BACHELOR THESIS

2023

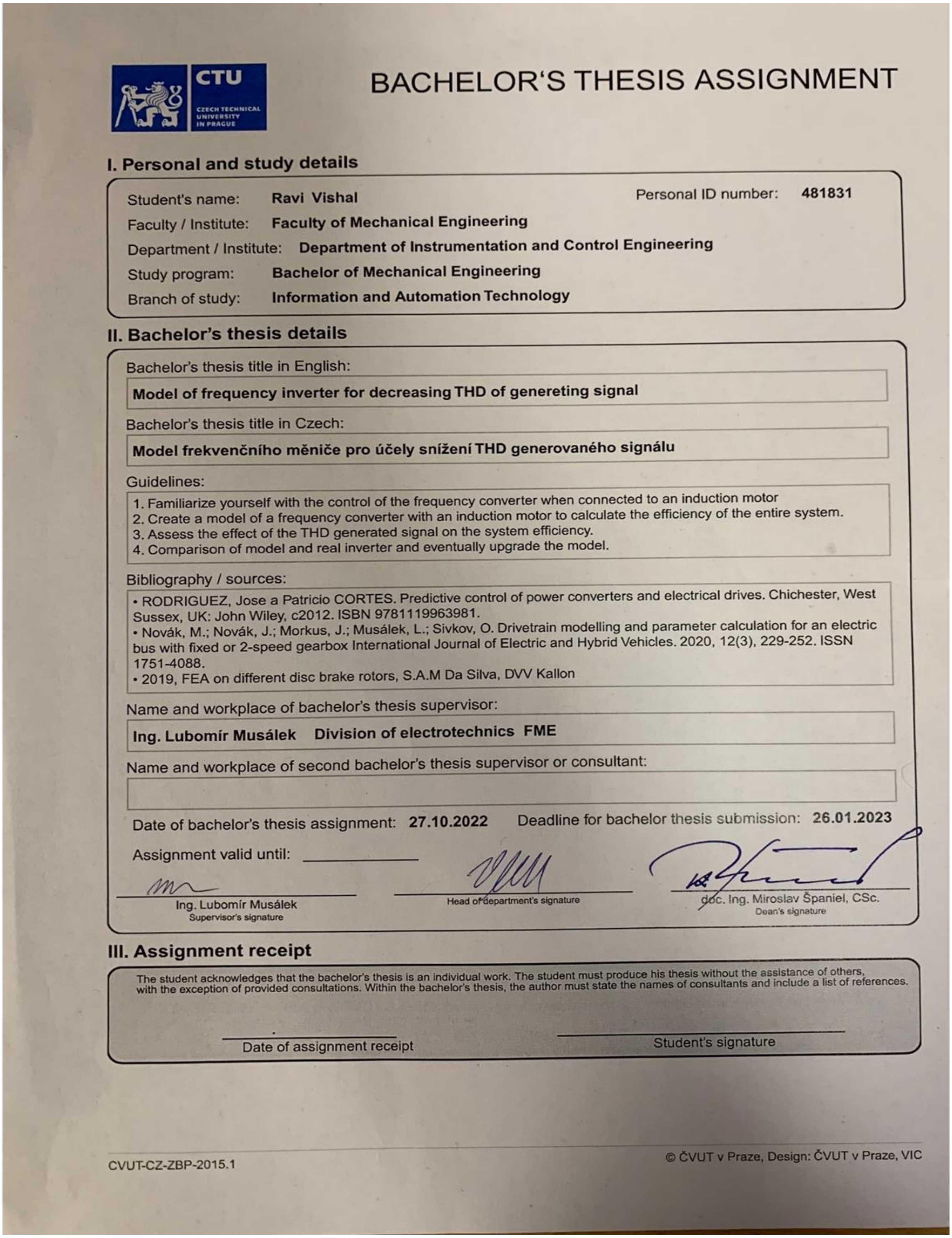
CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY
OF MECHANICAL
ENGINEERING

Frequency Inverter Model

Vishal Ravi

Vr130993@gmail.com



BACHELOR‘S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Ravi Vishal** Personal ID number: **481831**
Faculty / Institute: **Faculty of Mechanical Engineering**
Department / Institute: **Department of Instrumentation and Control Engineering**
Study program: **Bachelor of Mechanical Engineering**
Branch of study: **Information and Automation Technology**

II. Bachelor's thesis details

Bachelor's thesis title in English:

Model of frequency inverter for decreasing THD of genereting signal

Bachelor's thesis title in Czech:

Model frekvenčního měniče pro účely snížení THD generovaného signálu

Guidelines:

1. Familiarize yourself with the control of the frequency converter when connected to an induction motor
2. Create a model of a frequency converter with an induction motor to calculate the efficiency of the entire system.
3. Assess the effect of the THD generated signal on the system efficiency.
4. Comparison of model and real inverter and eventually upgrade the model.

Bibliography / sources:

- RODRIGUEZ, Jose a Patricio CORTES. Predictive control of power converters and electrical drives. Chichester, West Sussex, UK: John Wiley, c2012. ISBN 9781119963981.
- Novák, M.; Novák, J.; Morkus, J.; Musálek, L.; Sivkov, O. Drivetrain modelling and parameter calculation for an electric bus with fixed or 2-speed gearbox International Journal of Electric and Hybrid Vehicles. 2020, 12(3), 229-252. ISSN 1751-4088.
- 2019, FEA on different disc brake rotors, S.A.M Da Silva, DVV Kallon

Name and workplace of bachelor's thesis supervisor:

Ing. Lubomír Musálek Division of electrotechnics FME

Name and workplace of second bachelor's thesis supervisor or consultant:

Date of bachelor's thesis assignment: **27.10.2022** Deadline for bachelor thesis submission: **26.01.2023**

Assignment valid until: ____________

Ing. Lubomír Musálek
Supervisor's signature

Head of department's signature

doc. Ing. Miroslav Španiel, CSc.
Dean's signature

III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt

Student's signature

CVUT-CZ-ZBP-2015.1

Declaration

I declare that the following work in this Bachelor thesis has been prepared and presented under the guidance of my supervisor. It is authentic and there is an assumption that more practical work can be done to expand upon this. The sources cited at the end have been used to narrow down the focus in this thesis.

Acknowledgement

I would like to show my appreciation, admiration and gratitude to Ing.Lubomir Musalek who is my supervisor for this thesis. I thank him for his advice, Knowledge and guidance through this journey.

I also would like to thank the professors who have supported me and shown their faith in me. Lastly I would also like to show my appreciation to my friends who have always been there for me and to my parents for giving me this wonderful opportunity. I feel privileged.

Abstract

This Bachelor thesis has the goal to determine Total harmonic distortion from generated signals when a Frequency Inverter is connected to an Induction motor and to design a model of a Frequency Inverter. The steps taken to measure THD will be detailed upon. The use of functions like FFT(Fast Fourier Transform) are important and will be shown during this work. Also a model of an Inverter connected to three phase motor will be designed with the help of electrical Simulation software where the use of certain tools help us design the required components to build such a model. This model will be used to see how efficiency is affected by THD, as the results from a real Inverter will be used to make a comparison. It is designed using controller Pulse generators and imported spice model data for the transistors. The principles and understanding of THD is fundamental and this thesis will provide a focus on how we analyze it and to come up with a model that can be used or expanded upon further testing.

List of Figures

List of Tables

Table of Contents

1. Introduction

1.1. Inverter Advancements

1.1.1. Brief History

Recent developments in power electronics have made inverters more effective. A variety of inverter types are offered for various uses. The cascaded H-bridge structured inverter, the diode clamped inverter, and the flying capacitor inverter are the most often used multi-level inverters. In this thesis, the H-bridge built inverter is considered for analyzing Total Harmonic Distortion (THD). An H-shaped configuration of transistors or other switching components is used in an H-bridge inverter to convert direct current (DC) into alternating current (AC).

The H-bridge inverter is a flexible and frequently used inverter design because it can generate AC waveforms with variable frequency and magnitude. An H-bridge inverter's basic operation entails turning the circuit's transistors on and off in a predetermined pattern to produce an AC output waveform. The frequency and size of the output waveform can be changed by adjusting the duty cycle of the transistor switching. In applications like motor control, where they can be utilized to drive an AC motor at a variable speed, H-bridge inverters are frequently used. Numerous power-related applications, such as UPSs, power grids, renewable energy sources, motor speed control, induction heating, and many others, use inverters [1].

Figure 1 : Power Walker Inverter with a functional display

An inverter can be used to power a variety of electric appliances during a power outage.A power supply can be switched from a direct current to an alternating current with this device. The source of voltage for AC is typically sinusoidal or square, while the source of voltage for DC is positive.An electrical device known as a DC/AC inverter converts an input voltage, current, and frequency into an output voltage or frequency. In many different applications, inverters are used to convert low voltage DC sources, such as batteries, solar panels, or fuel cells, to AC electricity.[2]

1.1.2.Working Principle

The majority of inverters scale up the output voltage to mains voltage level using a transformer before reverting to DC. The H-bridge driver is used to convert the AC waveform back to DC once a low-voltage DC source has been converted to a high-voltage DC source. The output of an inverter circuit is referred to as voltage-fed or current-fed. The DC input voltage is nearly constant and unaffected by the load's electricity usage with VSI. While the load determines the form of the drawn current, the inverter determines the load voltage.[3-5]

Two parts of an inverter are the wave and the output wattage. In the first, electrical impulses are discussed that are picked up by an oscilloscope, whereas in the latter, power is discussed. While some power converters produce a square or blocky wave, the majority employ a straight DC line to generate a steady AC wave. A better power switch is produced by an AC/DC power inverter with a smoother wave than one with a square wave. The distinction between the two is negligible in terms of practical use, and it only has an impact on expensive equipment. How many devices a power converter can support simultaneously is also dependent on the output power of the device.

1.2. Cases In Inverters

1.2.1.Frequency Inverter

An electronic device known as a frequency Inverter transforms a fluctuating electrical current into a DC-AC wave. Several pieces of equipment, including air conditioners and three-phase motors, can be powered by this kind of system [18]. A variable frequency can be used to modify the motor's output voltage as well. The speed and power of the AC motor can be changed with a variable frequency. With the aid of this feature, the motor's effectiveness is guaranteed even while the variable frequency is in use. No matter whatever components the manufacturer uses, a frequency inverter's fundamental design remains the same. The intermediate circuit and the fast-acting switches are the two primary parts of this system.The former smoothens and stabilizes the output of the electric current, while the latter converts an input supply to a DC voltage [19].

Figure 2: Sample of a three phase Induction Motor

A DC bus's current supply voltage is roughly 1.414 times higher than an incoming ac supply's. It is known as a "super bus" voltage because of this. For this reason, it is used to transform an ac wave into a DC-AC wave in an integrated circuit. The output of an inverter section approximates the pulse width modulation concept rather than producing a true "sine wave." Power electronics frequently use this technology. This portion generates continuous voltage pulse levels using a string of quick switches. Six switches are used for each phase of a three-phase frequency inverter. These switch types use the DC bus voltage to produce the wave's positive and negative components, respectively. The output voltage of the device rises when the switch is "on," while it falls when the switch is "off." The pulse width is the length of time that a pulse is on-time. The output voltage and frequency of a certain instrument are calculated using the duration and intervals of these two positive and negative DC voltage pulses [20-22].

1.2.2. Total Harmonic Distortion and their Standards

The Total Harmonic Distortion (THD) is a type of electrical irregularity that occurs when the current exceeds the fundamental value of the harmonic. It is a vital component of power systems. The performance and efficiency of the motor can be impacted by the THD of the variable-frequency AC voltage that frequency inverters provide to drive the motor. Maintaining a low total harmonic distortion is very important to ensure that the system operates efficiently. A spectrum analyzer or other equivalent device is used to evaluate the AC waveform in order to measure THD. The magnitudes of the harmonic frequencies are determined, added, and contrasted with the magnitude of the fundamental frequency. Based on this ratio, the THD is then determined as a percentage. Filters, improved control algorithms, and careful component selection are just a few methods for lowering THD in a frequency inverter system.

In power systems, low THD is often associated with higher power factor and lower peak currents. This feature is important because international standards such as the IEC 61000-3-2 limit the harmonic currents of various types of equipment. In addition to power factor, AC circuit analysis also focuses on the phase relationship between the current and voltage. Although there is no national standard on the proper amount of total harmonic distortion (THD), there are various practices and requirements that can be used to maintain a low THD in power systems. Although there is no national standard on the proper amount of total harmonic distortion, there are guidelines that can be used to maintain a low THD in power systems. [6].

