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**ПОЯСНЮВАЛЬНА ЗАПИСКА**  
**кваліфікаційної роботи ступеню магістра**

(бакалавра, спеціаліста, магістра)

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4. Дослідження статички та динаміки електропривода	Виконання випробувань системи електроприводу. Аналіз результатів випробувань	
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## Реферат

Дана дипломна робота присвячена проектуванню автоматизованого випробувального стенду.

Основною метою є автоматизація проведення випробувальних робіт, з метою економії людських ресурсів та оптимізації часу роботи обладнання. Такі сучасні рішення автоматизації допомагають боротися з глобальним потеплінням та іншими проблемами.

В даній дипломній роботі була описана основна проблема, описані теоретичні обґрунтування, вибрано електрообладнання, описана конструкція випробувального стенду, проведені та проаналізовані випробування.

Пояснювальна записка містить: 54 сторінки, 22 рисунки, 9 таблиць, 17 найменувань використаних джерел.

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## Abstract

This thesis is dedicated to the design of the automated test stand.

The main goal is to automate the test procedures, in order to save human resources and optimize the working hours of the equipment. Such modern automation solutions helps to fight global warming and other problems.

In this thesis the main problem was described, the theoretical groundings were described, electrical equipment was selected, the design of the test stand were described, the tests were conducted and analyzed.

The present thesis consists of: pages 54, figures 22, tables 9, sources 17.

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## 1. Introduction

This thesis is the complex engineer project which deals with both the automated test stand development and the electrical drive system analysis.

It is really hard to overestimate the necessity of automation in industrial and general applications. Previously, the objects of automation were mainly productions processes. It means, it was solving such issues, as growth of the number of the produced products or goods, the sustainable quality of products, price reduction etc. But now, with the help of the new technologies, it becomes easier to automate the complex human processes, such as activity of research and development team. One of the main activities, besides development and research of such teams, is testing. A developer needs to design the system which has to fit in current standards, otherwise the product will be qualified as unsafe or unstable, in such case the potential customer will be lost. But, with growth of amount of different standards, such as automotive, aviation, sea or aero-space standards, the R&D team member needs to spend more and more time on testing and documentation. The time of workers are much more valuable than the time of computer. That`s why, the Refu Drive needs automated solution for testing and documentation processes.

In this thesis, the automation of the test stand, which is motor couple, is completed. Test stand consists of two motors: the induction motor and interior permanent magnets synchronous motor. These motors are in common application in the automotive industry. Automation of such stand reduces the workload of the research and development team optimizes the costs. Additionally, the automated approach to the tests, due to the ability to collect and analyze a lot of data easily, gives an access to the wide range analysis of both steady state and dynamic performances of the drive systems.

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## 2. Subject Area: Characteristics of IM Drive

Usually, every engineering system is designed according to the requirements, electrical drives systems are not an exception. Several tests needs to be conducted, in order to evaluate the compliance to the requirements. Steady state tests and dynamical tests are the two main groups of the tests. In this thesis, steady state tests are focused on obtaining the efficiency data in set of operating points of an electrical drive system. Meanwhile, dynamic tests are focused on obtaining the dynamic parameters, such as overshoot, stability, oscillations, in different operating conditions and system configurations.

Motor couple is the most widespread type of test benches, which are used for testing control systems of the drives. The common choice for such test stands are IM and IPMSM. IMs is used for the high-speed operations, due to the high efficiency in the steady-state high speed operation and bad performance while acceleration due to the high currents. While IPMSMs has no issue with the acceleration due to the additional flux from the permanent magnets, but permanent magnets has a huge disadvantage, magnets needs to be weakened in order to reduce the influence of back EMF, this additional energy lost is significant in the high-speed operation, that's why such types of motors are usually used for acceleration and low speed operation. Thanks to the intermediate DC-DC converters, the voltage on one of the motors could be chosen independently. This means that drive motor could be tested under the condition of low DC voltage, but in the same time load motor could keep the full strength with the rated or even higher voltage level.

### 2.1. Steady State Tests

In this project the controlled system consists of two main devices, an inverter, and an electrical motor. Each of these devices has its own behavior and functions. Main focus of the steady state test in this thesis is the efficiency measurement of the drive system. Main sources of the losses in an electrical drive systems are described in this chapter, in order to understand which parameters affects the efficiency level and how strong is the influence.

There different types of losses inside inverters. From the common hardware inverter structure, two main losses factors could be identified. First, losses in the transistors due to the switching, these are the switching losses. The switching losses occurs in the transition periods between closed and opened state of the transistor. Two transition states are described on the Figure 2.1, from the closed state to the opened state, then from the opened to the closed one. Blue line represents voltage on the terminals, between emitter and collector, of a transistor, red line represents current flowing through the transistor, purple line represents the losses. During the first transient the current starts to rise, in order to open the

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transistor. But transistor cannot be opened instantaneously, that`s why the voltage on the terminals are still present. These rising currents and dropping voltage are creating the losses, which are generating the heat. Same process occurs during closing transient.

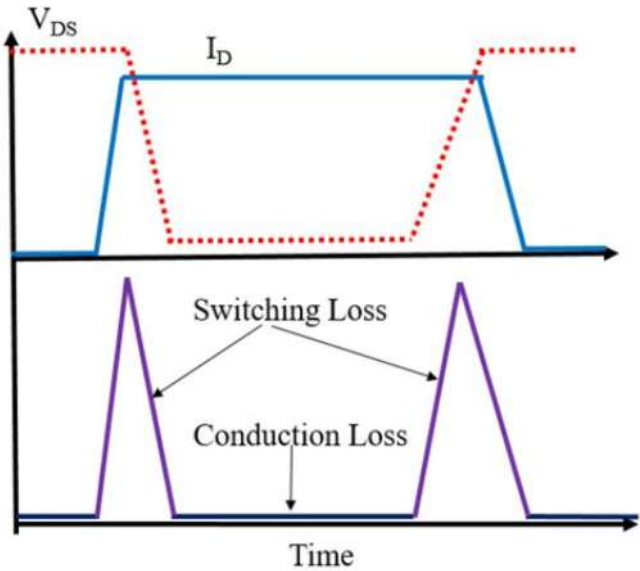


Figure 2.1 Losses in the switch

Second, conduction losses, such as losses in the internal elements of the device wires, inductances, etc. The current in the device is the current required by the electrical circuit, and the voltage on the terminals is the voltage drop caused by the device itself. These losses are directly related to the duty cycle of a transistor. Generally, conduction losses are smaller than switching losses.

Besides the hardware influence on the losses, software has huge influence as well. For example, different PWM methods or the time delay for compensation of processing time.

Considering losses in the electrical motors. In general, an electrical motor losses could be divided by several groups. An induction motor will be considered as the example.

First, *copper losses*. These losses are caused by the current flowing through the windings of the motor, usually expressed by equation  $I^2R$ . They occur both in stator and in rotor windings. Due to the skin effect on the higher frequencies, the resistance of the conductors is increased, which leads to the increase of losses. Environmental temperature changes the resistance of the windings, as well. So, it is always important to cool the motor properly, to minimize losses.

Second, *steel losses* or core losses. These losses are divided to the eddy current losses and the hysteresis losses. Eddy current losses are caused by the current, induced by the alternating magnetic field, flowing in the steel laminations of the



stator and rotor. Current, flowing in the steel results in heat generation. Usually, the stator and rotor cores are made from the set of thin steel laminations, to minimize the eddy current losses. Hysteresis losses are caused by so called hysteresis effect in steel laminations. Such effect leads to the need of additional energy to magnetize and demagnetize the steel in every period of the alternating magnetic field. Usually, stator and rotor steel laminations are made from soft ferromagnetic materials, to reduce the hysteresis effect.

Third, *mechanical and aerodynamical losses*. Mechanical losses are mainly caused by the friction in the bearings, so it is important to lubricate the bearing and keep the proper operational temperature range of the bearing. Aerodynamical losses are caused by the air friction in cooling fan and rotating rotor.

Fourth, the *stray losses*. Stray losses are caused by the design of the motor. For example, winding design, ratio of air gap length to rotor slot openings, air gap flux density. Such parameters are very hard to calculate and measure. In addition, stray losses are relatively small. That`s why in most cases it is neglected.

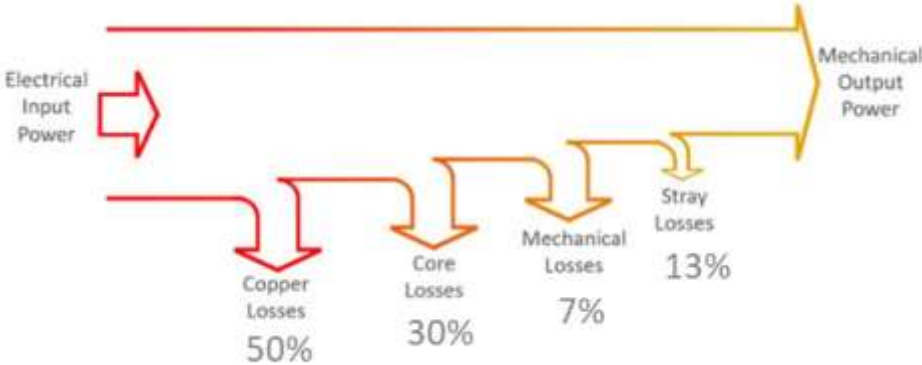


Figure 2.2 Power flow diagram of the IM

Figure 2.2 shows that, usually the largest and most important losses in the Induction Motor are copper losses and core losses.

So, from the description of main losses in the inverter and in the motors, it could be said that some losses are mainly caused by the design of the system, and it is very hard to change them directly. For example, friction in the bearings or the ferromagnetic steel properties. On the other hand, there a lot of losses which are dependent on the control algorithms applied to the system. For example, losses caused by high PWM frequency of the inverter or losses caused by not optimal control methods selection of the motor. Such Losses and the methods to reduce it will be mainly considered in this thesis.

After detailed analysis and reduction of the losses, it is always important to see the overall efficiency of the system in different operation conditions. Efficiency map helps to solve this issue. Efficiency map is 3-dimensional plot, variables, for

example torque and angular speed, are located on so called X axis and Y axis, but Z axis is usually reserved for the efficiency. The Efficiency map could be represented as 2D or 3D plots, the examples are shown on the Figure 2.3.

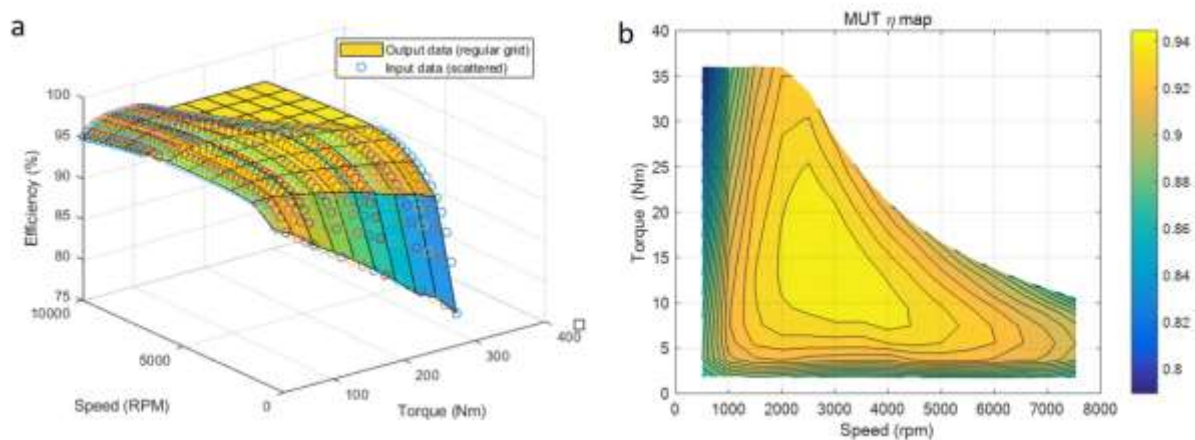


Figure 2.3 a – 3D representation of the efficiency map,  
b – 2D representation of the efficiency map

## 2.2 Dynamic Tests

Dynamical tests are applied to test the controllers design of the system, for example, speed controllers, current controllers, etc. The main focus of these measurements are the transients of the system. Transient process of the system represents the change over time of the coordinates or values of a dynamic system to some established state; it occurs under the influence of external disturbances which change its state, structure or parameters, or due to nonzero initial conditions.

