition, the system would be operating in a steady-state. [18] In Figure 24 an exemplary linear regression is presented.

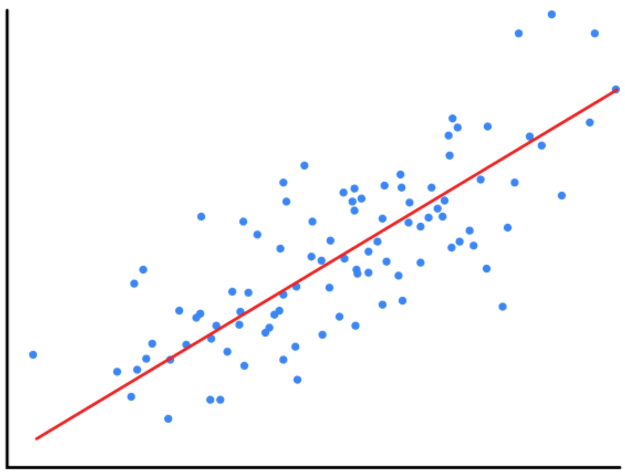

Figure 24 Linear regression

The problems while using only linear regression to detect steady-state are related to operation noise. Electric motor applications usually contain a lot of noise and linear regression could be affected heavily by it. Linear regression is also vulnerable to oscillating signals because they are dependent on the timescale of the regression. [19] Another difficulty arises in computational power. Creating a linear regression of continuous data requires a lot of memory and computing power to analyze. Automation is also a problem, as the time interval on which the linear regression is created, needs to be appropriate. For the determination of the timescale, there is no universal solution and it should be computed by user interaction. Therefore, not reaching an important goal for AC-drive steady-state detection technique, which is close to none human interaction to work. [20]

6.2 Student’s t-test

Student’s t-test is another straightforward method of determining steady-state. In the t-test approach, the means of the signal in successive windows are computed to determine if there is any change in data. The means between two subsequent data sets should be equal for the system to be in steady-state. However, noise in the signal will cause fluctuation in sequential averages. The critical t-value of the data should be computed along with the t-statistic of the data. If the t-statistic exceeds the critical t-value, the system can be claimed to be in a transient state. [19] The t-test can be calculated by

$$T = \frac{|x_2 - x_1|}{\sqrt{s_1^2 + s_2^2}}\sqrt{n} \tag{6.1}$$

Where x_1 is the mean during the first window, x_2 is the mean during the second window, s_1 is the variance in the first window, s_2 is the variance in the second window and n is the window. [19]

Problems with t-test are computationally related, like with linear regression. Performing t-tests on continuous processes require a lot of memory and computational power. At each time interval, the data should be updated and the tests reperformed for the averages and standard deviation. Oscillating signals cause a problem in t-tests as it did with linear regression. [18]

6.3 F-test

The F-test type statistic technique calculates the ratio of variances from data during one sequence. The variance is calculated by two different methods, to better the result. The first method is to compute the variance from the mean square deviation of data. The second is the mean of squared differences of successive data. During steady-state operation, the ratio of these two should be near unity. Near, due to random noise in the real process. In an ideal case, the ratio would be unity. [20]

One application of the F-test is the R-statistic approach, first introduced by Cao and Rhinehart (1995). The approach is based on a primitive F-test type of statistic. The R-statistic approach uses computationally inexpensive methods to calculate these ratios of variances. These ratios are compared to critical values to determine if the operation can be classified as a steady-state. Due to the measurements being ratios of estimations, they are independent of the process variance. Several tests have also shown that the approach is effectively independent of noise. [21] This approach is very popular and could be used in multiple applications that require steady-state detection, such as AC-drives.

6.4 Summary

In AC-drive applications, the steady-state detection technique must satisfy multiple important requirements. It should need little to none user input while operation because it would make the technique meaningless. As stated earlier, the detection is trivial when it is done by human interaction. The technique should be robust and reliable in detecting the steady-state with a small margin of error. And in AC-drive applications, the techniques should be universal in detecting the steady-state, due to the large scale of different electric motors using the same AC-drive software. [5, 19]

Steady-state detection techniques in real-world applications are usually a combination of the techniques reviewed above. This is to counter the weaknesses of one technique by applying another. These basic concepts are the basis of other more complex and precise techniques. Popular basic combinations are double t-test and f-t-test. [19]

When evaluating the reliability of steady-state detection techniques, it is important to note that there are a lot of different techniques with different features. Some techniques are great at handling noisy processes and some are better at more steady processes. The most challenging processes to detect are those that contain oscillating and noisy signals, and those processes that are highly volatile. When designing a detection technique for a certain system, the designer needs to consider the nature of the system. By applying correct techniques, an overall solution can be reached that corresponds to the requirements set for the system.

7. DISCUSSION AND CONCLUSION

The goal of this thesis was to examine steady-state detection techniques and how they can affect the performance of AC-drives. This thesis reviewed induction motors and the operating principles of the motor to understand what causes non-idealities in an induction motor system. This thesis assessed the structure and working principles of an AC-drive and reviewed different control schemes of AC-drive systems. Different optimization algorithms were evaluated that use steady-state information to optimize motor use. Steady-state detection was analyzed, and their difficulties were considered. And finally, steady-state detection techniques were reviewed.

As modern control circuits have allowed model-based control of AC-drive systems, AC-drive manufacturers have developed algorithms to measure and calculate better models of the motor. These algorithms gather steady-state information about the parameters and the operation of the motor. In order to gather this information, AC-drive must have information, whether it is operating under steady-state or not. Steady-state detection techniques are necessary for modern AC-drive systems. It enables better use of optimization algorithms, which are used because each electric motor is unique, and designer values of the motor contain error. Detecting the steady-state parameters of the motor allows optimization of the motor control by giving more accurate parameters for the model and more accurate information about the operation.

Optimization algorithms give huge advantages in AC-drive motor systems by lowering energy needs and enhancing precision in the operation. In modern industry applications where there are multiple electric motors in AC-drive systems, lowering energy consumption is hugely beneficial from an economic standpoint. These techniques give small improvements in efficiency when looking at the percentages, but the total outcome multiplies due to the sheer numbers of electric motors in industrial use. Improvements in efficiency can also be seen beneficial in environmental standpoint. Improved precision is useful in systems, which require complex control of the motors.

The use of steady-state detection techniques in AC-drive applications is necessary because it enables better use of optimization algorithms. The execution of these techniques is a difficult task for the AC-drive. Some techniques require a lot of computational power which might not be available. Other techniques may require user control, which is not acceptable in most AC-drive applications. In AC-drive applications, the used steady-state detection technique should be able to work in a variety of different applications, as the same AC-drive technology is used at different speeds and different sizes of systems. In the future, microprocessor-technology will enable the use of better techniques. The added computational power can be used to create more precise information from the operation.

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