1.2.3.Utilization of Pulse Width Modulation

Pulse Width Modulation (PWM) enables inverters to maintain a constant output voltage regardless of the load. When compared to other conventional device kinds, this technology is superior in terms of both performance and features. Using pulse width modulation (PWM), analog signals can be digitally encoded. It operates by quickly turning on and off a digital signal, with the average on-time dictating the total strength of the analog signal. The terms "pulse width" and "modulation" describe how long the digital signal is on and how long it is off, respectively, and how the pulse width is changed to carry information. These components' use makes them suitable for a range of loads. These devices also have control and protection in addition to the output stage.

The frequency of the digital pulses, the duty cycle which is the percentage of time that the digital signal is on, and the resolution are just a few of the variables that can be changed in a PWM signal defined as the number of possible values that the duty cycle can take. It is feasible to achieve a broad range of control over the analog output signal by carefully choosing these parameters.Most often, a mix of high-speed and low-noise components is used to generate power from the output switching stage. In comparison to conventional ones, the power generation system's integrated circuits are also more durable [14–17]. PWM is widely utilized in many different applications, such as communication systems, power conversion, and motor control. It is frequently used in place of a continuously adjustable resistor or potentiometer because it is a straightforward and efficient approach to manage the amount of power given to a load. Electronic switching devices such as transistors, thyristors, and MOSFETs can all be used to implement PWM.

2. Theory

2.1. Pulse Width Modulation Principle

2.1.1. Signal Generation

Several power circuit topologies and techniques are used in the design of inverters. The output waveform is one of the most crucial parts of the technology. The several inductors and capacitors that are utilized to filter the output are employed to accomplish this. A resonant filter can be employed if the output frequency of an electric motor is fixed. The filter should be tuned higher than the fundamental frequency if the output frequency is tunable. Additionally, when the switch is turned off, the peak current is bled using feedback rectifiers [14].If a square wave is antisymmetrical around 180 degrees, it contains odd harmonics like the third, fifth, and seventh. The additional harmonics can be cancelled if the wave has a width and height of a particular number of steps. To get rid of the remaining odd harmonics, a zero voltage step can also be added between the wave's negative and positive components [15]. The ratio of the pulse's width to the sum of its negative and positive steps within a specific period should be used. This permits a total pulse width for each step of 1/5 of the period.

By adjusting the switching pulse width, this method aims to alter the properties of the square wave. This procedure might be carried out prior to the supply of the load. If the power supply is not controlled, a fixed pulse width alternative is also possible. The electronic circuit of a power conversion system is intended to boost the effectiveness of a pulse width modulation motor, a type of variable frequency motor (PWM). It has a number of functions, including an output control, an AC mains sensor, and a sensor for battery charging. The internal circuits of the LM 494 or KA 3225 serve as the fundamental building blocks of this circuit. The IC additionally has an oscillator circuit to produce the switching frequency. The output is driven by a variety of switching components in the device's output driver portion. The switching MOSFETs also provide additional power to the primary step transformer.[16-17]

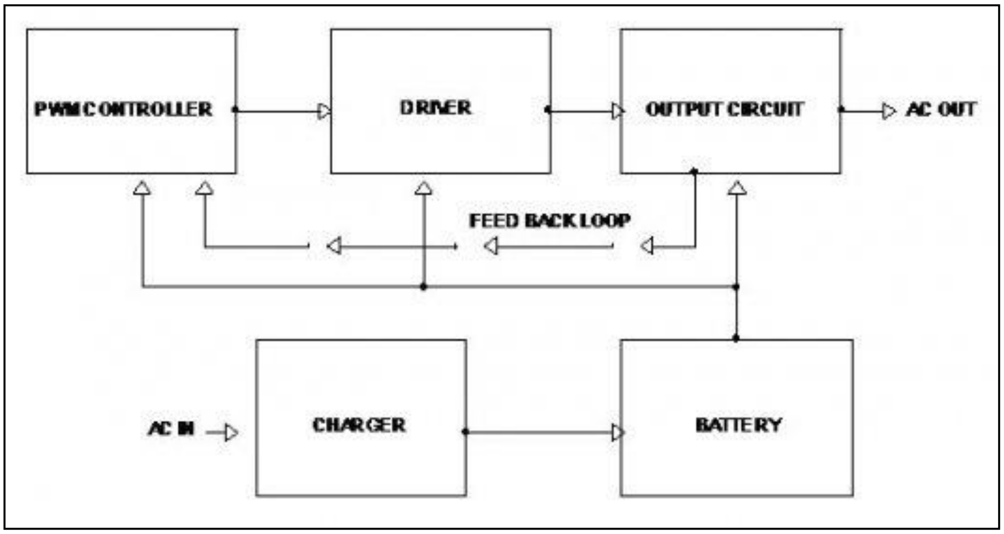


Figure 3: Pulse Width Modulation Block Diagram

There are many ways to generate a PWM signal, depending on the specific requirements of the application and the resources available in the circuit. Some common methods include:

- Using a timer/counter module in a microcontroller to generate the PWM signal. This method allows for precise control over the duty cycle and frequency of the PWM signal.
- Using a digital signal processor (DSP) to generate the PWM signal. DSPs are designed for high-speed signal processing and can generate PWM signals with very high resolution and accuracy.

- Using a pulse generator IC or a specialized PWM generator IC. These ICs are designed specifically for PWM signal generation and can be controlled using a simple digital interface.

Once the PWM signal is generated, it can be used to control the power delivered to a load by switching it on and off using a switching element such as a transistor. The switching element can be either an N-channel or P-channel MOSFET or an IGBT. With this technique, the average power delivered to the load is proportional to the duty cycle of the PWM signal. The frequency of the PWM signal is also a important parameter, as it sets the point in which the device can distinguish between a signal and noise. The typical frequency used in PWM is around 20kHz-30kHz.

2.1.2.Parameters Associated with PWM

The duty cycle of a PWM signal is the ratio of the on-time to the total period of the signal. The parameters that are commonly used to describe a PWM signal are:

- Frequency: The number of times per second that the signal switches between the high and low states. This is also known as the switching frequency. Common frequencies for PWM signals range from a few hertz to several kilohertz.
- Duty Cycle: The ratio of the on-time to the total period of the signal, expressed as a percentage. For example, a duty cycle of 50% means that the signal is high for half of the period, and low for the other half.
- Resolution: The number of distinct steps in the duty cycle. This is determined by the number of bits used to generate the PWM signal. For example, a PWM signal with 8-bit resolution can have 256 steps, while a 16-bit signal can have 65536 steps.
- Dead time: Also known as shoot-through protection, is the minimal time between the turn-off of one switch in an H-Bridge and the turn-on of the

opposite switch. This time is necessary to avoid a short-circuit between the voltage supply and the GND, which can damage the H-Bridge.

- Amplitude: The amplitude of a PWM signal is typically a constant value, and is not a parameter of the PWM itself but rather of the power stage, also it is dependent on the device and application.

These parameters can be adjusted to control the amount of power delivered to the load, as well as to minimize the effect of switching losses and electromagnetic interference (EMI) in the system.

2.1.3.Formula Principle

The "width" of the pulse refers to the amount of time that the power is on, compared to the amount of time that the power is off. The "modulation" refers to the fact that the width of the pulse can be adjusted to control the power delivered to the device.

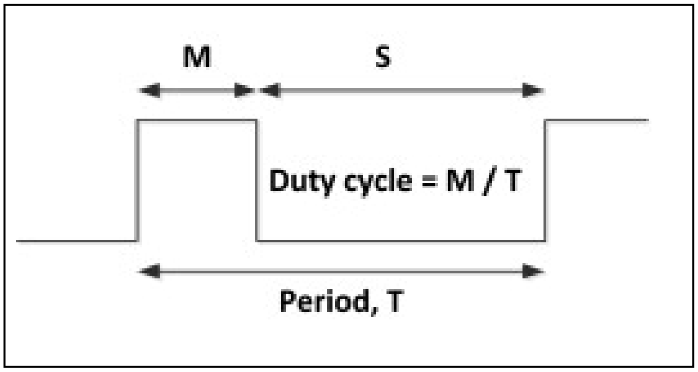


Figure 4: Typical PWM Signal

The basic formula for calculating the duty cycle, which is the ratio of the pulse width to the period of the PWM signal, is:

$$\text{Duty Cycle} = \frac{Pulse\ Width}{Period} * 100\% \qquad (1)$$

Where:

- Pulse Width – Amount of time the power is on [s]
- Period – Total Time of one cycle of PWM signal [s]

For example, if the pulse width is 0.01 seconds and the period is 0.1 seconds, the duty cycle would be:

$$\text{Duty Cycle} = \frac{0.01}{0.1} * 100\% = 10\%$$

So in this case, the power would be on for 10% of the time and off for 90% of the time. As mentioned above the PWM frequency which is also important is around 20Khz.

It is used in DC-AC power conversion, such as inverters, to control the average value of the output voltage. It works by switching the converter's power devices on and off at a high frequency, and varying the duty cycle of the pulses to control the average output voltage. PWM is considered to be better than traditional analog control methods for several reasons:

- High efficiency: PWM allows for a precise control of the output voltage, which can result in higher efficiency compared to traditional analog control methods.
- Low harmonic distortion: PWM generates less harmonic distortion in the output voltage compared to traditional analog control methods, which can result in a cleaner output voltage.

- Good load regulation: PWM allows for good load regulation, which means that the output voltage remains stable even when the load on the converter changes.
- Easy to implement: PWM is relatively easy to implement, as it only requires a simple control circuit and a power device to switch the converter's power on and off.
- Cost-effective: PWM is less expensive to implement compared to traditional analog control methods, as it requires less complex control circuitry.
- Better dynamic performance: PWM allows for fast changes in the output voltage, which allows for a better dynamic performance of the system.
- Better ability to handle nonlinear loads: PWM can handle nonlinear loads better than traditional analog control methods.

Easy to control by digital signals: The PWM signals can be generated by digital signals, this allows for easy integration with microcontrollers or digital signal processors.

2.2. Frequency Inverter theory

2.2.1. Working Principle

A frequency inverter, also referred to as a variable frequency drive (VFD), regulates the frequency of the electrical power sent to an electric motor to control how fast it spins. The inverter changes the incoming AC power to DC power, and then changes the DC power back to AC power at a different frequency using electrical switching. The inverter can control the speed of the motor by adjusting the electrical power's frequency, which can improve energy economy and give precise control over the speed of machinery like fans, pumps, and conveyors.

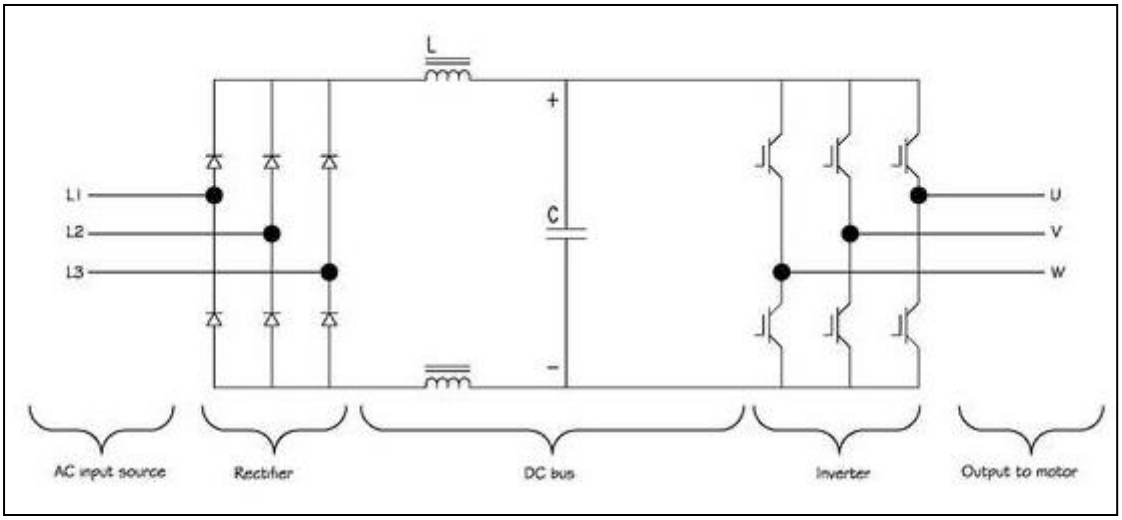


Figure 5: Frequency Inverter Circuit

2.2.2.Frequency Inverter Connected to an Induction Motor

When a frequency inverter is connected to an induction motor, it can control the speed of the motor by adjusting the frequency of the electrical power supplied to the motor. The inverter first converts the incoming AC power to DC power, and then uses electronic switching to convert the DC power back to AC power at a different frequency. By controlling the frequency of the electrical power, the inverter can control the speed of the motor.When the frequency is increased, the speed of the motor also increases, and when the frequency is decreased, the speed of the motor decreases. This allows the inverter to control the speed of the motor over a wide range, providing precise speed control and increased energy efficiency. The inverter also allows for control over the torque of the motor. This can be done by adjusting the voltage and frequency of the power supplied to the motor, which in turn controls the rotor speed and the torque of the motor. This allows for precise control over the torque of the motor, which can be useful in applications such as conveyors and pumps where precise control over the torque is required.In addition, the frequency inverter can also improve the power factor of the motor. When the motor is running at a lower speed, it draws less current and therefore can improve the power factor. Overall, connecting a frequency inverter to an induction motor can provide precise control over the speed and torque of the motor, as well as increased energy efficiency and improved power factor.