There are several important parameters, which represents the quality of the transient, shown on the Figure 2.4.

- Rise time – the time it takes the system to reach the reference value. Usually, controllers are designed in a way to minimize the rise time, to make a transient faster.
- Overshoot – time-limited ejection of a signal or function over the reference value. Usually, controllers are designed in a way to minimize the overshoot, to make a transient more stable.
- The number of the oscillations – parameter, which represents the stability of the system. Usually, the less oscillations the better the controller is designed.
- Settling time – time it takes for the system to reach the reference and operate within defined borders,  $ref \pm \delta$ .

- Steady state error - the difference between the reference value and the actual value of the system when the transient has reached a steady state. Minimizing the steady state, makes controller stiffer and more accurate.

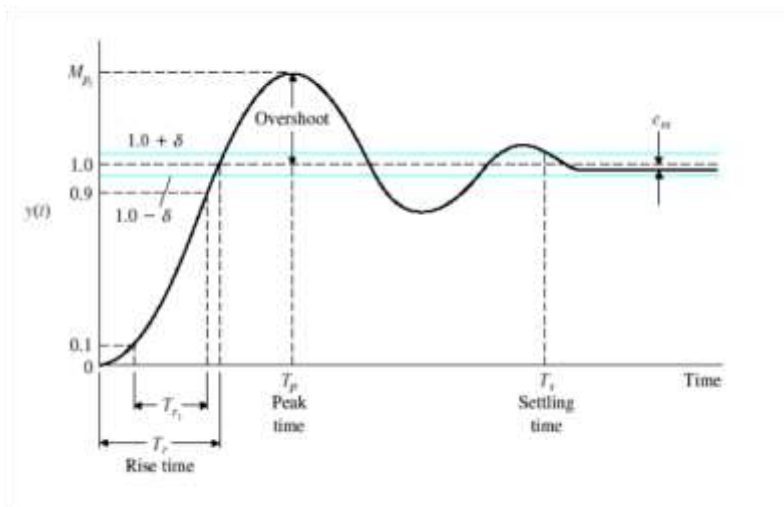


Figure 2.4 Dynamic response diagram

During transients, in the scope of electrical drive theory, it is important to analyze parameters of the system, such as:

- Mechanical speed –  $\omega$ , [rad/s]
- Torque on the shaft –  $T$ , [Nm]

These parameters are observed during load step tests. It means, load motor runs in the torque control mode with the reference torque, meanwhile motor under test is in the speed control mode and makes the speed step.

### 3. Terms of Reference

The main goal of the Refu Drive is to optimize the working flow of R&D department and to reduce the testing costs. So, the requirements were introduced. Two tests should be automated. First, efficiency map test, the steady state measurement of the electrical drive efficiency. Second, the dynamical test, the transient measurement of torque, speed and currents of the motors. So, one test stand was created to satisfy both requirements.

#### Mechanical hardware requirements

- The test stand should consist of two motors, with the similar power ratings.
- Motors should be mounted on the solid basement, to prevent an unwanted vibrations during operation.
- Shafts of the motors should be aligned at least for 3000 [rpm] operation in order to prevent vibration and damage of the equipment.
- Drive system should be designed in the easy-access way in order to provide ease of the maintenance and further modifications.
- Mechanical hardware should be safe for human operation, special protection sheets should be applied in order to protect user from touching the rotating elements.

#### Electrical hardware requirements

- Each of the motors should be supplied from its own inverter.
- Each inverter needs to be supplied with separate and individually adjustable voltage source.
- Motors should be in the 5 kW – 15kW power range.
- The height of the shaft should be in the 100 mm – 250 mm range.
- All electrical devices and components should be grounded in order to prevent the user from the electrical shock.
- All electrical components should be located out of user's reach and well covered in order to prevent the user from the electrical shock.

#### Software requirements

- Software should provide functionality to conduct steady state tests for efficiency measurements.
- Software should provide functionality to conduct dynamic tests for speed, torque and current measurements of the motors.
- Software should provide the functionality to run the tests in automatic way, with the minimum user involving. User is involved only for setting initial conditions, configuration and for obtaining of the output of the tests

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- The output, given from the software, should be in the Excel table form, with automated data post processing

### Concept

From the given requirements, the first concept of the project is introduced. The functional chart, described in the Figure 3.1, is selected as the form of the concept representation.

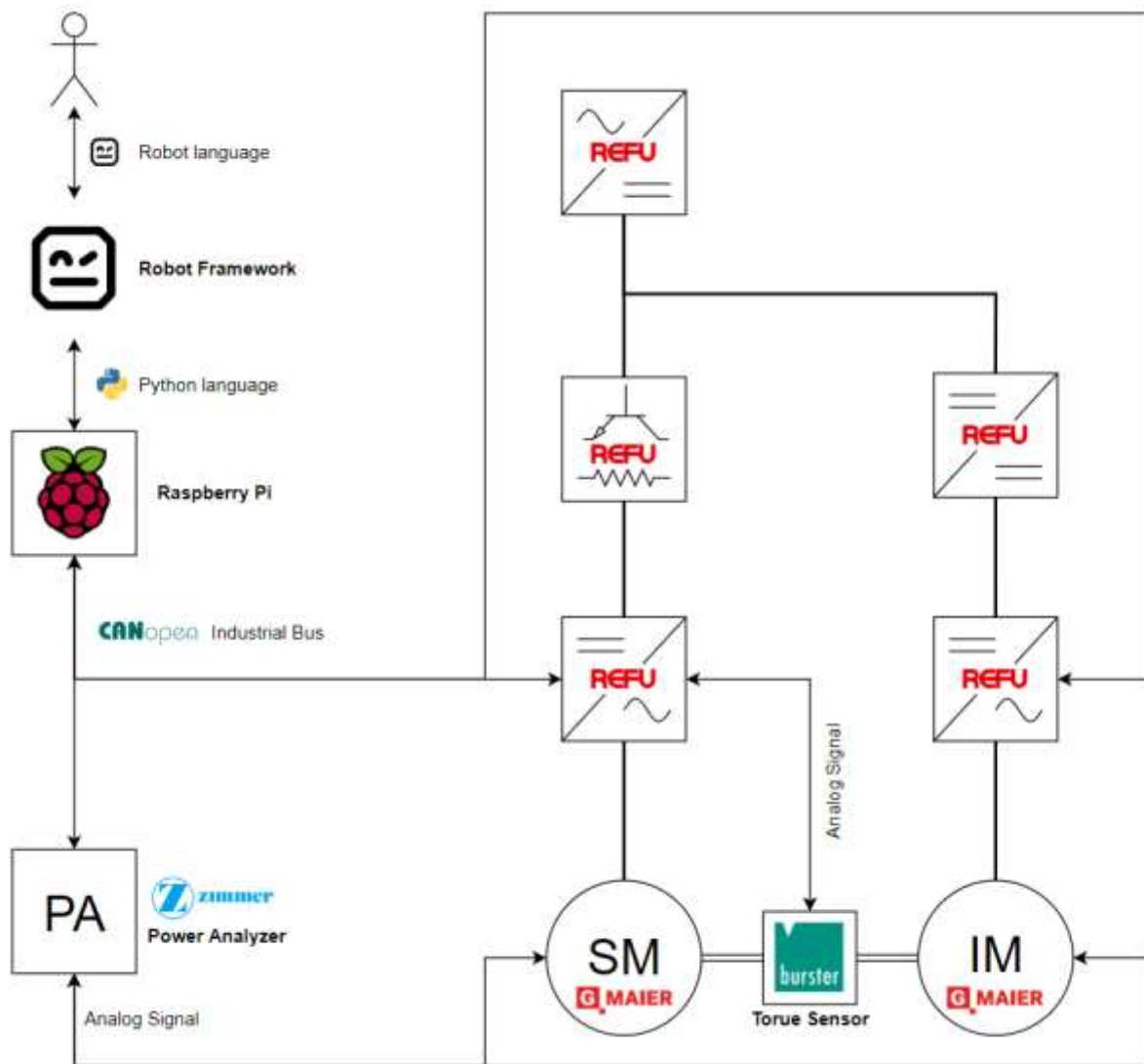


Figure 3.1 Functional diagram of the concept

The functional chart, described in the Figure 3.1, consists of two parts: signal part and power part. The signal part is mainly located on the right side of the chart. It consists of Robot Language, Raspberry Pi and communication channels. The main functionality is described by the following algorithm:

1. The user defines the requirements and conditions of the test case. These can be: estimation of the electric motor efficiency and it`s compliance with certain efficiency standards, assessment of control quality, etc.

2. The user composes the test program. The test program is the sequence of tests, which the user selects from the software interface (Robot Framework)
3. Robot Framework processes the code, written by the user, to the Python code for the Raspberry PI with the help of Python backend libraries.
4. Raspberry Pi communicates with the inverters and measurement equipment. Collects the necessary data, makes post processing and finally gives an output in the appropriate form to the user.

Power part consists of the electrical power supplies, the DC-DC converters and the main control objects – inverters and motors. The Gmaier motors were selected by the Refu Drive, as the drive and load machines for this project. The description of the motors will be given later. Motors are supplied with the inverters. One of the inverters is supplied with the DC-DC converter. Second inverter is fed directly from the adjustable DC power source. DC-DC converter is supplied by the power source. The intermediate DC-DC converters were introduced to have the different voltage levels on each of the motor. This feature provides more flexibility: the tests can be conducted in conditions which are equal to the real operating conditions of the of the industrial applications.

The connection of power and signal part is the communication channel between the Raspberry Pi and inverters.

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## 4. Design of an Automated Test Bench

### 4.1 Electrical Hardware

The principal electric connection diagram was designed according to the concept and requirements, described in the Chapter 3.

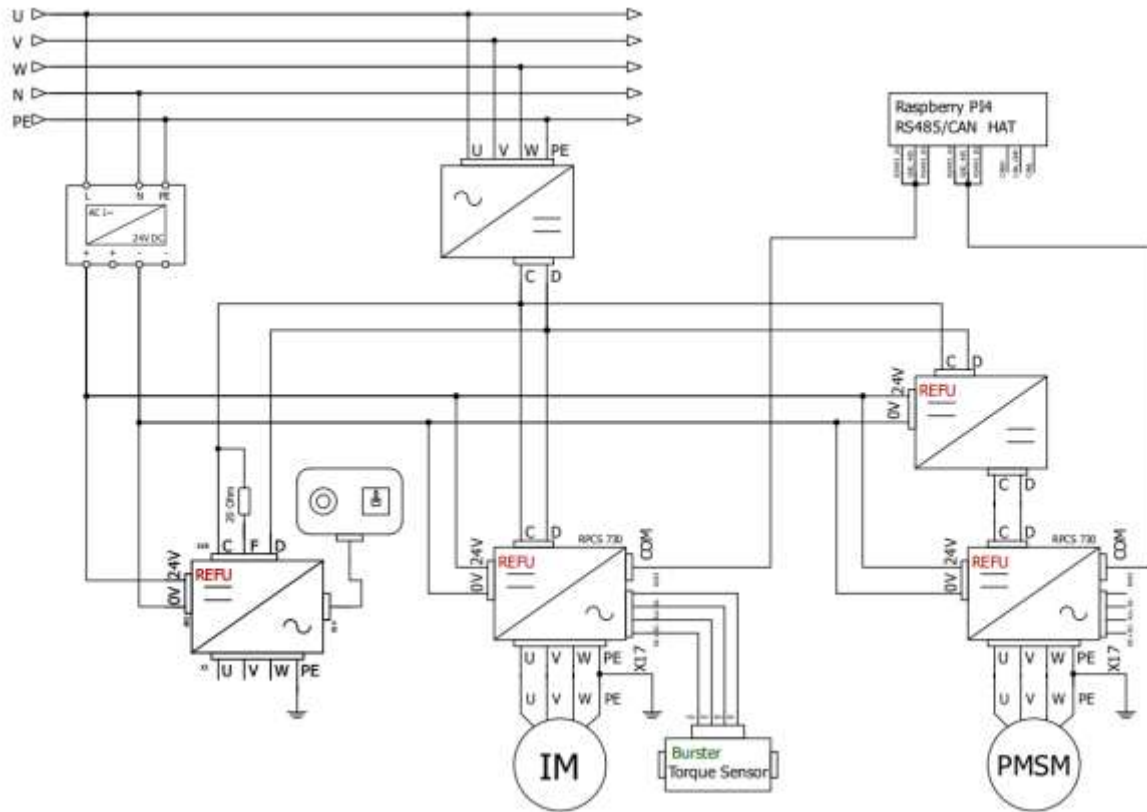


Figure 4.4 The Electric connection diagram

The whole test stand is supplied from three-phase power mains of 380 V. However, inverters of the RPCS 730 family cannot work with the grid voltage directly. Auxiliary equipment is used to transform the voltage into the required range of 400 – 750V.

There are four auxiliary devices within the test stand: 24V DC power supply, DC-DC converter, DC high power supply and breaking chopper unit. First, 24V DC is used to feed the 24V bus. 24V bus is necessary to feed the processors of the SR-board of the inverters independently of the DC high power input. Second, DC-DC converter is applied to vary the voltage level on one of the drive inverters. Third, DC high power supply is used for feeding the high-power DC bus. Inverters of the RPCS 730 family require the DC voltage as the power input. Fourth, the breaking chopper unit is connected directly to the DC bus. It prevents the uncontrollable rise of the DC bus voltage, by connecting the DC bus on the breaking resistor. Breaking chopper units are very important in the drive systems with the permanent magnets motors or generator applications. In case when the

electrical load suddenly disappears, but the generator motor keeps rotating and generating back-EMF the breaking chopper takes all of the generated energy, preventing the overvoltage and damage of the bus or connected devices.

Inverters RPCS 730 are supplied from different voltage levels and connected to different motors.

Technical data of the motors, connected to the inverters, are given in the Specification below.

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## 4.2 Mechanical Hardware

According to the requirements, the following equipment components were selected:

- Aluminum basement, with the thickness of 40 mm.
- Induction motor GMaier type 45478.
- Interior Permanent Magnet Synchronous Motor IE3-IPM132M/62-150.

Motors are mounted on the aluminum plate, specially designed and drilled for the mounting of two motors. Mechanical assembly is shown in the Figure 4.2. The motors and sensor are connected with the two flexible couplings. Flexible coupling provides soft connection between motors and the sensor. When such couplings are used, the requirements to the alignment of the motors could be less strict. Nevertheless, motors and sensors were aligned with the laser alignment tool, to reduce the error of the torque measurement. Motors are aligned according to the IV class standard, which corresponds to the 5000 - 6000 [rpm] operation of the motors. The data of the alignment quality is shown in the Figure 4.1.

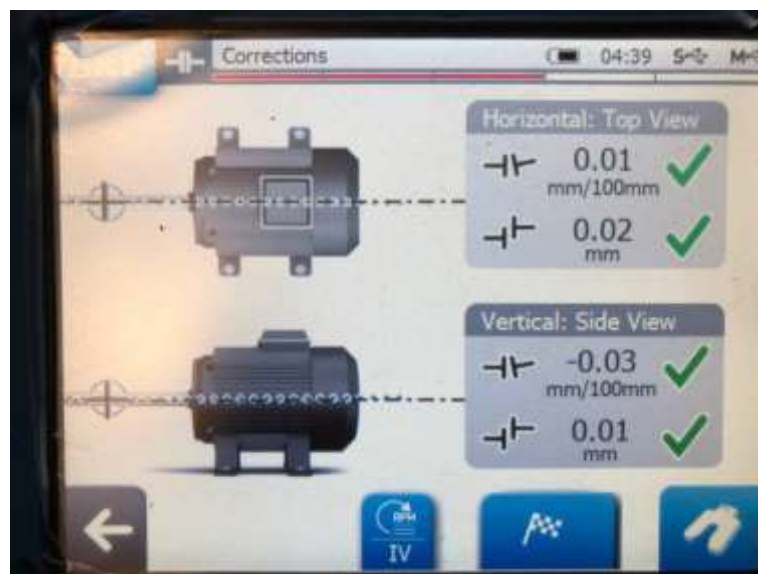


Figure 4.1 Alignment quality

Usually, the torque measurement error occurs due to the extra tension in the shafts or extra friction in the bearings. After alignment, the torque sensor was fixed in order to prevent the vibrations or oscillations of the sensor body due to the shaft rotation.



Figure 4.2 Mechanical assembly

In order to satisfy the safety requirement, the shafts were covered with the red protective sheet of metal, shown in the Figure 4.3



Figure 4.3 Installed red protective cover

*A huge Thank You to Prof. Schullerus, for providing the laser equipment.*

## Specification

The technical data of Induction motor, shown in the Figure 4.5, is given in the Table 4.1



Figure 4.5 Induction motor

Parameter	Unit	Value
Typ / Type		45478
Sin/Cos-Geber / Sin/Cos Sensor		ITD22 A4 Y47 Impulse 2048
Leistung / Power	kW	7,5 - 11,5
Spannung / Voltage		230-350 V DR / 400 Y
Schaltung / Connection		DR. / Y
Strom / Current		22,7 DR / 13,2 Y
Frequenz / Frequency		50 - 77 Hz
Leistungsfaktor / Power Factor		0,91
Bemessungsdrehmoment / Rated Torque		24,5 [Nm]
Drehzahl / Speed		2940 -4540 U/min
Temperaturfühler / Temperature Sensor		PT 1000

Table 4.1. Technical data of the induction motor

The technical data of Interior Permanent Magnet Synchronous Motor, shown in the Figure 4.6, is given in the Table 4.2



Figure 4.6 Interior permanent magnet synchronous motor

Parameter	Unit	Value
Typ / Type -		IE3-IPM132M/62-150
IEC-Baugröße / IEC- frame size -		132
Ident-Code -		A205513T
Max. Umgebungstemperatur Max. Ambient Temperature		°C 40
Schutzart / Degree of Protection -		IP 55
Wärmeklasse / Insulation Class -		F
Bemessungsleistung / Rated Output	kW	7,5/11,2
Betriebsart / Operating Mode -		S9
Bemessungsspannung / Rated Voltage	V	350
Schaltung / Connection		Y
Bemessungsfrequenz / Rated Frequency	Hz	225
Polzahl / Pole Number -		6
Bemessungsdrehzahl / Rated Speed	1/min	4500
Bemessungsstrom / Rated Current	A	13,5/20,2
Leistungsfaktor / Power Factor	cos $\phi$	0,99/0,98
Bemessungsmoment / Rated Torque	Nm	15,9/23,7
Maximalmoment (2 min.) / peak torque (2 min.)	Nm	25,4/37,9
Kühlverfahren / Cooling Method -		IC 416
Wirkungsgradklasse / Efficiency Class -		IE3
Kaltwiderstand Klemme (20°C) / Cold Resistance Terminal (U-V)	Ohm	0,091
Kaltwiderstand Strang (20°C) / Cold Resistance Phase (U1-U2)	Ohm	0,0455
EMK bei 1000 1/min / EMF at 1000 [rpm]	V	74

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Haupt Reaktanz / Main Inductive Reactance / Xh	Ohm	1,02
Streu Reaktanz / Diffusion Inductive Reactance / X1sigma	Ohm	0,34
Haupt Induktivität / Main Inductance / Lh	mH	0,75
Streu Induktivität / Diffusion Inductance / L1sigma	mH	0,24
Induktivität d-Richtung / Inductance d-direction / Ld	mH	1,25
Induktivität q-Richtung / Inductance q-direction / Lq	mH	1,42
Rotor Trägheitsmoment / Rotor inertia / J	kgm <sup>2</sup>	0,0312
- Permanenterregter Synchronmotor / Permanent excited Synchronous motor - Rotor mit innenliegenden Magneten (IPM) / Rotor with interior magnets (IPM) - Betrieb nur mit geeignetem Frequenzumrichter / Operation only with suitable frequency inverter		

Table 4.2 The technical data of the interior permanent magnet synchronous motor

From the analysis of the data in the Table 4.2, it can be said that interior permanent magnet synchronous motor behaves like a surface permanent magnet synchronous motor due to the close equality of Ld and Lq inductances. Such behavior is unusual, but it will be not taken into the consideration or focus of this project.

The technical data of the RPCS 730 28kVA inverter, shown in the figure 4.7, is given in the Table 4.3



Figure 4.7 RPCS 730 28kVA inverter

Parameter	Unit	Value
AC output power @ 570 V DC		28 kVA

Nominal DC voltage	V	750
DC input voltage range	V	400 – 850
max. AC output voltage @ 3 AC	V	500
Rated current @ 4 kHz	A	40
Peak current for 60 s @ 4 kHz	A	48
Peak current for 1 s @ 4 kHz	A	60
Output frequency	Hz	0 – 599 (optional up to 1,200)
Control supply voltage	V DC	24 (± 20 %) optional 12 (± 20 %)
Ambient temperature	°C	- 25 to 85 (beyond 45 with derating)
Coolant temperature	°C	-25 to 55

Table 4.3 The technical data of the RPCS 730 28kVA inverter

The technical data of the Burster 8656 torque sensor, shown in the figure 4.8, is given in the Table 4.4



Figure 4.8 Burster 8656 torque sensor

Parameter	Unit	Value
Type		8656
Accuracy Relative non-linearity	F.S.	0.2 %
Relative hysteresis	F.S.	0.15 %
Tolerance of sensitivity	F.S.	0.25 %
Electrical values Rated supply voltage range	V DC	10 ... 30 (or 5 via USB)
DC power consumption	W	approx. 2
Output voltage at $\pm$ rated torque	V	$\pm 10$
Output resistance	$\Omega$	330
Insulation resistance	M $\Omega$	> 5
Update rate	Hz	400
Ripple	mV <sub>ss</sub>	< 50
Control signal	V DC	10

Table 4.4 The technical data of the Burster 8656 torque sensor

### 4.3. Experimental Data Processing

#### Steady State

In order to plot the efficiency map, acquired signals of the inverter and the power analyzer are used for efficiency calculation.

Signals from the inverter:

- Mechanical speed of the motor shaft –  $n, rpm$
- Torque on the shaft –  $T, Nm$

Signals from the power analyzer:

- Input power of the inverter, DC power –  $P_{DC}, W$
- Output power of the inverter, AC power –  $P_{AC}, W$

From these values three different types of efficiency are calculated.

Motor efficiency –  $\eta_{motor}$ :

$$\eta_{motor} = \frac{T \cdot n \cdot 2\pi}{60 \cdot P_{AC}} \cdot 100\%, [\%] \quad (4.1)$$

Inverter efficiency –  $\eta_{inverter}$ :

$$\eta_{inverter} = \frac{P_{AC}}{P_{DC}} \cdot 100\%, [\%] \quad (4.2)$$

Electric drive system efficiency –  $\eta_{system}$ :

$$\eta_{system} = \frac{\eta_{motor} \cdot \eta_{inverter}}{100}, [\%] \quad (4.3)$$

From measured and calculated data three efficiency maps are plotted. On the x axis the mechanical speed of the motor shaft is plotted, on the y axis the torque on the shaft. On z axis one of three efficiency types are plotted, dependent on the efficiency map type: motor efficiency; inverter efficiency; electric drive system efficiency.



## Dynamic

In order to analyze the quality of the transients of the dynamic test, acquired signals of the inverter are used.

Signals from the inverter:

- Mechanical speed of the motor shaft –  $n, rpm$
- Torque on the shaft –  $T, Nm$

Based on the obtained signals the quality analysis of the transients are completed. Several parameters has to be evaluated, to show the performance of the transient.

Rise time,  $T_{rise}$ .

$$T_{rise} = t_{90\%} - t_0, [s] \quad (4.4)$$

Where,  $t_0$  – initial time,  $t_{90\%}$  – time it takes for the signal to reach the 90 % of the step value.

Overshoot,  $Q$ .

$$Q = \frac{x_{max}}{x_{ref}} \cdot 100\%, [\%] \quad (4.5)$$

Where,  $x_{ref}$  – reference value of the signal or setpoint,  $x_{max}$  – maximum value of the signal, which exceeds the reference value for the short amount of time.

The number of the oscillations,  $N$ . Number of peaks over the tolerance borders of the reference value.