Voltage vector control, also known as Direct Torque Control (DTC), is a method of controlling the speed and torque of an induction motor when it is connected to a Variable Frequency Drive (VFD) in an HVAC system.The voltage vector control uses a combination of the voltage and frequency supplied to the motor to control the speed and torque of the motor. The VFD uses a control algorithm to calculate the appropriate voltage and frequency to apply to the motor based on the load and speed of the motor. This allows for precise control of the motor's speed and torque and can result in improved system performance and efficiency.Voltage vector control also allows the VFD to respond quickly to changes in the load, which can result in a more stable system and improved system performance. It also allows the use of smaller and less expensive motors, which can reduce the overall cost of the system.

In a variable frequency drive (VFD), the magnetic flux is directly related to the voltage and frequency of the power supplied to the motor. The VFD controls the speed of the motor by adjusting the frequency of the power supplied to the motor, which affects the magnetic flux of the motor.When the frequency of the power supplied to the motor is increased, the magnetic flux also increases, and the motor's speed increases. Conversely, when the frequency of the power supplied to the motor is decreased, the magnetic flux decreases, and the motor's speed decreases.The VFD also controls the voltage supplied to the motor, which affects the magnetic flux. By controlling the voltage, the VFD can adjust the torque of the motor, which is directly related to the magnetic flux.It's important to note that in induction motors, a decrease in frequency also causes a decrease in voltage, this is known as V/F control, this is done to maintain the power factor close to 1, which means that the motor will not be overloaded, and it will be able to handle the varying load.Overall, magnetic flux plays a crucial role in the operation of a VFD-controlled motor, and the VFD uses adjustments to the voltage and frequency of the power supplied to the motor to control the magnetic flux and, in turn, the speed and torque of the motor.

Frequency control for constant magnetic flux is a technique used to maintain a constant magnetic field in an electric motor or generator by adjusting the frequency of the electrical power supplied to the machine. This is typically done by using a feedback loop that monitors the magnetic field and adjusts the frequency accordingly. The goal of this technique is to improve the efficiency and performance of the machine by keeping the magnetic field constant, which can help to reduce heat loss and increase power output.

This condition is expressed as :

$$\frac{U_s}{f} = \text{constant} \qquad (2)$$

The frequency and value of the frequency of the electric motor's variable components are known as the U_S, f-rms respectively. The modifications made to the static moment curve allow the machine to maintain its main magnetic flux. However, this law can only be used in certain cases.

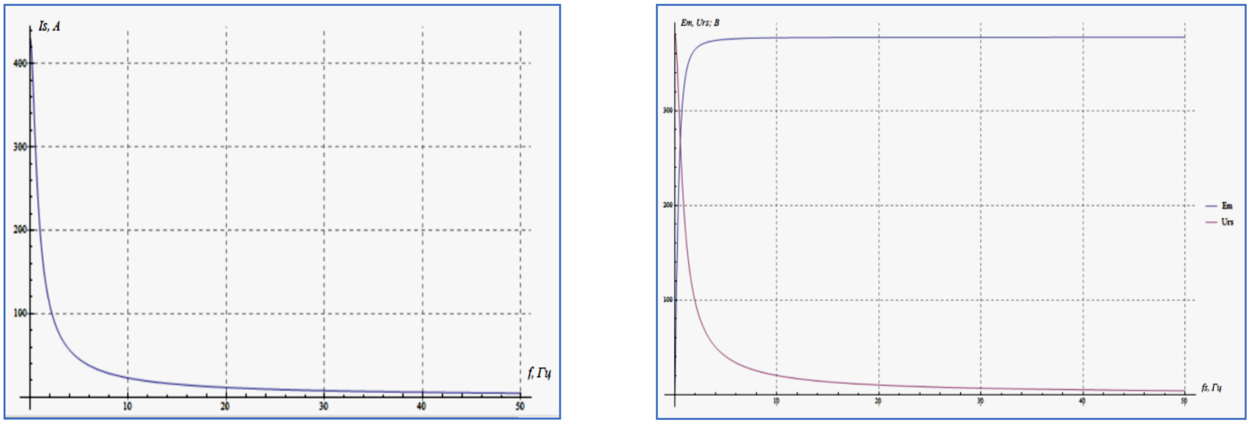


Figure 6: The effects of the magnetization Em, the current I_s, and the voltage drop on the active resistance of the Urs AM are some of the factors that influence the supply voltage at Us=const.

The current at Us=cons increases rapidly, starting from the 25 hertz frequency [18-22]. For high-power WRIM drives, the frequency range is limited to about 25 hertz (Hz). This means that the control range is only about a 2:1 speed down from the rated speed. When the voltage level of the stator goes below this value, the efficiency and overload capacity of the machine decrease dramatically, and the critical slip increases. This is unsuitable for such machines [21-22].

Another concept to know would be the torque-slip relation which will be expanded upon. The Torque-slip equation is a fundamental equation that relates the torque produced by an induction motor to the slip, which is the difference between the synchronous speed and the actual speed of the rotor. The torque-slip equation is expressed as:

$$T = \frac{3}{2}Ps(1-s)\varphi \tag{3}$$

Where:

- T is the torque produced by the motor [Nm]
- P is the number of pole pairs in the motor
- s is the slip
- φ is the flux density in the rotor [Wb]

This equation shows that the torque produced by the motor is directly proportional to the product of the flux density in the rotor, the slip and the number of pole pairs. The torque also increases with the increase of slip. The torque is zero when the slip is zero and is maximum when the slip is one.

The torque-slip equation is based on the assumption that the stator and rotor currents are in phase with each other. When the rotor is rotating at synchronous speed, the slip is zero, and the torque is zero. As the rotor speed deviates from synchronous speed, the slip becomes non-zero, and the torque becomes non-zero.It is is a useful tool for understanding the behavior of induction motors and for designing control strategies that can be used to control the speed and torque of the motor. For example, by controlling the slip, it is possible to control the torque produced by the motor, which can be used to control the speed of the motor.It is important to note that the torque-slip equation is a simplification of the actual behavior of the motor and it is only valid for a certain operating range. The actual torque-slip characteristic of an induction motor depends on many factors such as the design of the motor, the load and the operating conditions.

To determine slip which is expressed per unit we use the equation:

$$s = \frac{N_s - N_r}{N_s} \tag{4}$$

Where:

- Ns is the synchronous speed [r/min]
- Nr is the rotor speed [r/min]

2.2.3.THD Principle

Total harmonic distortion (THD) is a measure of the amount of harmonic distortion present in an electrical signal. It is typically used to characterize the quality of the output of an electrical power system, such as a generator or an inverter.The principle behind THD measurement is based on the fact that most electrical signals are not pure sine waves, but instead contain a combination of sine waves at different frequencies, known as harmonics. Harmonics are multiples of the fundamental frequency of the signal and are caused by non-linearities in the system or device generating or processing the signal.When measuring THD, the harmonic content of a signal is analyzed and the relative amplitudes of the harmonics are compared to the amplitude of the fundamental frequency. The THD is calculated as the ratio of the root mean square (RMS) value of all harmonic components to the RMS value of the fundamental frequency, and then multiplied by 100% to express it as a percentage.

Fast Fourier Transform Mathematically:

The THD measurement is done in a frequency domain, by applying the FFT (Fast Fourier Transform) on the time domain signal. The FFT algorithm is based on the idea of breaking down a signal into smaller and smaller pieces until it can be represented as a combination of simple sinusoids. The FFT works by decomposing an N-point signal into two N/2-point signals, and then recursively decomposing each of those signals. This process is repeated until the signals are reduced to single points. At each step, the FFT uses a set of complex exponentials, called "twiddle factors", to combine the signals from the previous step.

The Discrete Fourier Transform Of Vector is expressed as:

$$Y(k) = \sum_{j=1}^{n} X(j)\, W_n^{(j-1)(k-1)} \tag{5}$$

$$W_n = e^{\frac{-2\pi j}{n}} \tag{6}$$

Where:

- Y(k) is the amplitude and phase of the different frequency components of X(j)

- X(j) is the original signal and input vector
- W_n is the nth root of unity
- K is the frequency index
- j is the element index

In the equation, for each value of k from 1 to N, the DFT calculates the sum of the product of each element in the input vector, X(j). The weighting factor is a complex exponential that depends on both the frequency index k and the element index j, and it is used to adjust the phase of each element in the input vector. The DFT can be computed efficiently using the Fast Fourier Transform (FFT) algorithm, which has a time complexity of O(n log n).The DFT is a linear and invertible transform, which means that the original vector can be recovered from the DFT by applying the inverse DFT.

2.2.4. Principle formula Of THD

$$\mathrm{THD}(\%) = \frac{\sum\sqrt{Vn^2}}{V1} * 100 \tag{7}$$

Where:

- Vn = amplitude of the nth harmonic [V]
- V1 = amplitude of the fundamental frequency [V]

There are several common ways to calculate THD (Total Harmonic Distortion) for a signal, including:

- Using a THD meter: These devices are specifically designed to measure THD and usually display the results as a percentage.
- Using a spectrum analyzer: A spectrum analyzer can be used to measure the power levels of the various harmonic frequencies present in a signal, and then the THD can be calculated using one of the above formulas.
- Using a harmonic distortion analyzer: This is a specialized piece of equipment that measures the harmonic distortion in a signal.

2.3. Determination of Efficiency and the effects of THD

Total harmonic distortion (THD) can have a negative impact on the efficiency of a frequency inverter (VFD) connected to an induction motor. THD is a measure of the harmonic distortion present in the current waveform, and it is usually measured as a percentage of the fundamental waveform. When a VFD generates harmonic distortion in the current waveform, it can increase the power losses in the motor and other parts of the system, and can cause overheating, reduced life expectancy, and other issues. This can lead to a decrease in the efficiency of the system.

The harmonic distortion can affect the efficiency in several ways:

- Increased power losses: Harmonic distortion causes additional power losses in the motor and other parts of the system, which reduces the overall efficiency.
- Reduced cooling efficiency: Overheating caused by harmonic distortion can reduce the cooling efficiency of the motor and other parts of the system, which further reduces the efficiency.

- Reduced life expectancy: Harmonic distortion can cause accelerated wear and tear on the motor and other parts of the system, which can lead to reduced life expectancy and higher maintenance costs.

Therefore, it is important to design the VFD-motor system properly, and take into account the harmonic distortion, in order to maintain high efficiency and avoid potential problems. It is also important to note that the harmonic distortion can also affect other equipment connected to the same electrical network, and cause interference and other issues. Therefore, it is important to consider the THD when designing and operating a VFD-motor system.

Efficiency Formula:

$$\eta m = \frac{Tm * \omega m}{Pin} * 100 \tag{8}$$

Where:

- ηm- Efficiency[%]
- Tm -torque delivered to the load [Nm]
- ωm -Angular Speed is the speed of the motor shaft [Rad/s]
- Pin -Input Power is the power consumed by the motor [W]

This formula also gives the efficiency as a percentage, with values between 0% and 100%. It shows that efficiency is the product of torque and angular speed divided by the input power. It is important to note that the efficiency of the motor system is not constant, it varies with respect to load, angular speed, voltage and frequency.