Settling time,  $T_{set}$ .

$$T_{set} = t_{\delta} - t_0, [s] \quad (4.6)$$

Where,  $t_0$  – initial time,  $t_{\delta}$  – time it takes for the signal to enter the tolerance borders. In this project tolerance borders,  $\delta$  are  $\pm 2\%$  from the reference value

Steady state error,  $e_s$ .

$$e_s = \frac{x_{ref} - x_{std}}{x_{ref}} \cdot 100\%, [\%] \quad (4.7)$$

Where,  $x_{ref}$  – reference value of the signal or setpoint,  $x_{std}$  – actual value of the system when the transient has reached a steady state.

## 4.4 Software Implementation

As it is mentioned in the Chapter 3, software is required to provide functionality to conduct steady state tests and dynamic tests in automatic way. In order to achieve that, a single-board microcomputer Raspberry Pi is selected as the communication center of the system. Raspberry Pi communicates with two inverters and power analyzer via serial port. The main logic of the program is written in the Robot language. Robot language, part of the Robot Framework, is the human-friendly programming language, which is based on Python. Robot Framework is a generic opensource automation framework. It can be used for test automation and robotic process automation. Due to this, all complicated functionality, such as communication drivers, can be left to the Python back-end libraries and call when needed through the special keywords. Such approach shifts the main focus of the programmer more to the main functionality of the program, instead auxiliary tools. In addition, use of Python opens a wide access to the different functionality, due to the great amount of the opensource Python libraries.

In this chapter, the design of the tests programs is considered. It means, all information about initial conditions and the output of conducted tests are described and analyzed in the Chapter 5.

Two test programs are developed, first for steady state tests, second for the dynamic tests.

### Steady State Test

First, the steady-state or the efficiency map test. As it is clear from the name, the expected output of the test is the efficiency map. Map is built step by step, with the jumping from one operating point to another, by incrementing torque and speed. After each incrementation step the data from inverter and power analyzer is recorded. The program working principle is described as an algorithm. For the ease of understanding the program algorithm is represented as a pseudo code. The full code is shown and described in the Appendix.

```
Set initial values
Start communication with devices

Set inverters to the initial operating point

Make the measurement of power, speed and torque
Calculate the efficiency of the motor, inverter and system
Record data to the table

WHILE Cycle through the speed range
    Step the speed
```

WHILE Cycle through the torque range

Step the torque

Make the measurement of power, speed and torque

Calculate the efficiency of the motor, inverter and system

Record data to the table

Reset the torque

Reset the speed

Save data as Excel File

Save data as csv file

Visualize data as 3-D efficiency map

## Output

Example Excel file, shown on the Figure 4.9, is provided to the user as an output.

	A	B	C	D	E	F	G	H
1	speed_set	speed_act	torque_act	ac_power	dc_power	eff_motor	eff_inverter	eff_system
2	500000	509.2611	0.962983	86.3582	-175.897	59.40012	49.09589	29.16302
3	550000	549.5289	1.608349	141.845	-234.966	65.17613	60.36831	39.34573
4	550000	551.0709	2.373151	188.904	-281.703	72.41415	67.05786	48.55938
5	550000	551.1643	3.152842	235.672	-329.63	77.12709	71.49592	55.14272
6	550000	550.1442	3.931709	284.494	-381.3	79.52735	74.61159	59.33662
7	550000	551.3277	4.730763	335.265	-431.65	81.37378	77.67057	63.20347
8	550000	551.8443	5.554743	387.057	-485.902	82.83946	79.65742	65.98778
9	550000	551.3817	6.39031	440.536	-540.085	83.66129	81.5679	68.24076
10	550000	549.5114	7.221265	496.339	-599.61	83.62637	82.77697	69.22338
11	550000	550.5883	8.063506	551.443	-659.966	84.21354	83.55627	70.3657
12	550000	547.8043	8.934616	611.786	-718.838	83.62228	85.10763	71.22001

Figure 4.9 Example output to the user

## Dynamic Test

Second, Dynamic test is the test, which collects the data from a system transients. In this project the speed step test, with the different speed levels, is considered. The multiple speed step tests are conducted, due to the change of initial and final conditions for every iteration. The set of initial and final conditions, such as torque and speed, is considered to be an input. The set of signal plots and measured data are considered to be an output of the test.

```
Set initial values
Set the range of initial and final conditions of the tests
Start communication with devices

Set inverters to the initializing operating point

WHILE Cycle through the tests

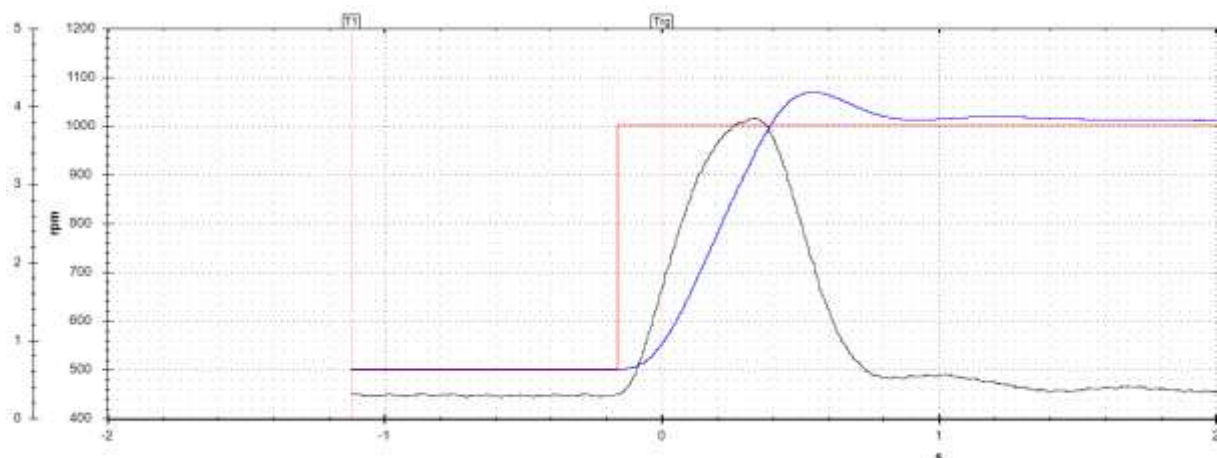
    Set initial conditions of the test
    Switch the trigger of the oscilloscope to the waiting state
    Set the final conditions of the test

    Wait for the completion of the oscilloscope Shot
    Save The oscilloscope shot as .trc
    Save The oscilloscope shot as .csv

Stop operation
Make data analysis
```

Output:

Set of the speed and torque signals plots, shown on the Figure 4.10, is provided to the user as an output.



Where, red line corresponds to the speed reference value [rpm], blue line – actual speed of the motor shaft [rpm], black line – torque on the motor shaft [Nm].

## 5. Test Results

### Steady State Test

Steady state test is conducted. The data obtained from the test is shown in the Appendix Table 1. Conditions of the test are:

- Ambient temperature is 22 C°.
- Speed range is 550 – 750 [rpm]
- Speed step is 50 [rpm]
- Iq current of the load machine range is 1 – 10 A
- Iq current of the load machine step is 1 A
- Motor under test is IM. Inverter of the IM is set in the speed control mode.
- Load motor is IPMSM. Inverter of the IPMSM is set in the manual Id/Iq current configuration mode.

Efficiency map of motor, inverter and drive system, shown in the Figures 5.1 - 5.3, are plotted based on the data from Appendix Table 1.

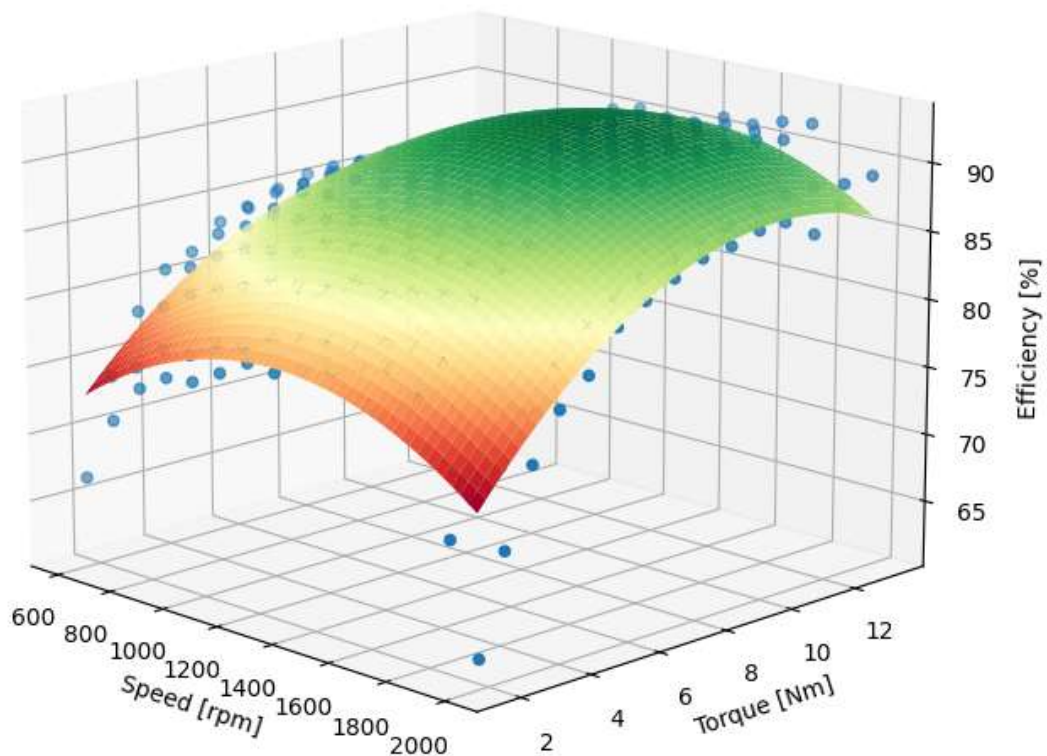


Figure 5.1 Motor efficiency map

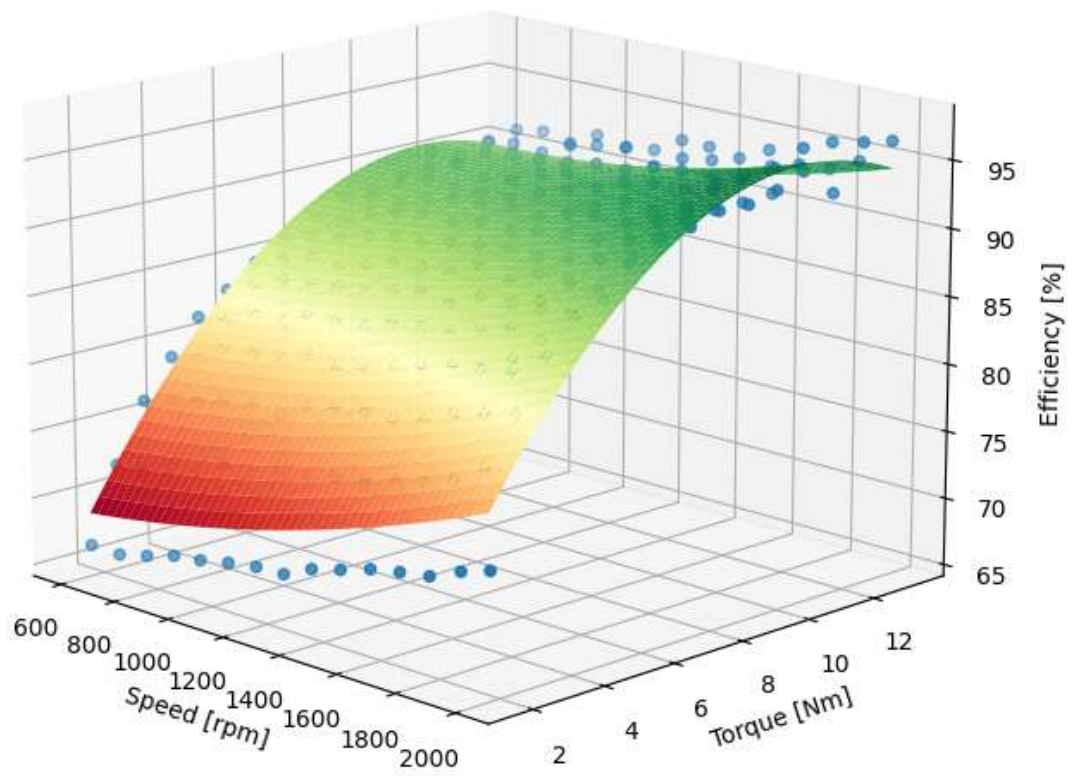


Figure 5.2 Inverter efficiency map

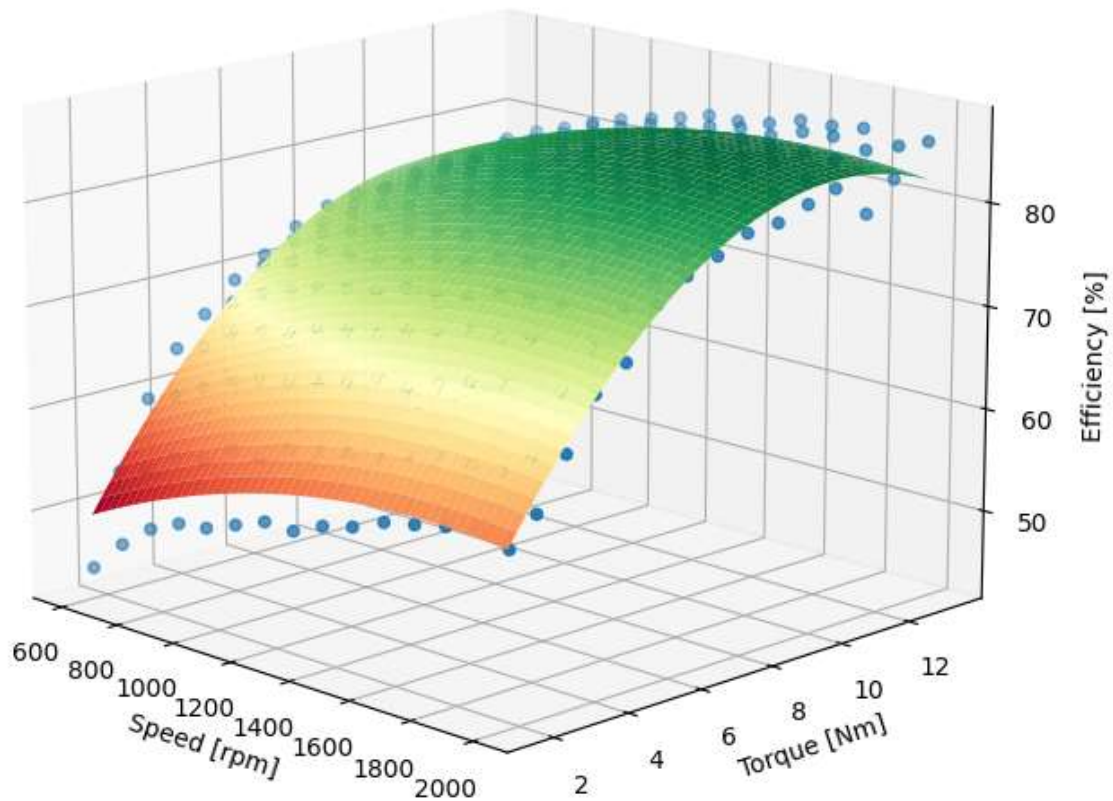


Figure 5.3 Drive system efficiency map

First, the data is build using scatter point plot. Then quadratic approximation is applied to obtain an approximated surface based on the scatter points. Such approach gives describes real data as the surface with relatively small global error, but with the drawback of higher local errors. Figures 5.1 - 5.3, shows nonlinearity in the efficiency of the motor, inverter, and drive system. It is recommended to operate at the high speed-torque ranges, 1800-2000 [rpm] 8-12[Nm], to obtain the maximum efficiency

## Dynamic Test

Dynamic test is conducted. The data obtained from the test is shown in the Figures 5.4 – 5.6. Where, red line corresponds to the speed reference value [rpm], blue line – actual speed of the motor shaft [rpm], black line – torque on the motor shaft [Nm]. Conditions of the test are:

- Ambient temperature is 22 C°.
- Initial speed is 500 [rpm]
- Final speed is 1000 [rpm]
- Torque of the load machine range is 0, 6, 12.5 [Nm]
- Motor under test is IM. Inverter of the IM is set in the speed control mode.
- Load motor is IPMSM. Inverter of the IPMSM is set in the manual Id/Iq current configuration mode.

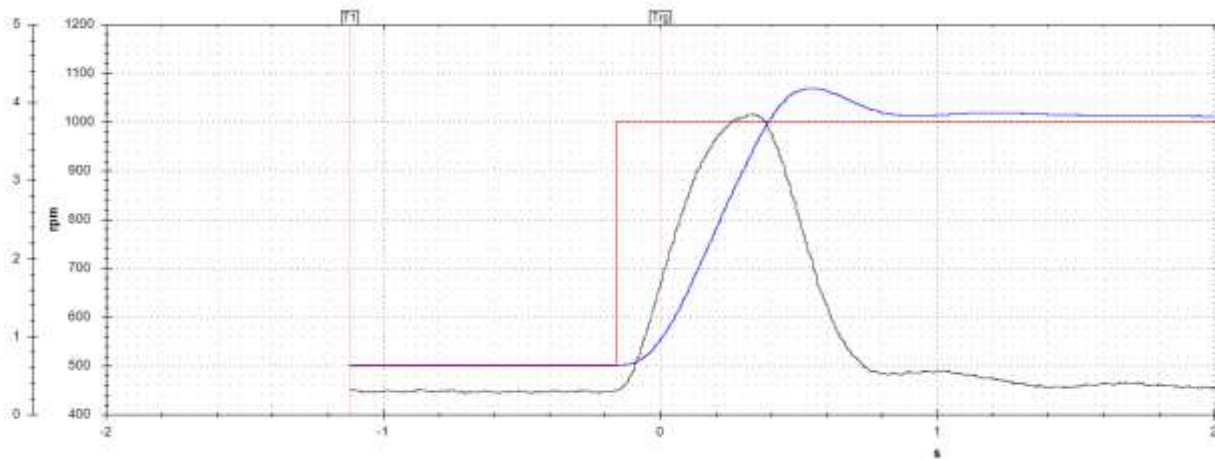


Figure 5.4 No load speed step response

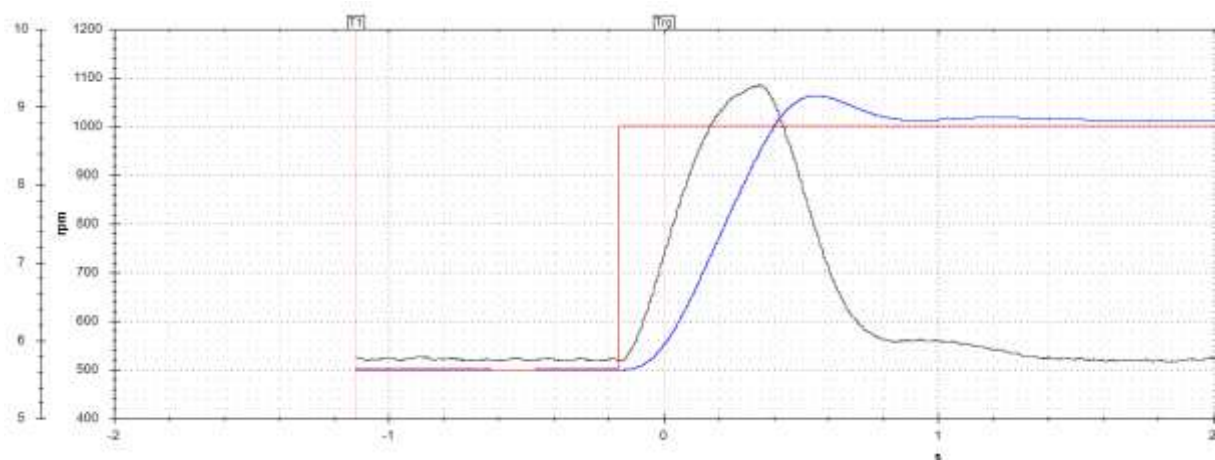


Figure 5.5 Load 6 [Nm] speed step response



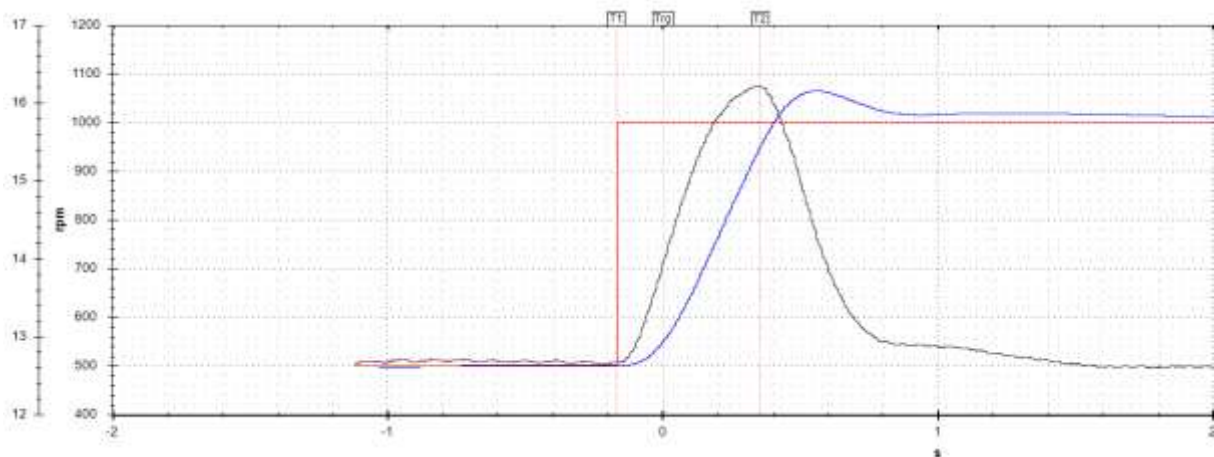


Figure 5.6 Load 12.5 [Nm] speed step response

The speed transients shown on the Figures 5.4-5.6 has the same form. So, based on this information the speed controller is considered to be stable. Because all speed transients, shown on the Figures 5.4-5.6, are the same, the transient quality parameters are described only for Figure 5.6 and considered to be valid for two other figures. Parameters are defined based on the equations 4.4-4.7.

Rise time,  $T_{rise}$ .

$$T_{rise} = 0.525 - 0 = 0.525 [s] \quad (6.1)$$

Overshoot,  $Q$ .

$$Q = \frac{1064}{1000} \cdot 100\% = 6,4 [\%] \quad (6.2)$$

The number of the oscillations,  $N = 1$ .

Settling time,  $T_{set}$ .

$$T_{set} = 0.99 - 0 = 0.99 [s] \quad (6.3)$$

Steady state error,  $e_s$ .

$$e_s = \frac{1000 - 1011}{1000} \cdot 100\% = 1,1 [\%] \quad (6.4)$$

Steady state error is calculated at the time point 2s, with the longer time the steady state error tends to zero.

## 6. Technical and Economical Grounding

### Introduction

This thesis describes the development of automated test stand for electrical drive systems research.

In this thesis, the design of automated test stand is described. Test stand consists of two motors: the induction motor and interior permanent magnets synchronous motor. These motors are in common application in the automotive industry. Automation of such stand reduces the workload of the research and development team, optimizes the costs. Additionally, the automated approach to the tests, due to the ability to collect and analyze a lot of data easily, gives an access to the wide range analysis of both steady state and dynamic performances of the drive systems.

Refu inverter (VFD) – is an electronic device for changing the frequency of an electric current and voltage. The inverters of the RPCS 730 series in the power classes 150K and 320K enable optimized electrical drives even for heavy machinery. Both devices are available as plug versions and as cable gland versions. Thanks to their robustness and high resistance to shock and vibration, they can be used even in harsh conditions. The series also offers flexible and individual configuration for optimal interaction and meets the requirements up to protection class IP6K9K. They allow the operation of all types of motors, with or without an encoder and are suitable for motor speeds up to 20,000 [rpm].

The actuality of the automated test stand implementation is very high. It will help to save human resources, by automating of process, which leads to optimization of the budget for test purposes.

In the previous chapters of the thesis, the subject area was described, the hardware equipment was selected, the design and measurement processes were described.

In the section " Technical and economical grounding " it is necessary to evaluate the capital costs, operating costs and other economical parameters.