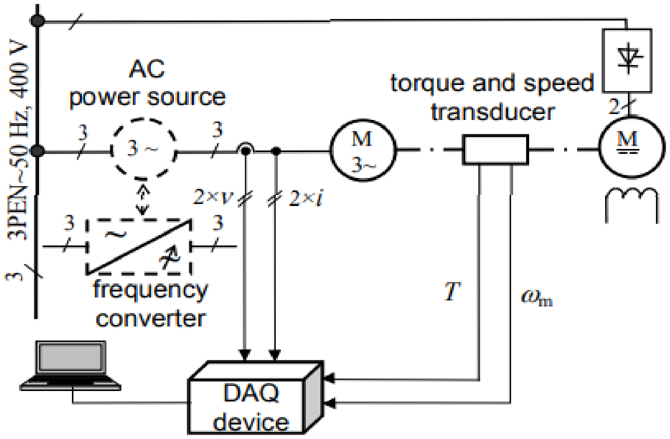


Figure 7: Testing System for Frequency Inverter

2.4. Model Predictive Control

Model Predictive Control (MPC) is a control strategy that uses a mathematical model of a system to predict its future behavior and optimizes control actions to achieve a desired performance. It uses a model of the system dynamics and constraints, and an optimization algorithm to determine the control actions that minimize a given cost function over a prediction horizon. The prediction horizon is the number of future time steps for which the system behavior is predicted. The control actions are then applied to the system, and the process is repeated at each time step.

MPC is a type of feedback control, where the controller uses the current measurements of the system to adjust the control inputs. The control inputs are chosen to minimize a performance index, which is a measure of the deviation of the system from the desired behavior. The performance index can be defined as a function of the system states, inputs, and output.MPC is widely used in industrial process control, robotics, and autonomous systems because of its ability to handle constraints and optimize performance. It is particularly useful in systems with multiple interacting variables and constraints, where traditional feedback controllers may not be able to achieve satisfactory performance.One of the key advantages of MPC is that it allows for the incorporation of constraints on the system states, inputs, and outputs, which ensures that the system remains safe and stable.

MPC involves the following basic steps:

- Modeling: A mathematical model of the system is constructed, which describes the relationship between the inputs and outputs of the system.
- Prediction: Using the model, the future behavior of the system is predicted for a given set of control inputs.
- Optimization: An optimization algorithm is used to determine the control inputs that will achieve a desired performance, while satisfying constraints on the system.
- Control: The control inputs determined by the optimization algorithm are applied to the system.
- Measurement: The actual outputs of the system are measured and used to update the model and repeat the prediction, optimization, and control steps.

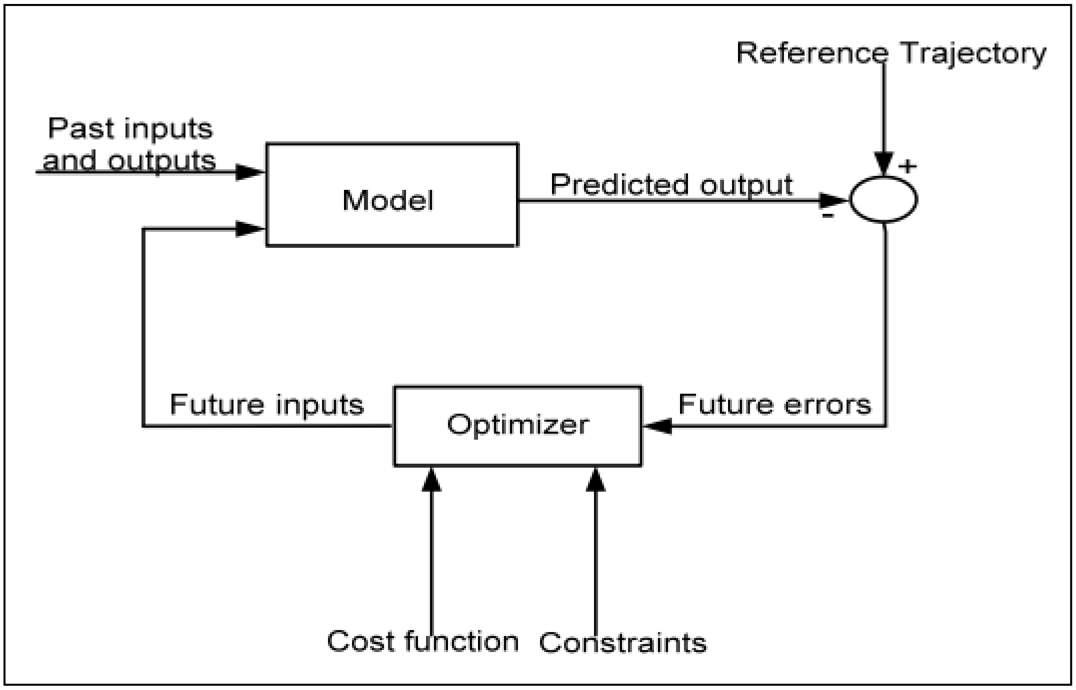


Figure 8: Basic Components OF MPC

The Optimization problem in MPC typically has the following form:

$$J = \sum [\text{Costs } (x(t),u(t),t)] \tag{9}$$

For Which:

- $x(t+1) = f(x(t),u(t),t)$
- $g(x(t),u(t),t) <= 0$
- $h(x(t),u(t),t) = 0$

where J is the cost function, x(t) is the state of the system at time t, u(t) is the control input at time t, t is the time index, f is the system dynamics, g and h are the inequality and equality constraints, respectively. The cost function, J, is designed to capture the desired performance of the system. It can be designed to minimize a measure of the deviation from a setpoint, to minimize energy consumption, or to minimize the deviation from a desired trajectory, for example. The constraints g and h are used to limit the control inputs and states of the system within safe and acceptable limits. Once the optimization problem is solved, the control input that minimizes the cost function is applied to the system, and the process is repeated at the next time step.

They can be used in the control of DC-AC power converters such as Inverters:

To optimize the performance and efficiency of the system.In a DC-AC power converter, the DC input voltage is converted to a controlled AC output voltage. The main control task in a DC-AC converter is to regulate the AC output voltage and/or frequency, while taking into account the constraints on the system, such as the maximum allowable switching frequency, the maximum allowable current, and the maximum allowable voltage.MPC can be used to control the DC-AC converter by solving an optimization problem at each time step that takes into account the system model, the desired performance, and the constraints on the system. The optimization problem can be designed to minimize a measure of the deviation from a setpoint, to minimize energy consumption, or to minimize the deviation from a desired trajectory, for example.

The constraints on the system can include limits on the switching frequency, the maximum allowable current, and the maximum allowable voltage. The optimization problem can also take into account the nonlinearity of the converter and the switching losses. Once the optimization problem is solved, the control inputs that minimize the cost function are applied to the converter, and the process is repeated at the next time step. MPC can provide better performance over traditional control methods by taking into account the system model, predicting the future behavior of the system, and optimizing the control inputs. It can also provide a systematic way to take into account constraints on the system and allows for the integration of multiple objectives in the control design. It's worth noting that MPC can be quite complex and computationally intensive, and it requires a good mathematical model of the converter and an accurate prediction of the future behavior of the system.

Additionally, it's important to tune the parameters of the MPC algorithm to achieve good performance, especially when dealing with nonlinear systems.

3. Practical

3.1. Design and selection of Real Frequency Inverter

3.1.1. VLT HVAC Drive

The VLT HVAC Drive is designed to control the speed of induction motors used in heating, ventilation, and air conditioning (HVAC) systems. It uses a variable frequency drive (VFD) to adjust the frequency of the power supplied to the motor, which in turn adjusts the speed of the motor.It typically includes a control circuit that receives commands from the user or a building management system (BMS) and generates the appropriate frequency and voltage for the motor. It also includes feedback circuits that monitor the motor's speed and current and send this information back to the control circuit. It features a user-friendly interface and a variety of advanced features such as energy saving modes, soft start and stop, and motor protection. It can be configured to work with different types of motors and can be connected to building management systems (BMS)

Figure 9: VLT HVAC Drive with a variable frequency drive(VFD)

to enable remote monitoring and control. It improves the efficiency and performance of HVAC systems and to provide reliable and precise control of the motor speed. It's designed to be easy to install and use, and to integrate with other building automation systems.

An HVAC VLT drive typically converts DC power to AC power to control the speed of the HVAC system's motors. The DC power is usually generated by an inverter, which is powered by the incoming AC power. The inverter converts the incoming AC power to a variable-frequency, variable-voltage DC power, which is then used to generate the variable-frequency AC power that is supplied to the motor.The design of a VLT drive includes a DC/AC inverter, a control circuit, and a user interface. The control circuit, which can be a microcontroller, PLC or DSP, receives input from sensors and user settings and uses this information to adjust the frequency and voltage of the power supplied to the motor. The user interface allows for the setting of parameters, monitoring of the drive's operation, and status indication. The drive also includes safety features like overcurrent and overvoltage protection, thermal protection, etc.

Other key aspects of an HVAC VLT drive include:

- Compatibility: The drive must be compatible with the specific make and model of the HVAC system's motor in order to function properly.
- EMI (Electromagnetic Interference) filter: EMI filter is used to suppress high-frequency voltage transients that may be generated by the drive, which can cause interference with other electronic equipment.
- Harmonic Filter: Harmonic filter is used to reduce the harmonic distortion caused by the drive, which can cause power quality problems in the electrical distribution system.

- Communication capabilities: Many VLT drives include communication options such as Modbus, Profibus, BACnet, etc. that allow the drive to be connected to a building automation system or other control system.
- Remote monitoring and control: Some VLT drives include remote monitoring and control capabilities that allow the drive to be monitored and controlled remotely via a web-based interface.
- Software and Firmware updates: VLT drives can have firmware and software updates for bug fixes, performance enhancement and additional features.
- Energy efficiency: VLT drives can significantly improve the energy efficiency of HVAC systems by allowing the motors to run at the optimal speed for a given load, thus reducing energy consumption and costs.

Another factor of HVAC VLT drives is the ability to provide motor protection. This can include features such as over-current, over-voltage, under-voltage, and over-heating protection. These features help to protect the motor from damage caused by abnormal operating conditions.Another feature that can be found in some HVAC VLT drives is the ability to perform auto-tuning. This allows the drive to automatically adjust its settings based on the performance of the motor, which can help to improve the overall efficiency and performance of the HVAC system.Additionally, many VLT drives include a built-in PLC (Programmable Logic Controller) which can be used to perform simple control functions, like on/off control, sequence control, etc. This feature can help to reduce the cost of the control system and increase the reliability of the overall system.Lastly, VLT drives can have a wide range of power ratings, from a few horsepower to several hundred horsepower. It's important to select the drive with the appropriate power rating to match the motor and the HVAC system.Overall, HVAC VLT drives are a valuable tool for improving the efficiency and performance of HVAC systems, as well as providing protection for the motors and allowing for remote monitoring and control.

3.2. Connection of components

3.2.1. Wattmeter

A wattmeter is a device used to measure the power consumption of an electrical system. To connect a wattmeter to an HVAC VLT (Variable Frequency Drive) and an induction motor, the wattmeter would typically be connected in series with the power cables that provide power to the motor.

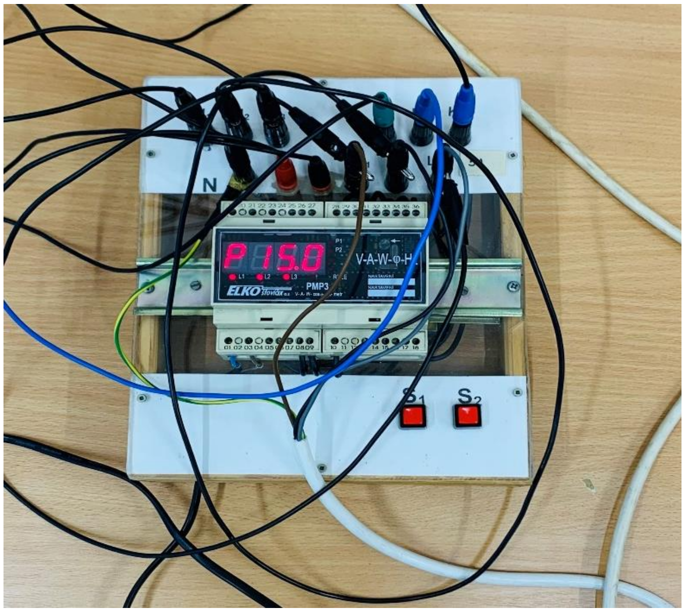


Figure 8: Wattmeter

It would involve the following steps:

- Turn off the power to the VLT Drive and the induction motor before making any connections to avoid electrical hazards.
- Locate the power cables that provide power to the motor. These cables will typically be connected to the VLT Drive and the motor's power terminals.
- Disconnect the power cables from the VLT Drive and the motor.