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## Calculation of capital costs

Capital investments are funds intended for the creation and acquisition of fixed assets and intangible assets subject to depreciation. Capital investments, for the implementation of the project technical solution, includes the cost of purchase, transportation of equipment and costs associated with installation and commissioning.

When determining the amount of project capital investment  $K_p$ , you can use the formula:

$$K_{\text{пр}} = K_{\text{об}} \left( \sum_{i=1}^{\kappa} \Pi_i \right) + \mathcal{Z}_{\text{ТЗС}} + \mathcal{Z}_{\text{М}} + \mathcal{Z}_{\text{Н}} + \mathcal{Z}_{\text{пр}} \quad (6.1)$$

Where  $K_{\text{об}} (\sum_{i=1}^{\kappa} \Pi_i)$  – cost of purchasing of the electrical devices (software, hardware), in according to the project plan or the sum of needed  $i$ -type elements for the project realization.

$\kappa$  — number of needed elements.

$\mathcal{Z}_{\text{ТЗС}}$  — delivery costs.

$\mathcal{Z}_{\text{М}}$  — montage costs.

$\mathcal{Z}_{\text{Н}}$  — commissioning costs.

$\mathcal{Z}_{\text{пр}}$  — other costs.

The costs for the purchase of technical means and components are summarized in Table 6.1

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Table 6.1 Capital costs

No.	Name	Type	Qnt.	Price in EUR	Price in UAH	Cost in UAH
1	Refu Inverter 2`8K, motor drive unit	SAP 500203	2	4,200 [6]	162,960	325,920
2	Refu Inverter 55K, DC-DC converter unit	SAP 500271	1	7,420 [6]	287,896	287,896
3	Refu Inverter 28K, break chopper unit	RPCS 630 series	1	4,000 [6]	155,200	155,200
4	Burster Torque Sensor, 0.1-100 [Nm]	8656-5100 series	1	1,860 [7]	72,168	72,168
5	Burster additional equipment for sensor	8600-Z023	1	1,415 [7]	54,902	54,902
Total Cost						896,086

The cost of the elements and currency are valid for 19s October 2022

Delivery costs are assumed to be zero, because all equipment were present on the local distribution stores with free of charge delivery. Other electrical equipment, such as cables, electrical connectors, contactors were taken from refurbished waste materials or from the not used test equipment of Refu Drive. Such approach will decrease the carbon footprint of this technical project, which will help to fight against global warming. Also, it helps to decrease the capital costs of the project. Such materials and devices does not require any additional maintenance, so it will not influence the maintenance costs and will be totally neglected in calculations.

Installation costs  $Z_M$  can be defined as follows:

$$Z_M = \sum (\Psi_i \cdot a_i \cdot t_i) \cdot K_d \cdot K_{CM} \cdot K_{PP}, \quad (6.2)$$

Where,  $\Psi_i = 2$  – number of workers with III category, necessary for montage work of the certain volume.

$a_i = 44,64$  – hourly wage for electro montage worker with III category, UAH.

$t_i = 8$  – time, necessary for montage work of certain volume, h

$K_d = 1,1$  – extra-payment coefficient.

$K_{CM} = 1,22$  – coefficient that considers the uniform social contribution.

$K_{PP} = 1,05$  – coefficient that considers other costs of montage works.

Витрати на монтажні роботи становлять:

$$\begin{aligned} Z_M &= \sum (C_i \cdot a_i \cdot t_i) \cdot K_d \cdot K_{CM} \cdot K_{PP} =, \\ &= (2 \cdot 93.75 \cdot 8) \cdot 1,1 \cdot 1,22 \cdot 1,05 = 2\,114 \text{ UAH} \end{aligned} \quad (6.3)$$

Costs for the commissioning works  $Z_H$  are evaluated with such approach:

$$Z_H = \sum (C_i \cdot a_i \cdot t_i) \cdot K_d \cdot K_{CM} \cdot K_{PP}, \quad (6.4)$$

where  $C_i = 2$  – the number of employees of V category required to perform a certain amount of commissioning work.

$a_i = 132.5$  – hourly wage rate of electrician of V category, UAH.

$t_i = 24$  – time required to perform a certain amount of commissioning works, h.

$K_d = 1,1$  – coefficient that considers the amount of surcharges.

$K_{CM} = 1,22$  – coefficient that considers the single social contribution.

$K_{PP} = 1,05$  – coefficient that considers other costs of commissioning works.

The costs of adjustment works are as follows:

$$\begin{aligned} Z_H &= \sum (C_i \cdot a_i \cdot t_i) \cdot K_d \cdot K_{CM} \cdot K_{PP} = \\ &= (2 \cdot 132.5 \cdot 24) \cdot 1,1 \cdot 1,22 \cdot 1,05 = 8\,962 \text{ UAH} \end{aligned} \quad (6.5)$$

Calculation of the capital investments:

$$\begin{aligned} K_{PP} &= K_{Ob} \left( \sum_{i=1}^K C_i \right) + Z_{T3C} + Z_M + Z_H + Z_{PP} = \\ &= 896\,086 + 2\,114 + 8\,962 = 907\,162 \text{ UAH} \end{aligned} \quad (6.6)$$

### Calculation of amortization costs

Amortization of an item of property, plant and equipment is calculated on the basis of its useful life. The useful life (operation) of fixed assets is determined by the company independently based on the expected economic benefits, technical and qualitative characteristics of the fixed asset, moral and physical deterioration, as well as other factors that may affect the possibility of use. The useful life should not be less than the minimum allowable useful life. Table 6.2 shows the minimum allowable useful lives for certain groups of fixed assets.

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Table 6.2 Minimum allowable useful lives by individual groups of property, plant and equipment

Group	Main capital	Time of useful life
3	Buildings	20
	Constructions	15
	Transmission devices	10
4	Machinery and tools	5
	General IT devices Industrial IT devices	2
5	Transport	5
6	Tools, appliances, inventory (furniture)	4

According to Table 6.2 the acquired equipment belongs to group 4, the minimum allowable useful life is 2 years.

The Tax Code of Ukraine allows the use of straight-line (proportional) method of amortization, in which the annual amount of amortization is determined by dividing the depreciable value by the useful life of the fixed asset. The depreciable amount of property, plant and equipment and intangible assets is the cost or revalued amount of property, plant and equipment and intangible assets less their residual value:

$$\Phi_a = \Phi_{\pi} - Л \quad (6.7)$$

Where,  $\Phi_{\pi}$  — initial cost of main capital,  $Л$  — estimated liquidation of main capital.

In case of purchased equipment, we accept the liquidation value as 10% of the original cost.

$$Л = \Phi_{\pi} \cdot 0,1 = 907\,162 \cdot 0,1 = 90\,716 \text{ UAH} \quad (6.8)$$

Then, the cost of main capital, which will be amortized,  $\Phi_a$  is:

$$\Phi_a = \Phi_{\pi} - Л = 907\,162 - 90\,716 = 816\,446 \text{ UAH} \quad (6.9)$$

Amortization is calculated on a straight-line basis using the following formula:

$$AO = \Phi_a / T_{\pi} \quad (6.10)$$

Where,  $T_{\pi}$  — time of useful life (amortization period)

The annual amortization fund is:

$$AO = \frac{\Phi_a}{T_n} = \frac{816\,446}{2} = 408\,223 \text{ UAH} \quad (6.11)$$

### Determination of cost of electricity consumed

The cost of electricity consumed by the design object during the year is determined based on its installed capacity, annual working hours of the design object, losses and electricity tariff according to the formula:

$$C_3 = W_p \cdot \Pi_e \quad (6.12)$$

Where,  $W_p$  is the amount of electricity consumed per year, taking into account its losses, kWh;

$\Pi_e$  is the electricity tariff as of a specific date, UAH/kWh;

The estimated working time for this equipment is 1000 hours per year. The average power consumption is 1 kW. So, the amount of electricity consumed per year is  $W_p = 1000$  kWh. The cost of the electrical energy in the region of city Reutlingen, according to the tariff of the FairNetz electricity provider, is 23 UAH for 1. The elect

ricity price is valid for the date 29.11.2022.

The cost of electricity consumed is:

$$C_3 = 1\,000 \cdot 23 = 23\,000 \text{ UAH} \quad (6.13)$$

### Determination of annual maintenance and repair costs

Annual maintenance and repair costs of electrical equipment include the cost of materials, spare parts, salaries of maintenance personnel to update the software version.

Similar equipment requires maintenance and repair costs of 0.5% of total capital costs, per year:

$$C_T = 907\,162 \cdot 0.5\% = 4\,535 \text{ UAH} \quad (6.14)$$

### Calculation of the operating costs

Operating costs are the current costs of operation and maintenance of the design object for a certain period (year), expressed in monetary terms.

Thus, the annual operating costs are:

$$C = A_0 + C_T \quad (6.15)$$

$$C = 408\,223 + 23\,000 + 4\,535 = 435\,758 \quad (6.16)$$

### Determination of annual savings

Full annual savings from the implementation of the adopted scientific and technical solution is determined taking into account the operating costs of this facility.

The main source of savings is no human operation. Usually, all tests are done manually with at least on qualified worker. The cost of one working hour of qualified worker, in the company Refu Drive, is 3200 UAH for the company Refu Drive. According to the estimated working time of the test, 1000 hours per year, the costs for qualified personal to conduct experiments is 3 200 000 UAH. Previously, it was an expense or costs, but now since the test stand is fully automated no worker presence is required to conduct tests, this can be considered as money savings. So, annual money savings  $E_{кп}$  are 3 200 000 UAH. Based on this information and operating costs, several economic parameters are determined.

Full annual savings  $E_{кп}$  from the implementation of the adopted scientific and technical solution is determined taking into account the operating costs of this facility:

$$E_{кп} = E_{кр} - C \quad (6.17)$$

$$E_{кп} = 3\,200\,000 - 435\,758 = 2\,764\,242 \text{ UAH} \quad (6.18)$$

### Determination and analysis of economical effectiveness parameters

The effectiveness (profitability) coefficient of capital costs  $E_p$  shows how much additional profit (savings) one hryvnia of capital costs brings:

$$E_p = E_{кп}/K_{пр} \quad (6.19)$$

$$E_p = 2\,764\,242/907\,162 = 3.04 \quad (6.20)$$

The payback period of capital costs  $T_r$  shows how many years they will pay off due to the total savings from the implementation of the adopted technical solution:

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$$T_p = K_{пр}/E_{кп} \quad (6.21)$$

$$T_p = 907\,162/2\,764\,242 = 0.32 \text{ years} \quad (6.22)$$

Normative/Expected payback period  $T_H$  or useful working time of equipment is 2 years.

Project is considered to be reasonable, because  $T_p < E_H$ .

Table 6.3 Economical coefficients

№	Name	Unit	Project
1	2	3	4
1	Capital costs	th. UAH	907,162
2	Operating costs	th. UAH	435,728
	including:		
	* amortization charges	th. UAH	408,223
	* technical maintenance	th. UAH	4,535
	* the cost of consumed electricity	th. UAH	23
3	Annual savings	th. UAH	2 764,242
4	Estimated economical effectiveness coefficient	units	3,04
5	Estimated payback period of capital investments	years	0,32

The main economical coefficients are shown in the Table 6.3.

## Conclusions

In this chapter the capital, operating costs were calculated and main economical parameters were analyzed.

For the implementation of this diploma project the project capital investment is 907 162 UAH, annual operating costs – 435 728 UAH. Estimated payback period is 0.32 years, annual savings – 2 764 242 UAH. The project is considered as economically reliable.

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```
Inverter1.Set Q Current Setpoint    ${current_setpoint}
${current_setpoint_check}=    Inverter1.Get Q Current Setpoint
Should Be Equal    ${current_setpoint_check}    ${current_setpoint}
```

The initial values of torque and speed are written to the corresponding parameters of the inverter. Special function is implemented, in order to verify the correspondence between the value sent and the value written in the parameter, lines 3-4.

```
# 2. Set devices to the operation
```

```
Inverter1.Start Operation
Inverter2.Start Operation
```

After speed and torque values were set, in the previous step, the inverters are set from idle to the operation mode.

```
# 3. Make initial measurements
```

```
Sleep    ${init_sleep}
# speed
${speed_act}=    Inverter2.Get Speed Actual
# torque
${torque_act}=    Inverter2.Get Torque Actual
# ac power
${ac_power}=    power_meter.measure activepower ac
# dc power
${dc_power}=    power_meter.measure activepower dc
```

Now the drive is in the operation, it starts to accelerate the motor shaft. But it needs some time to settle in the initial operating point. So, the sleep function is implemented in order to give system some time to settle. After the sleep time ends the measurement of the speed, torque, ac power and dc power is made.

```
# 4. Efficiency calculation
```

```
${eff_motor}=    Inverter2.Calculate Eff
...Motor    ${speed_act}    ${torque_act}    ${ac_power}

    ${eff_inverter}=    Inverter2.Calculate Eff
...Inverter    ${ac_power}    ${dc_power}

    ${eff_system}=    Inverter2.Calculate Eff
...System    ${eff_motor}    ${eff_inverter}
```

Based on equations 4.1-4.3 and the data from measurement, the three types of efficiency are calculated

```
# 5. write data to the table
```

```
${list_values}=    Create List
...    ${speed_setpoint_check}
...    ${speed_act}
...    ${torque_act}
```

```

...   ${ac_power}
...   ${dc_power}
...   ${eff_motor}
...   ${eff_inverter}
...   ${eff_system}

${list_names}=    Create List
...   speed_setpoint
...   speed_act
...   torque_act
...   ac_power
...   dc_power
...   eff_motor
...   eff_inverter
...   eff_system

${table}=    Create Table    ${None}    columns=${list_names}
Add Table Row    ${table}    ${list_values}

```

Table is created from two lists list of values and list of names. List of values is created from the measured and calculated data. List of names is used as the title for each column of the table.

```

# 6. Torque Cycle in Speed Cycle
  WHILE    ${speed_setpoint} < ${max_speed}    limit=100
    # set the speed
    ${speed_setpoint}=    Set Variable    ${${speed_setpoint} +
...${speed_step}}
    Inverter2.Set Speed Setpoint    ${speed_setpoint}
    ${speed_setpoint_check}=    Inverter2.Get Speed Setpoint
    Should Be Equal    ${speed_setpoint_check}    ${speed_setpoint}

    # Torque Cycle
    WHILE    ${current_setpoint} > ${max_current}    limit=15
      # set the torque
      ${current_setpoint}=    Set Variable    ${${current_setpoint} +
...${current_step}}
      Inverter1.Set Q Current Setpoint    ${${current_setpoint}}
      ${current_setpoint_check}=    Inverter1.Get Q Current Setpoint
      Should Be
...Equal    ${current_setpoint_check}    ${current_setpoint}
      Sleep    ${cycle_sleep}

      # read data
      # speed
      ${speed_act}=    Inverter2.Get Speed Actual
      # torque
      ${torque_act}=    Inverter2.Get Torque Actual
      # ac power
      ${ac_power}=    power_meter.measure activepower ac

```

```

# dc power
${dc_power}=    power_meter.measure activepower dc

# Efficiency calculation

${eff_motor}=    Inverter2.Calculate Eff
...Motor    ${speed_act}    ${torque_act}    ${ac_power}
${eff_inverter}=    Inverter2.Calculate Eff
...Inverter    ${ac_power}    ${dc_power}
${eff_system}=    Inverter2.Calculate Eff
...System    ${eff_motor}    ${eff_inverter}

# write data to table
${list_values}=    Create List
...    ${speed_setpoint_check}
...    ${speed_act}
...    ${torque_act}
...    ${ac_power}
...    ${dc_power}
...    ${eff_motor}
...    ${eff_inverter}
...    ${eff_system}

Add Table Row    ${table}    ${list_values}
END

# reset of the torque
${current_setpoint}=    Set Variable    ${0}
Inverter1.Set Q Current Setpoint    ${current_setpoint}
${current_setpoint_check}=    Inverter1.Get Q Current Setpoint
Should Be Equal    ${current_setpoint_check}    ${current_setpoint}

Sleep    ${cycle_sleep}
END

```

On the next step the torque cycle in speed cycle is implemented in order to go step by step from one operating point to another. The measurement and calculation of speed, torque, ac power, dc power, efficiency is made in every iteration of the torque cycle. The measured and calculated data, in every iteration, in the format of the list, is appended to table as a new row. The sleep function after the torque incrementation, is implemented in order to give some time for mechanical transient to settle.

```
# 7. Reset of the speed
```

```

${speed_setpoint}=    Set Variable    ${0}
Inverter2.Set Speed Setpoint    ${speed_setpoint}
${speed_setpoint_check}=    Inverter2.Get Speed Setpoint
Should Be Equal    ${speed_setpoint_check}    ${speed_setpoint}

```



Reset of torque, in the last step, and reset of speed in the current step are made, in order to bring the system back to the initial conditions.

# 8. Stop operation

```
Inverter1.Stop Operation
Inverter2.Stop Operation
Inverter1.Stop Uss
Inverter2.Stop Uss
power_meter.Close
```

Both inverters are set back from operation to the idle mode. Then, the communication with inverters and power analyzer is stopped.

# 9. convert table to the excel