- Connect the wattmeter in series with the power cables. This means that the wattmeter's input terminals should be connected in line with the power cables, so that the electrical current flows through the wattmeter before reaching the VLT Drive and the motor.
- Reconnect the power cables to the VLT Drive and the motor, making sure that the connections are secure.
- Turn on the power to the VLT Drive and the induction motor.
- The wattmeter will now measure the power consumption of the system and can be used to monitor the energy consumption of the HVAC system, and also can help to identify any issues or inefficiencies in the system.

3.2.2. Oscilloscope for displaying Signals to determine Total Harmonic Distortion

To connect an oscilloscope to a VLT HVAC drive for measuring THD, you will typically need to use voltage and current probes. The voltage probe is typically connected in parallel with the load, and the current probe is typically connected in series with the load.

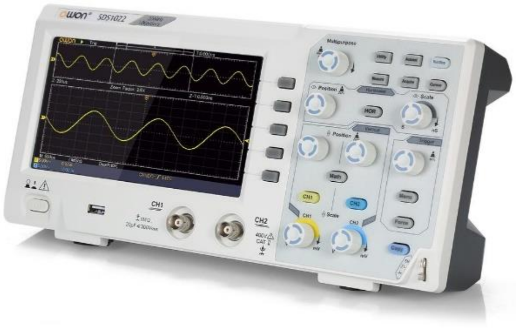


Figure 9:Oscilloscope

The voltage probe is connected to one of the oscilloscope's voltage input channels using a BNC connector. The other end of the probe is connected to the load by clipping the probe's connector onto the load's wire.The current probe is connected in a similar way, with one end connected to the oscilloscope's current input channel using a BNC connector, and the other end connected to the load by clamping the probe around the load's wire.Once the probes are connected, you will need to configure the oscilloscope to measure and display the voltage and current waveforms. This typically involves setting the oscilloscope's input range and coupling to match the voltage and current levels of the HVAC drive.

3.2.3. Voltage and Current Sensors

Voltage and current sensors in an induction motor are typically connected through analog inputs on a control system or data acquisition system. The voltage sensor (VT) and current sensor (CT) are wired in series with the power cables that lead to the motor's input terminals, which allows them to measure the voltage and current flowing into the motor.

Figure 10: Current and Voltage Sensor

For voltage sensor, it is connected in parallel to the input voltage terminals of the motor. This allows the sensor to measure the voltage without affecting the current flowing into the motor.For current sensor, it is connected in series with the input current, typically using a current transformer (CT) that wraps around one of the power cables leading to the motor. This allows the sensor to measure the current without affecting the voltage across the motor.

3.2.4. Induction Motor

An induction motor is typically connected to a power source through a set of input terminals, which are located on the motor's control panel or terminal box. The motor is connected to the power source using a set of three wires: two for the main power and one for the ground.The two main power wires are connected to the input terminals of the motor. These are typically labeled "L1", "L2", and "L3" for a three-phase motor.The VFD circuit allows the speed and torque of the motor to be controlled by varying the frequency and voltage of the power supplied to the motor.

Figure 11: Three Phase Induction Motor

These are the following steps:

- Turn off power to the VLT drive and the motor.
- Connect the power cables from the power source to the VLT drive's input terminals. The cables should be connected to the terminals labeled "L1", "L2", and "L3" for a three-phase motor.
- Connect the motor's power cables to the VLT drive's output terminals. The cables should be connected to the terminals labeled "U1", "V1", "W1" for a three-phase motor.
- Connect the ground wire to the ground terminal of the VLT drive.
- Turn on power to the VLT drive and the motor and check for proper operation.
- Adjust the VLT drive's parameters such as voltage, current, and frequency to match the motor's rated values.

3.3. FFT (Fast Fourier Transform)

3.3.1. Use of MATLAB Software

One common method of measuring THD is to use the Fast Fourier Transform (FFT) to transform the time-domain signal into the frequency domain, and then measure the ratio of the amplitude of the fundamental frequency to the amplitudes of the harmonic frequencies.

In MATLAB ,the process of measuring THD using FFT would typically involve the following steps:

- Acquire the time-domain signal: The signal can be acquired using a measurement device such as an oscilloscope.

- Perform the FFT: Use the fft() function to compute the FFT of the time-domain signal.
- Compute the magnitude of the FFT: Use the abs() function to compute the magnitude of the FFT. This will give the amplitude of each frequency component of the signal.
- Identify the fundamental frequency: The fundamental frequency is the frequency component with the highest amplitude.
- Compute the THD: The THD is computed as the ratio of the sum of the amplitudes of the harmonic frequencies to the amplitude of the fundamental frequency.
- Plot the result: The results can be plotted using the plot() function.

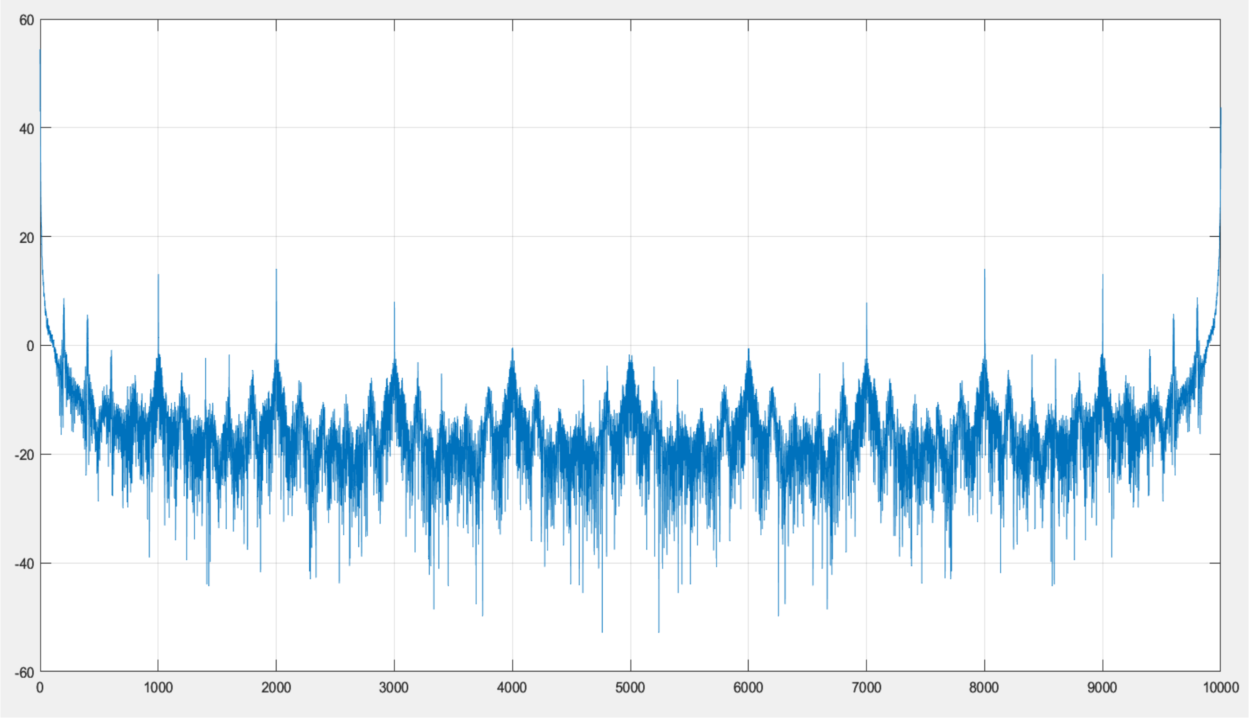


Figure 12: Sample of harmonic frequencies used to determine THD in MATLAB

Simple FFT Program Code In MATLAB:

```
NFFT = 10000;
X = fft(x,NFFT);
Xabs = abs(X) / NFFT;
GdB = 20*log10(Xabs);

figure(1);
plot(GdB);
grid on
xlim([0 NFFT/2]);
```

As we can see above, the peak points are the harmonic frequencies and we have a display of the complete sample but only require the harmonics for half the cycle to determine THD. This can be programmed on MATLAB by using the function xlim([0 NFFT/2]). What this does is it sets the lower limit of the x-axis to zero and the upper limit to NFFT/2. This means that the x-axis of the plot will only display values from 0 to NFFT/2. This can be useful when plotting the results of a Fast Fourier Transform (FFT) because the FFT output is symmetric about the NFFT/2 point, and displaying only half of the output can make it easier to interpret the results. It means that the x-axis of the plot will display the frequency range from 0 to half of the sampling frequency.

3.4. Final Practical Setup of HVAC VLT Drive for assessing THD

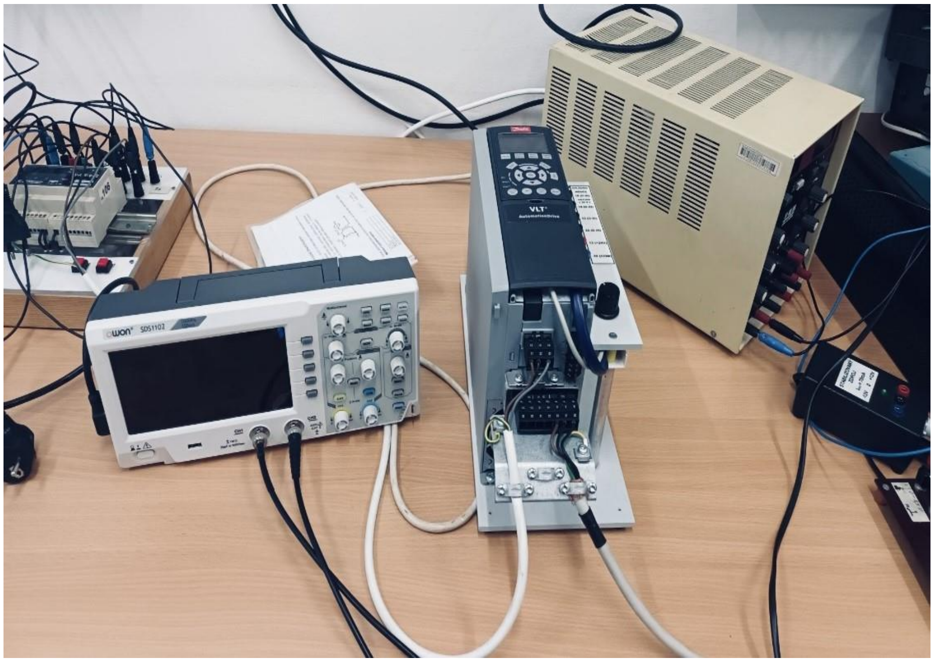


Figure 13: Connection of oscilloscope and wattmeter to HVAC VLT Drive

As we can see, it has been set up using the steps that were detailed upon during the connecting of components and we can now proceed.

4. Results

4.1. Calculation Procedure Methodology

The output current was varied and experiments were conducted for 1.60A, 1.70A, 1.80A, 2.00A, 2.20A and 2.30A.Currents around 2,80A would cause an overheat which causes power dissipation and damage to the motor and Inverter.

1) By adjusting the voltage and frequency supplied to the motor which in turn can help control the torque, the measurements were taken.
2) The Oscilloscope is used to analyze waveforms, but it is a time domain signal and needs to be transformed into a frequency domain by using FFT(Fast Fourier Transform) as mentioned before. So we save the data in flash disk using the CSV format from the oscilloscope and use this in MATLAB.

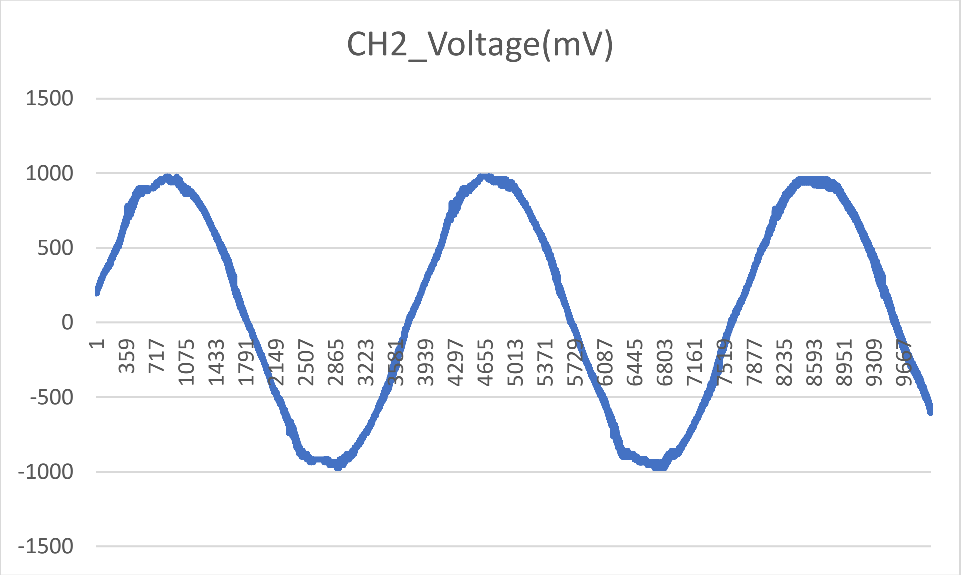
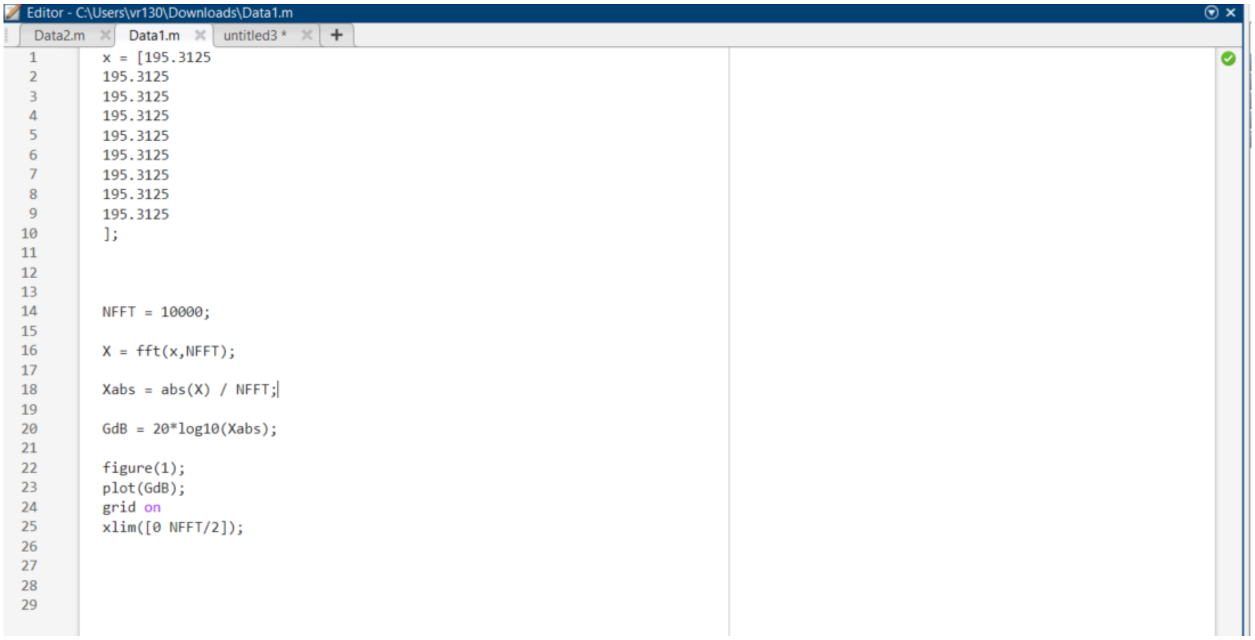


Figure 14: Plotting of data from Oscilloscope on Excel which shows the sinusoidal wave.

3)We program the FFT function using MATLAB software and plot the harmonic frequencies. Once they are determined they can be used to find the fundamental and harmonic voltages.



```
x = [195.3125
195.3125
195.3125
195.3125
195.3125
195.3125
195.3125
195.3125
195.3125
];



NFFT = 10000;

X = fft(x,NFFT);

Xabs = abs(X) / NFFT;

GdB = 20*log10(Xabs);

figure(1);
plot(GdB);
grid on
xlim([0 NFFT/2]);
```

Figure 15: Use of data to plot Harmonics

According to the program created on MATLAB for FFT, the voltages can be calculated from the fundamental and harmonic frequencies by converting the amplitude in dB to volts by the equation:

$$\text{Volts} = \sqrt{10^{\frac{\text{dB}}{20}}} \qquad (9)$$

As we have seen in the theory section, formula (7) can then be applied to calculate THD.

4.2. Calculation Results

1)For Iout = 1.60A:

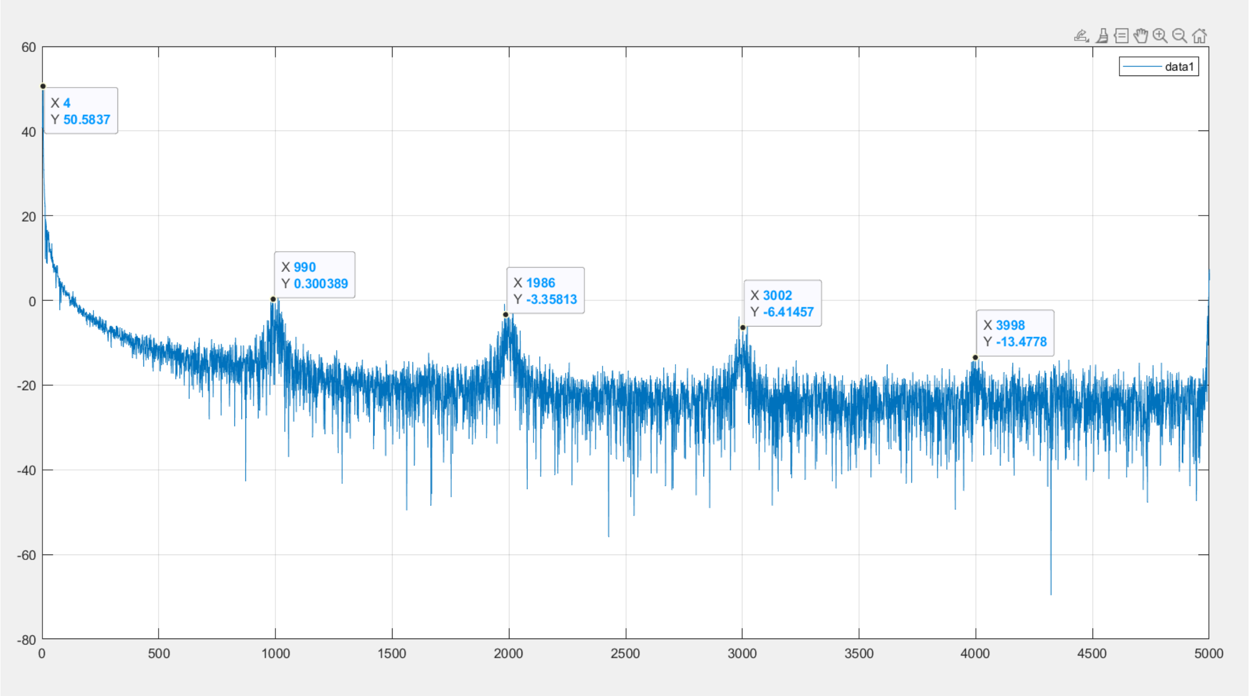


Figure 14: Harmonic frequencies for 1.60A

Determination of Fundamental Voltage and harmonic voltages using formula (9):

- Fundamental Voltage, V_1 = 18.39V
- Harmonic Voltage, V_2 = 1.02V
- Harmonic Voltage, V_3 = 0.823V
- Harmonic Voltage, V_4 = 0.691V
- Harmonic Voltage, V_5 = 0.460V

We only consider the voltages at peak points and where harmonic distortion is visible hence we only consider the points for the harmonic voltages. The sample size is 10000 and we only use half of the sample as the current is low and it is easier to observe the distortion.

Determination Of Total Harmonic Distortion using formula (7):

$$\mathrm{THD} = \frac{\sqrt{V_2^{\,2} + V_3^{\,2} + V_4^{\,2} + V_5^{\,2}}}{V_1} * 100$$

$$\mathrm{THD} = 8.44\%$$

Using the above equation we calculated THD as a percentage as it is expressed in this form.

2)For Iout = 1.70A:

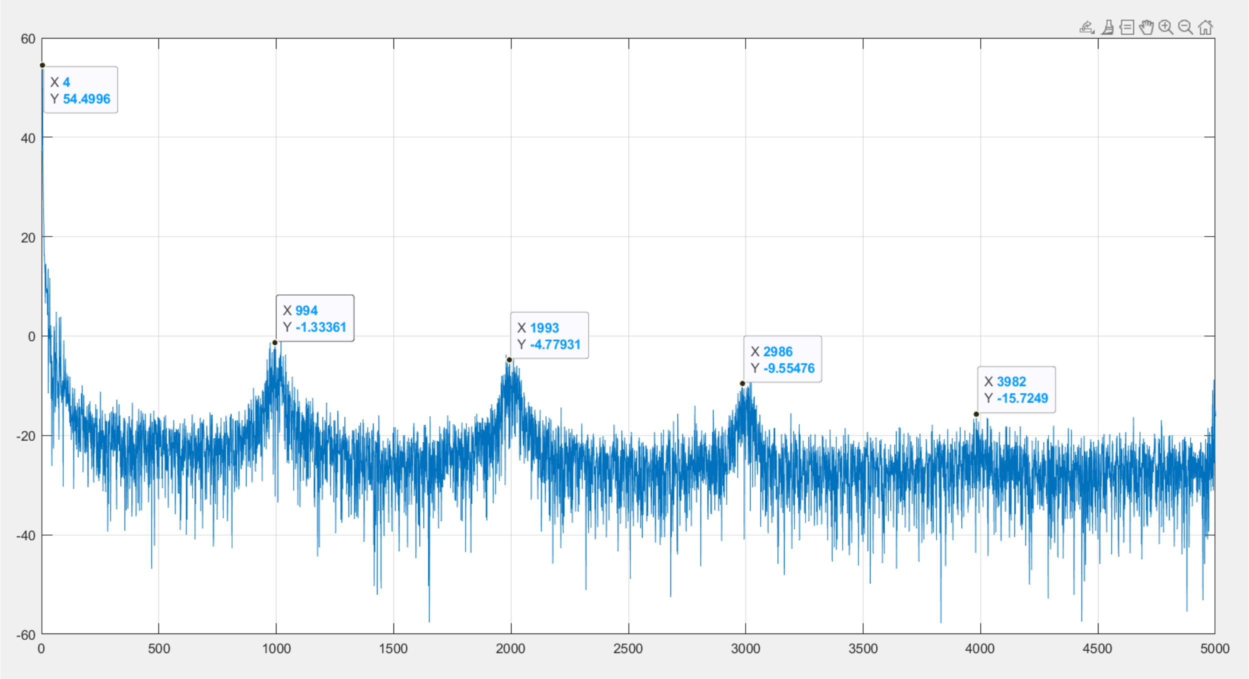


Figure 15: Harmonic frequencies for 1.70A

- Fundamental Voltage, V_1 = 23.04V
- Harmonic Voltage, V_2 = 0.926V
- Harmonic Voltage, V_3 = 0.759V
- Harmonic Voltage, V_4 = 0.577V
- Harmonic Voltage, V_5 = 0.405V
- THD = 6.03%

3)For Iout = 1.80A:

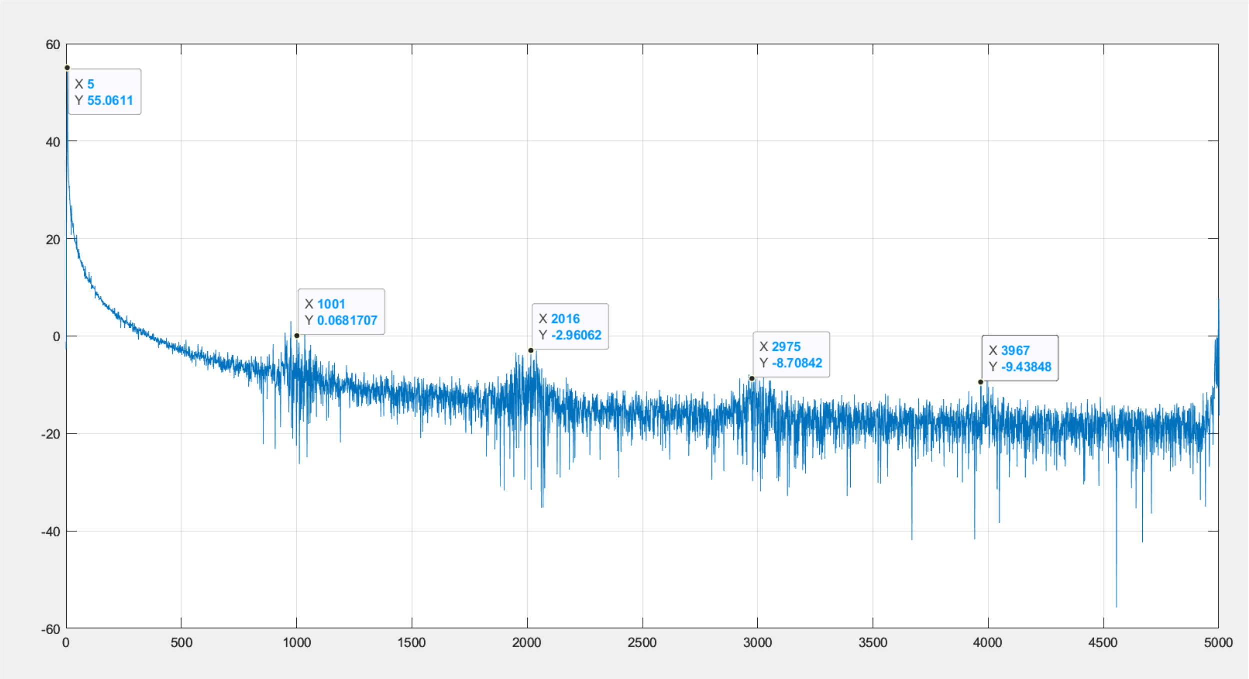


Figure 16: Harmonic frequencies for 1.80A

- Fundamental Voltage, V_1 = 23.80V
- Harmonic Voltage, V_2 = 1.00V
- Harmonic Voltage, V_3 = 0.840V

- Harmonic Voltage, V_4 = 0.606V
- Harmonic Voltage, V_5 = 0.581V
- THD = 6.52%

4)For Iout = 2.00A:

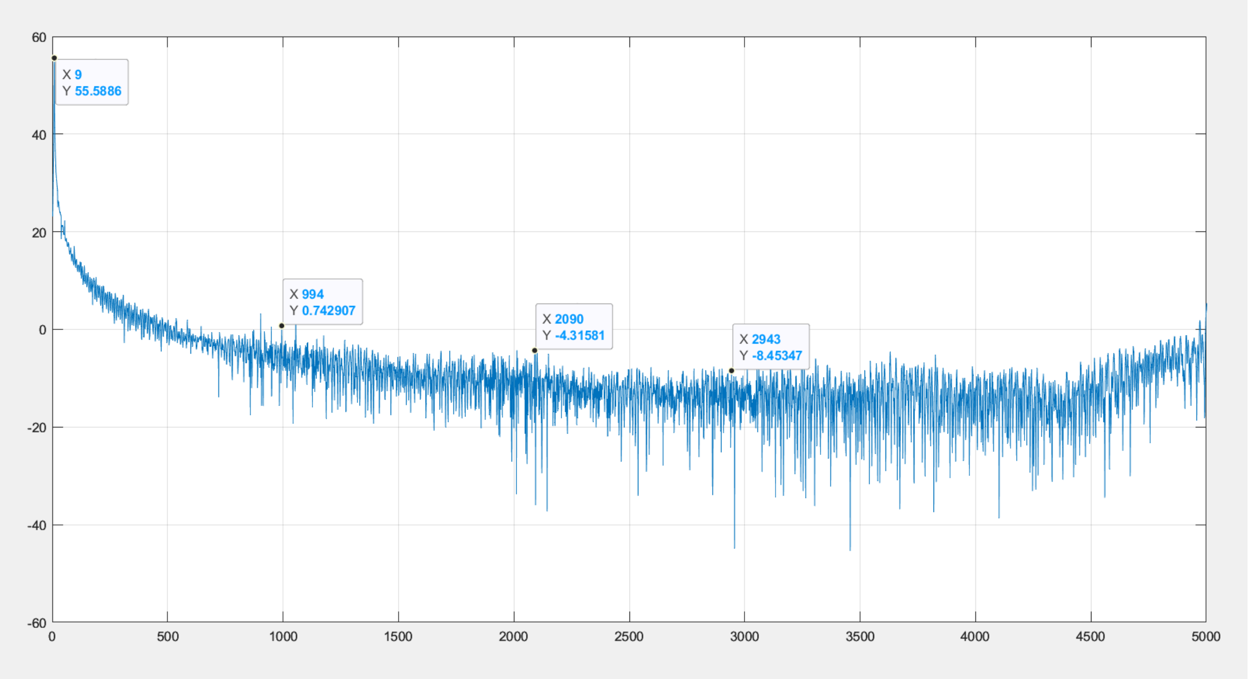


Figure 17: Harmonic frequencies for 2.00A

- Fundamental Voltage, V_1 = 24.53V
- Harmonic Voltage, V_2 = 1.044V
- Harmonic Voltage, V_3 = 0.780V
- Harmonic Voltage, V_4 = 0.615V
- THD = 5.87%

As we can see over here, the peak voltages showing us harmonic distortion are getting less as the current increases making it harder to measure them.

5)For Iout = 2.20A

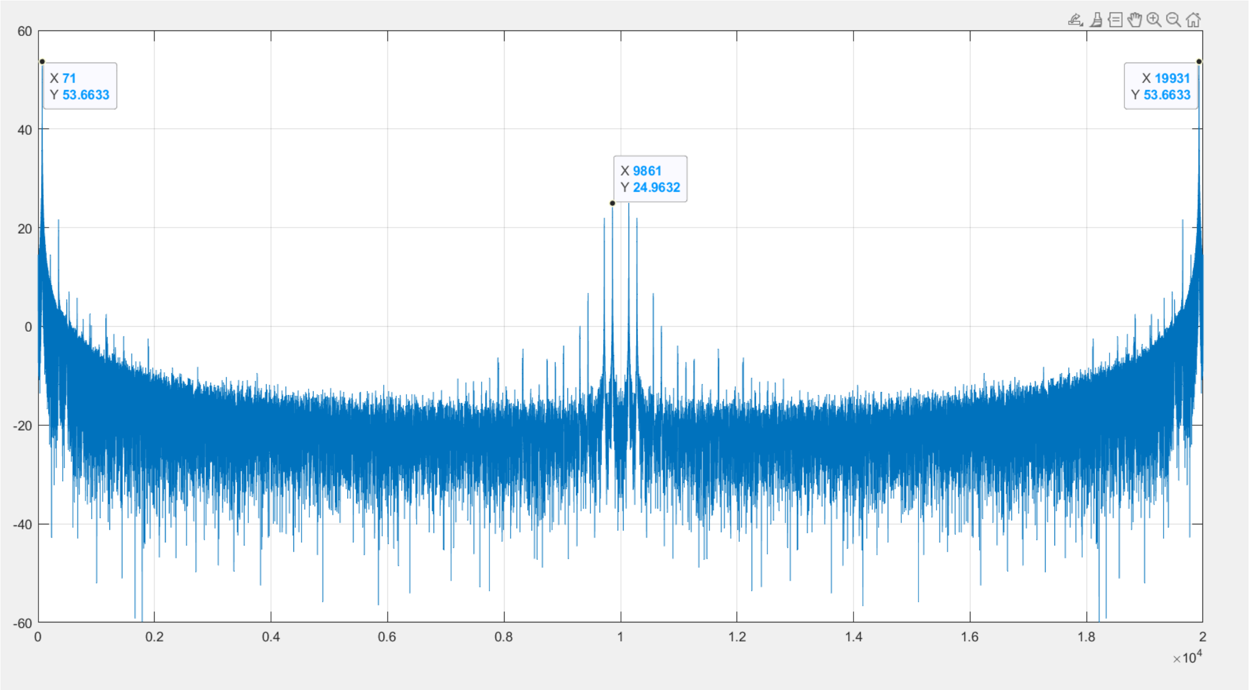


Figure 18 : Harmonic frequencies for 2.00A

- Fundamental Voltage, V_1 = 21.95V
- Harmonic Voltage, V_2 = 4.20V
- THD = 19.13%

As we approach the peak current value of Iout, the distortion levels are high and to assess the distortion we need to use a higher sample. Hence we set the NFFT sample rate to 20000. As we can see the distortion is so high that it reaches the fundamental Voltage, which is the peak voltage point among the harmonic voltages and our THD has evidently increased beyond the usual acceptable limits of 5% for voltages which shows how much harmonic distortion is present.

6)For Iout = 2.30A

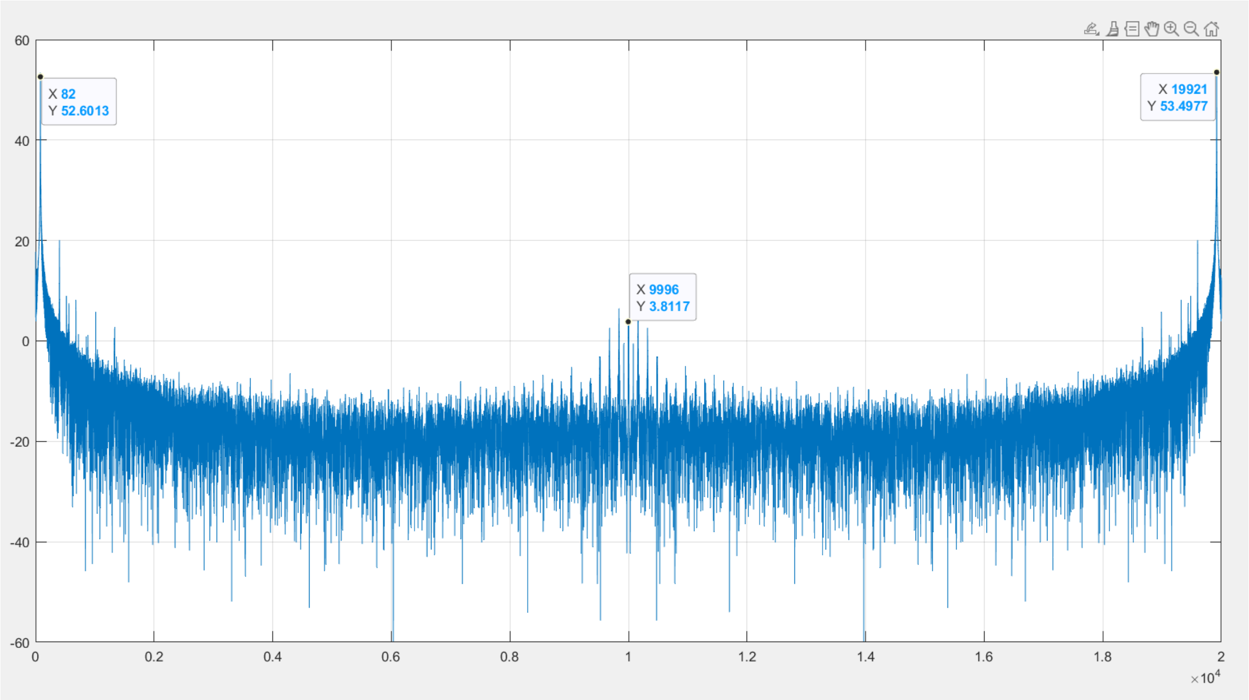


Figure 16 : Harmonic frequencies for 2.30A

- Fundamental Voltage, V_1 = 20.65V
- Harmonic Voltage, V_2 = 1.245V
- THD = 6.029%

Finally as we reach our peak current Iout, we can see the harmonic distortion is beyond the fundamental voltage which is the highest point for harmonic voltage, which shows us it is at its limits in terms of the current which runs through motor.

Efficiency is calculated using Formula (8):

$$\eta m = \frac{0.9*2*\pi*2.6}{93.7}*100$$

$$= 15.70\%$$

The Table below displays the complete results of the calculated efficiency along with other parameters such as torque and frequency as well as our fundamental Voltages and THD.

Iout[A]	V1[V]	Tm[Nm]	F[Hz]	Pin[W]	THD[%]	ηm[%]
1.60	18.39	0.9	2.6	93.7	8.44	15.70
1.70	23.04	1.4	3.2	111.2	6.03	25.31
1.80	23.80	1.9	4.3	127.0	6.25	40.42
2.00	24.53	2.6	7.6	182.0	5.87	68.22
2.20	21.95	3.7	35	235.0	19.13	346.24
2.30	20.65	4.8	4.2	309.0	6.029	40.99

Table 1: Calculated results of Real Inverter

As we can see from the results above there is a relation between efficiency and THD and we can see how they impact each other. There is an anomaly in one of the results for Iout = 2.20A. During this measurement it is clear to see that the efficiency determined is not an accurate reading as our THD has a spike where it becomes 19.13% which is not in the range of 5%, the typical THD measurement for harmonic voltages. In terms of current, 20% is acceptable but that is not in our interest as we are focusing on the harmonic frequencies and voltages.

5. Model of Frequency Inverter

5.1. Model on LtSpice

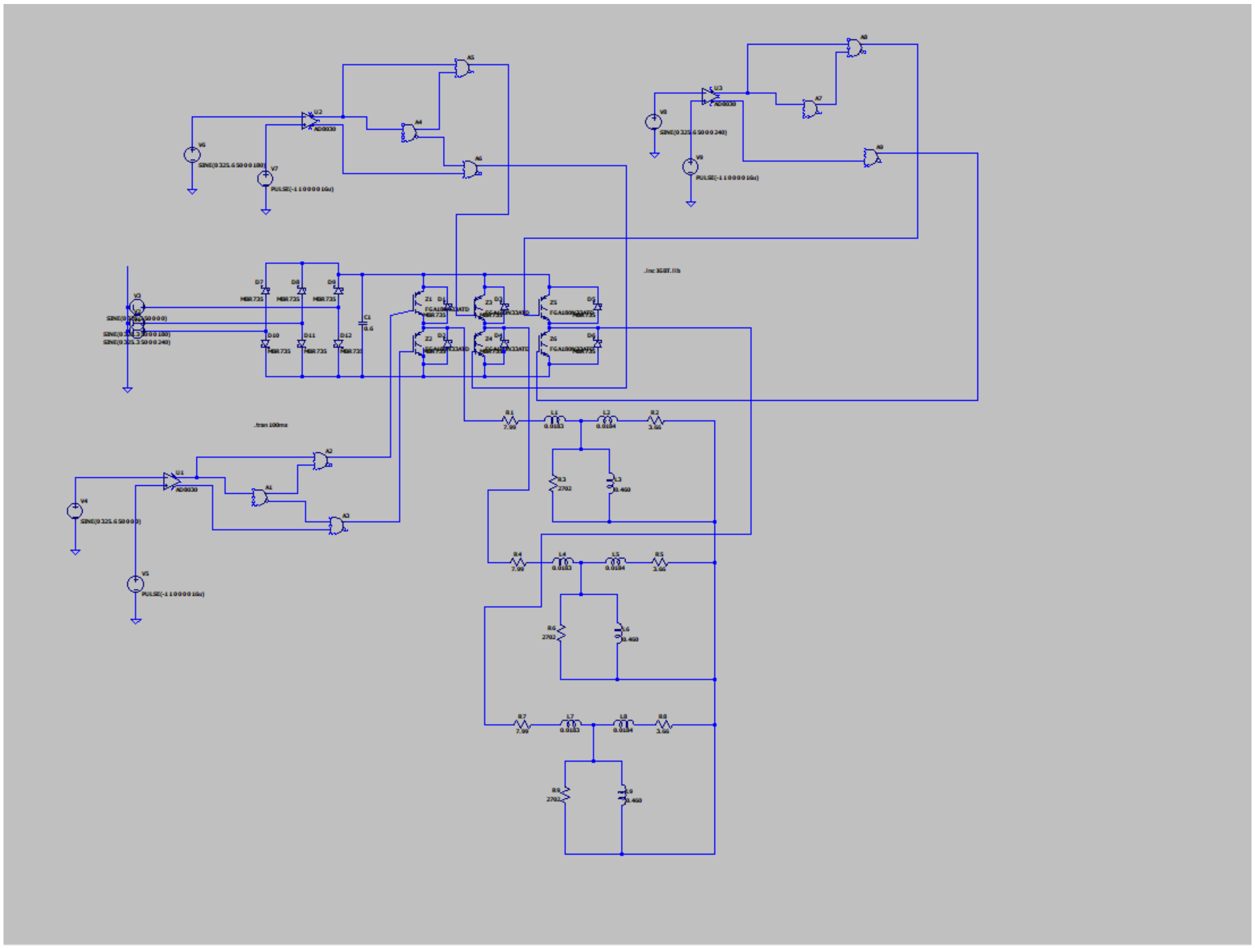


Figure 24: Model of frequency Inverter designed on LtSpice

The above model has been designed using values for frequency and voltages that are not concrete as it has been done on a simulation software as opposed to the real Inverter. It has been designed in a way where we have our Induction motor in Three phase and we use a spice model that has been imported to enable us to use the NIGBT transistor. We have a six transistors and have designed three controller pulse generators, where we connect one to two transistors. We will see how results vary compared to our real Inverter.

Efficiency is calculated using:

$$\frac{\text{Pout}}{\text{Pin}}*100$$

Iout[A]	Pin[W]	Pout[W]	F[Hz]	ηm[%]
1.60	243	219	21.3	90.10
1.70	320	290	23.0	90.62
1.80	439	402	27.7	91.57
2.00	708	642	36.7	90.68
2.20	903	829	39.7	91.80
2.40	1211	1103	46.4	91.08
2.60	1450	1365	51.5	94.14

Table 2: Results of Frequency Inverter Model

As we can see the system seems to run smooth and this shows us how a model not affected by THD runs, as evident with results above. This model can further be improved upon by using different softwares to test out results. Additionally the controller pulse generators could be designed more precisely to give us a greater degree of accuracy.

6. Conclusion

6.1. Overview of Results

Now that we have the results from both the real Inverter and the model designed to meet our needs we can make a comparison as our results from the practical experiments seem to be accurate. The reason for this is as seen with our real Inverter our efficiency seems to be on average 38.1%. Ofcourse this is not including the anomaly where our THD was 19.13% as our calculated efficiency for that particular measurement was 346.24 which is theoretically and practically impossible as efficiency is expressed as a percentage out of 100. However the other measurements conducted seem to have a degree of accuracy to them as evident by our results.

Rather than trying to get results directly using an oscilloscope software which can be unreliable, we used the data in MATLAB to perform Fast Fourier Transform(FFT). This is because MATLAB can be used to determine functions which may be rather complicated in a theoretical sense. This is because the function of FFT is to break down signals into smaller pieces and during the experiments conducted, it is understandable that with the assessing of pulse width modulation and harmonics there may be multiple signals to break down and it is simply too time consuming and complex, hence the use of MATLAB software. It is used world wide and is an extremely useful tool and one which it is safe to say is as accurate as it gets.

The Model designed on LtSpice gives us results which even though can be expanded upon still shows us how a model not affected by THD can operate smoothly and very efficiently as evidenced by the results which show us an efficiency of atleast 90%. The design may not be concrete as it a simulation software compared to the real Inverter and some assumptions were made, however assumptions are a part of our field and without testing out methods and parameters for different processes a breakthrough would not be possible.

6.2. Future working possibilities

Initially when the experiments were conducted there had been problems with determining harmonics from the oscilloscope and its software and from the use of the FFT function in MATLAB, we could see how easily the harmonic frequencies could be determined and from the results we arrived at, this could be a way in which we can move forward. Also the model of the Frequency Inverter can be further improved upon by using different electrical simulation softwares to improve upon the connection and design of the controller pulse generator as well. It is possible that the model and can further be developed and implemented and only actual tests may be able to tell us that.

Citations

[1] Ali Khan, M. Y., Liu, H., Yang, Z., & Yuan, X. (2020). A comprehensive review on grid connected photovoltaic inverters, their modulation techniques, and control strategies. *Energies*, *13*(16), 4185.

[2] Maharjan, L., Yamagishi, T., &Akagi, H. (2010). Active-power control of individual converter cells for a battery energy storage system based on a multilevel cascade PWM converter. *IEEE Transactions on Power Electronics*, *27*(3), 1099-1107.

[3] Dwivedi, S., Jain, S., Gupta, K. K., &Chaturvedi, P. (2018). *Modeling and control of power electronics converter system for power quality improvements*. Academic Press.

[4] Wakileh, G. J. (2019). *Power systems harmonics: fundamentals, analysis and filter design*. Springer Nature.

[5] Esa, M., Nawaz, M. A. M., &Naheed, S. (2017). Harmonic Analysis of three level flying capacitor inverter. *International Research Journal of Engineering and Technology (IRJET)*, *4*(10), 1687-1694.

[6] Zou, H. Y., Wu, H. L., OuYang, L. Q., Zhang, Y., Nie, J. F., Fu, H. Y., & Yu, R. Q. (2009). Fluorescent quantification of terazosin hydrochloride content in human plasma and tablets using second-order calibration based on both parallel factor analysis and alternating penalty trilinear decomposition. *Analyticachimicaacta*, *650*(1), 143-149.

[7] Camacho, E. F., Ramírez, D. R., Limón, D., De La Peña, D. M., & Alamo, T. (2010). Model predictive control techniques for hybrid systems. *Annual reviews in control*, *34*(1), 21-31.

[8] De Dona, J., Goodwin, G. C., Seron, M., & De Dona, J. (2005). *Constrained Control and Estimation: An Optimisation Approach*. Springer.

[9] Quevedo, D. E., Aguilera, R. P., & Geyer, T. (2014). Predictive control in power electronics and drives: Basic concepts, theory, and methods. In *Advanced and Intelligent Control in Power Electronics and Drives* (pp. 181-226). Springer, Cham.

[10] Schulze Darup, M. (2020). Encrypted model predictive control in the cloud. In *Privacy in Dynamical Systems* (pp. 231-265). Springer, Singapore.

[11] Mayne, D. Q., Rawlings, J. B., Rao, C. V., &Scokaert, P. O. (2000). Constrained model predictive control: Stability and optimality. *Automatica*, *36*(6), 789-814.

[12] Qin, S. J., &Badgwell, T. A. (2003). A survey of industrial model predictive control technology. *Control engineering practice*, *11*(7), 733-764.

[13] Cortés, P., Kazmierkowski, M. P., Kennel, R. M., Quevedo, D. E., & Rodríguez, J. (2008). Predictive control in power electronics and drives. *IEEE Transactions on industrial electronics*, *55*(12), 4312-4324.

[14] Bruckner, T., & Holmes, D. G. (2005). Optimal pulse-width modulation for three-level inverters. *IEEE Transactions on Power Electronics*, *20*(1), 82-89.

[15] Adam, G. P., Anaya-Lara, O., Burt, G. M., Telford, D., Williams, B. W., & McDonald, J. R. (2010). Modular multilevel inverter: Pulse width modulation and capacitor balancing technique. *IET power electronics*, *3*(5), 702-715.

[16] Koutroulis, E., Chatzakis, J., Kalaitzakis, K., & Voulgaris, N. C. (2001). A bidirectional, sinusoidal, high-frequency inverter design. *IEE Proceedings-Electric Power Applications*, *148*(4), 315-321.

[17] Venkataramanan, G., Divan, D. M., & Jahns, T. M. (1993). Discrete pulse modulation strategies for high-frequency inverter systems. *IEEE Transactions on Power Electronics*, *8*(3), 279-287.

[18] Braun, W. D., & Perreault, D. J. (2019). A high-frequency inverter for variable-load operation. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *7*(2), 706-721.

[19] Liaw, C. M., Lin, Y. M., Wu, C. H., & Hwu, K. I. (2000). Analysis, design, and implementation of a random frequency PWM inverter. *IEEE Transactions on Power Electronics*, *15*(5), 843-854.

[20] Koudriavtsev, O., Wang, S., Konishi, Y., & Nakaoka, M. (2002). A novel pulse-density-modulated high-frequency inverter for silent-discharge-type ozonizer. *IEEE Transactions on industry applications*, *38*(2), 369-378.

[21] Kifune, H., Hatanaka, Y., & Nakaoka, M. (2004). Cost effective phase shifted pulse modulation soft switching high frequency inverter for induction heating applications. *IEE Proceedings-Electric Power Applications*, *151*(1), 19-25.

[22] Da Silva, S. A. M., & Kallon, D. V. V. (2019). FEA on different disc brake rotors. *Procedia Manufacturing*, *35*, 181-186.

[23] Daeri, A. M., & Ibseam, R. (2017, December). Effects of Harmonics on Motors in Electrical Networks. In 5th Int. Conf. Control Engineering & Information Technology, Sousse, Tunisia.