```
Put Table Into Excel    ${table}
Plot Data
```

As the final step, the table with measured and calculated data is converted to the Excel file.

**Table 1**

Speed setpoint, [rpm]	Speed act, [rpm]	Torque act, [Nm]	AC power, W	DC power, W	Eff motor, %	Eff inverter, %	Eff system, %
500	508.73	0.99	90.38	162.48	58.21	55.63	32.38
600	601.26	1.64	154.75	232.78	66.77	66.48	44.39
600	601.95	2.37	202.00	280.49	73.83	72.01	53.17
600	602.11	3.15	254.04	333.06	78.17	76.27	59.63
600	601.40	3.94	306.65	388.03	80.81	79.03	63.86
600	598.40	4.73	362.34	444.51	81.63	81.51	66.54
600	599.12	5.55	417.09	502.35	83.39	83.03	69.24
600	598.56	6.38	476.07	562.59	83.93	84.62	71.02
600	600.19	7.24	535.14	621.22	84.90	86.14	73.13
600	601.85	8.11	596.75	685.23	85.53	87.09	74.49
600	600.60	8.95	659.62	749.34	85.22	88.03	75.02
600	598.78	9.82	722.66	819.49	85.08	88.18	75.03
600	599.45	10.70	786.86	888.32	85.30	88.58	75.56
600	599.21	11.57	859.02	954.86	84.41	89.96	75.94
600	601.71	12.46	919.84	1030.66	85.28	89.25	76.11
600	600.67	13.35	989.17	1101.52	84.83	89.80	76.17
700	701.71	1.68	172.29	259.58	71.56	66.37	47.50
700	701.44	2.35	230.01	318.25	75.07	72.27	54.26
700	701.48	3.14	291.15	378.95	79.02	76.83	60.71
700	700.19	3.92	352.70	443.39	81.47	79.55	64.81

Speed setpoint, [rpm]	Speed act, [rpm]	Torque act, [Nm]	AC power, W	DC power, W	Eff motor, %	Eff inverter, %	Eff system, %
700	701.58	4.72	415.21	506.34	83.49	82.00	68.46
700	700.53	5.57	479.93	571.81	85.02	83.93	71.36
700	700.23	6.40	547.73	640.80	85.61	85.48	73.18
700	698.34	7.24	617.27	713.19	85.73	86.55	74.20
700	699.24	8.11	684.86	786.74	86.57	87.05	75.36
700	697.94	8.96	758.68	856.97	86.18	88.53	76.30
700	699.84	9.84	830.86	933.41	86.69	89.01	77.16
700	700.69	10.70	905.34	1009.78	86.66	89.66	77.70
700	699.76	11.58	979.79	1094.67	86.54	89.51	77.45
700	702.39	12.47	1059.51	1167.26	86.49	90.77	78.51
700	702.51	13.35	1138.80	1249.01	86.15	91.18	78.55
800	801.64	1.70	191.80	286.78	74.49	66.88	49.82
800	801.38	2.38	259.55	355.61	76.95	72.99	56.16
800	801.81	3.16	329.28	425.96	80.52	77.30	62.24
800	799.68	3.95	399.18	494.69	82.77	80.69	66.79
800	802.30	4.75	472.07	569.44	84.52	82.90	70.07
800	800.71	5.57	546.98	644.19	85.34	84.91	72.46
800	802.14	6.41	620.02	720.33	86.72	86.08	74.65
800	799.78	7.25	696.19	800.60	87.12	86.96	75.76
800	799.97	8.12	776.85	879.21	87.44	88.36	77.26
800	799.57	8.96	856.43	966.52	87.54	88.61	77.57
800	799.45	9.83	942.29	1049.51	87.25	89.78	78.34
800	797.77	10.70	1029.24	1136.26	86.74	90.58	78.57
800	800.73	11.58	1110.20	1221.86	87.38	90.86	79.40
800	797.81	12.46	1197.46	1315.18	86.85	91.05	79.08
800	800.14	13.35	1285.33	1404.65	86.95	91.51	79.56
900	899.79	1.72	213.12	315.74	75.80	67.50	51.16
900	901.91	2.37	290.20	394.25	77.05	73.61	56.72
900	901.26	3.18	368.28	471.49	81.37	78.11	63.56
900	902.66	3.96	445.40	550.27	83.85	80.94	67.87
900	901.67	4.77	524.12	632.96	85.84	82.80	71.08
900	902.02	5.60	607.34	712.35	87.03	85.26	74.20
900	901.51	6.42	689.85	802.57	87.74	85.96	75.42
900	902.52	7.27	777.67	887.69	88.23	87.61	77.29
900	899.33	8.12	869.44	978.55	87.91	88.85	78.10
900	900.53	8.98	956.32	1068.71	88.41	89.48	79.12
900	898.76	9.84	1047.62	1168.05	88.29	89.69	79.19
900	899.77	10.70	1138.53	1266.42	88.45	89.90	79.52
900	897.74	11.56	1238.62	1357.42	87.65	91.25	79.98
900	900.39	12.46	1326.67	1460.32	88.43	90.85	80.33
900	900.90	13.33	1423.30	1562.67	88.29	91.08	80.41
1000	1000.92	1.69	232.60	342.90	76.08	67.83	51.60
1000	1001.72	2.37	316.07	425.20	78.47	74.33	58.33
1000	1002.10	3.15	401.99	511.97	82.13	78.52	64.49
1000	1001.03	3.94	489.84	603.03	84.17	81.23	68.37

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Speed setpoint, [rpm]	Speed act, [rpm]	Torque act, [Nm]	AC power, W	DC power, W	Eff motor, %	Eff inverter, %	Eff system, %
1000	999.59	4.74	577.05	689.07	85.96	83.74	71.99
1000	1002.28	5.57	668.20	781.57	87.34	85.49	74.67
1000	999.13	6.40	759.83	877.99	87.97	86.54	76.13
1000	1000.44	7.23	857.04	972.60	88.31	88.12	77.82
1000	998.84	8.10	958.20	1072.77	88.30	89.32	78.87
1000	1000.02	8.94	1052.50	1171.76	88.90	89.82	79.85
1000	998.01	9.81	1152.75	1283.62	88.87	89.80	79.81
1000	999.72	10.68	1252.28	1387.71	89.16	90.24	80.46
1000	998.09	11.54	1362.54	1492.57	88.46	91.29	80.75
1000	1003.37	12.45	1463.85	1593.06	89.25	91.89	82.01
1000	998.58	13.33	1570.88	1704.86	88.64	92.14	81.67
1100	1102.71	1.69	251.73	368.69	77.28	68.28	52.77
1100	1098.93	2.37	346.62	466.43	78.59	74.31	58.40
1100	1101.09	3.16	438.68	561.59	83.06	78.11	64.89
1100	1100.44	3.94	535.63	653.15	84.67	82.01	69.44
1100	1099.38	4.74	630.39	750.92	86.49	83.95	72.61
1100	1099.52	5.55	732.44	855.11	87.12	85.65	74.62
1100	1099.72	6.40	836.50	958.56	88.04	87.27	76.83
1100	1098.07	7.24	943.20	1071.34	88.15	88.04	77.61
1100	1099.88	8.10	1047.95	1176.00	88.92	89.11	79.24
1100	1100.26	8.94	1156.16	1285.01	89.01	89.97	80.08
1100	1099.86	9.81	1262.85	1405.74	89.37	89.84	80.28
1100	1102.97	10.69	1380.08	1512.07	89.35	91.27	81.55
1100	1100.46	11.53	1489.50	1626.37	89.14	91.58	81.64
1100	1100.69	12.44	1607.13	1740.47	89.10	92.34	82.28
1100	1103.07	13.33	1711.28	1865.69	89.86	91.72	82.42
1200	1202.16	1.70	272.42	397.04	78.54	68.61	53.89
1200	1199.97	2.38	373.06	497.31	79.97	75.02	59.99
1200	1199.45	3.16	476.68	601.04	83.06	79.31	65.87
1200	1199.02	3.95	578.10	706.91	85.62	81.78	70.02
1200	1199.98	4.74	684.68	813.50	86.91	84.16	73.15
1200	1199.61	5.56	797.69	925.32	87.53	86.21	75.46
1200	1200.06	6.40	908.44	1039.53	88.48	87.39	77.32
1200	1199.77	7.23	1021.06	1151.45	88.88	88.68	78.82
1200	1203.34	8.08	1141.09	1272.56	89.14	89.67	79.93
1200	1201.21	8.95	1252.91	1389.76	89.74	90.15	80.90
1200	1203.07	9.81	1371.38	1509.90	89.98	90.83	81.73
1200	1201.16	10.67	1498.20	1633.38	89.49	91.72	82.09
1200	1201.01	11.55	1616.12	1758.05	89.76	91.93	82.52
1200	1201.38	12.44	1742.36	1880.56	89.73	92.65	83.14
1200	1203.39	13.31	1854.33	2016.02	90.37	91.98	83.12
1300	1302.41	1.68	291.29	423.83	78.39	68.73	53.87
1300	1303.03	2.37	400.76	531.54	80.44	75.40	60.65
1300	1299.51	3.15	512.70	643.07	83.46	79.73	66.54
1300	1298.96	3.94	623.31	759.77	85.98	82.04	70.54

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Speed setpoint, [rpm]	Speed act, [rpm]	Torque act, [Nm]	AC power, W	DC power, W	Eff motor, %	Eff inverter, %	Eff system, %
1300	1299.81	4.76	740.10	873.41	87.46	84.74	74.11
1300	1300.03	5.58	860.20	993.10	88.15	86.62	76.36
1300	1300.41	6.39	978.01	1116.21	88.93	87.62	77.92
1300	1302.78	7.24	1101.63	1239.32	89.55	88.89	79.60
1300	1303.90	8.09	1225.58	1369.58	90.00	89.49	80.54
1300	1301.39	8.94	1352.69	1501.75	89.97	90.07	81.04
1300	1302.36	9.82	1486.53	1625.81	89.95	91.43	82.25
1300	1303.18	10.69	1606.26	1763.32	90.73	91.09	82.65
1300	1304.03	11.55	1738.04	1889.59	90.66	91.98	83.39
1300	1303.16	12.43	1866.21	2034.18	90.81	91.74	83.31
1300	1299.69	13.31	2008.52	2155.75	90.12	93.17	83.96
1400	1399.90	1.69	311.98	447.48	79.09	69.72	55.14
1400	1399.91	2.37	429.15	565.50	80.83	75.89	61.34
1400	1404.56	3.16	548.28	685.26	84.59	80.01	67.68
1400	1399.71	3.96	671.47	809.74	86.27	82.92	71.54
1400	1397.89	4.76	799.55	939.22	86.96	85.13	74.03
1400	1398.86	5.58	920.18	1066.52	88.80	86.28	76.62
1400	1398.22	6.40	1057.14	1194.55	88.57	88.50	78.39
1400	1398.28	7.25	1188.13	1331.69	89.19	89.22	79.58
1400	1403.41	8.08	1316.33	1463.16	90.13	89.96	81.08
1400	1403.68	8.95	1451.47	1600.47	90.49	90.69	82.07
1400	1399.02	9.80	1585.73	1747.88	90.48	90.72	82.08
1400	1400.83	10.68	1728.52	1878.94	90.52	91.99	83.27
1400	1399.88	11.54	1871.82	2021.11	90.27	92.61	83.60
1400	1401.11	12.42	2006.70	2162.65	90.71	92.79	84.17
1400	1397.68	13.29	2154.06	2312.74	90.22	93.14	84.03
1500	1500.24	1.69	332.64	473.17	79.53	70.30	55.91
1500	1502.30	2.38	461.66	605.94	80.94	76.19	61.67
1500	1498.46	3.16	588.78	735.48	84.14	80.05	67.36
1500	1500.39	3.95	718.54	861.06	86.35	83.45	72.05
1500	1499.26	4.75	849.88	995.39	87.62	85.38	74.81
1500	1503.05	5.59	988.23	1132.46	88.94	87.26	77.62
1500	1503.24	6.40	1122.25	1275.80	89.67	87.96	78.88
1500	1499.67	7.24	1262.81	1417.97	89.96	89.06	80.12
1500	1500.26	8.10	1407.09	1559.16	90.33	90.25	81.52
1500	1500.85	8.96	1552.86	1706.15	90.62	91.02	82.48
1500	1500.12	9.81	1696.88	1851.61	90.73	91.64	83.15
1500	1498.99	10.68	1851.76	2004.82	90.39	92.37	83.49
1500	1497.60	11.54	2001.32	2155.43	90.32	92.85	83.86
1500	1500.18	12.44	2145.76	2304.52	90.94	93.11	84.67
1500	1499.59	13.30	2291.51	2470.10	91.04	92.77	84.46
1600	1601.05	1.71	354.89	499.95	80.54	70.98	57.17
1600	1602.79	2.39	490.04	637.12	81.69	76.92	62.83
1600	1603.00	3.17	625.57	774.82	84.84	80.74	68.50
1600	1603.27	3.97	767.76	914.12	86.77	83.99	72.88

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Арк.

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Speed setpoint, [rpm]	Speed act, [rpm]	Torque act, [Nm]	AC power, W	DC power, W	Eff motor, %	Eff inverter, %	Eff system, %
1600	1603.25	4.77	907.45	1055.90	88.15	85.94	75.76
1600	1603.72	5.60	1050.40	1202.39	89.37	87.36	78.08
1600	1599.64	6.42	1199.35	1348.61	89.52	88.93	79.61
1600	1602.11	7.26	1350.56	1508.31	90.08	89.54	80.66
1600	1603.80	8.11	1497.41	1656.88	90.91	90.38	82.16
1600	1603.87	8.97	1650.24	1812.82	91.15	91.03	82.97
1600	1598.38	9.81	1806.73	1978.04	90.82	91.34	82.95
1600	1600.75	10.70	1962.99	2123.60	91.23	92.44	84.33
1600	1601.18	11.57	2121.85	2283.27	91.30	92.93	84.84
1600	1600.62	12.42	2274.47	2458.78	91.43	92.50	84.57
1600	1599.35	13.31	2447.72	2608.43	90.96	93.84	85.35
1700	1700.08	1.72	377.45	528.69	80.92	71.39	57.77
1700	1700.39	2.39	518.70	670.54	82.02	77.35	63.44
1700	1700.43	3.19	665.16	815.24	85.25	81.59	69.56
1700	1699.44	3.97	814.41	967.29	86.69	84.20	72.99
1700	1702.98	4.77	969.75	1118.57	87.68	86.70	76.01
1700	1703.03	5.61	1121.62	1274.22	89.06	88.02	78.39
1700	1700.19	6.42	1273.80	1429.57	89.66	89.10	79.89
1700	1704.05	7.25	1428.76	1586.98	90.46	90.03	81.45
1700	1704.70	8.13	1593.00	1753.58	90.99	90.84	82.66
1700	1704.24	8.96	1758.53	1915.93	90.79	91.78	83.33
1700	1704.96	9.82	1915.16	2077.00	91.47	92.21	84.34
1700	1697.59	10.70	2090.77	2250.40	90.90	92.91	84.45
1700	1697.81	11.55	2255.48	2421.47	90.93	93.15	84.70
1700	1700.10	12.44	2421.58	2587.12	91.38	93.60	85.53
1700	1699.21	13.32	2583.74	2770.70	91.62	93.25	85.43
1800	1800.92	1.72	397.16	553.61	79.47	71.74	58.45
1800	1798.62	2.39	553.48	709.05	81.39	78.06	63.54
1800	1804.10	3.20	707.54	860.46	85.31	82.23	70.15
1800	1804.07	3.96	860.04	1017.14	86.95	84.55	73.52
1800	1802.47	4.77	1020.94	1183.05	88.12	86.30	76.05
1800	1803.74	5.60	1177.18	1343.61	89.79	87.61	78.66
1800	1802.71	6.42	1345.39	1513.42	90.02	88.90	80.03
1800	1805.08	7.27	1510.70	1675.42	90.81	90.17	81.88
1800	1798.22	8.13	1688.69	1847.60	90.55	91.40	82.76
1800	1798.00	8.96	1860.26	2019.68	90.55	92.11	83.40
1800	1800.67	9.83	2027.95	2194.13	91.29	92.43	84.37
1800	1798.72	10.69	2197.95	2377.72	91.48	92.44	84.57
1800	1803.74	11.53	2372.34	2561.00	91.72	92.63	84.96
1800	1798.06	12.44	2564.95	2729.31	91.21	93.98	85.72
1800	1800.13	13.32	2727.70	2920.75	91.92	93.39	85.84
1900	1903.99	1.73	424.23	583.34	70.06	72.72	58.95
1900	1898.58	2.40	615.49	581.82	72.39	79.53	63.54
1900	1898.72	3.19	855.60	741.04	74.12	86.61	64.20
1900	1898.84	3.98	1019.40	912.83	77.63	89.55	69.51

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Арк.

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Змн. Арк. № докум. Підпис Дата

Speed setpoint, [rpm]	Speed act, [rpm]	Torque act, [Nm]	AC power, W	DC power, W	Eff motor, %	Eff inverter, %	Eff system, %
1900	1899.48	4.78	1185.31	1075.73	80.17	90.76	72.76
1900	1900.31	5.62	1354.78	1245.77	82.47	91.95	75.83
1900	1904.98	6.43	1527.56	1417.37	83.91	92.79	77.85
1900	1899.63	7.27	1704.79	1593.07	84.78	93.45	79.22
1900	1900.24	8.14	1890.34	1774.52	85.55	93.87	80.31
1900	1898.10	8.96	2058.92	1960.39	86.40	95.21	82.27
1900	1898.32	9.82	2246.04	2143.04	86.85	95.41	82.86
1900	1900.72	10.71	2427.54	2316.20	87.68	95.41	83.65
1900	1902.34	11.54	2606.62	2512.80	88.11	96.40	84.93
1900	1902.43	12.43	2799.93	2697.20	88.31	96.33	85.07
1900	1899.50	13.31	3060.71	2890.19	86.38	94.43	81.57
2000	2000.89	1.73	1160.09	445.42	62.27	73.40	58.00
2000	2004.45	2.42	730.12	611.19	69.38	83.71	60.59
2000	2004.55	3.20	895.56	781.60	74.86	87.27	65.33
2000	2003.14	3.98	1067.88	957.23	78.16	89.64	70.06
2000	2004.88	4.79	1254.36	1132.32	80.03	90.27	72.25
2000	2004.18	5.62	1420.29	1316.82	82.89	92.71	76.85
2000	2003.75	6.44	1602.26	1499.08	84.21	93.56	78.79
2000	2005.59	7.27	1787.06	1675.34	85.29	93.75	79.95
2000	2003.83	8.12	1974.53	1863.82	86.18	94.39	81.35
2000	2004.90	8.97	2173.38	2049.98	86.54	94.32	81.62
2000	2004.53	9.82	2363.45	2241.66	87.15	94.85	82.66
2000	1997.94	10.67	2557.36	2446.90	87.20	95.68	83.43
2000	2000.28	11.55	2815.52	2635.58	85.82	93.61	80.33
2000	2004.41	12.43	2929.32	2835.61	88.97	96.80	86.12
2000	2006.09	13.30	3132.69	3020.20	89.08	96.41	85.88

Відгук економічна частина

Економічна частина виконана у повному обсязі та згідно з завданням.

Заслуговує на оцінку \_\_\_\_\_ балів.

\_\_\_\_\_ Тимошенко Л.В.

					<i>ЕП.ПД.22.24.11.ПЗ.</i>	Арк.
<i>Змн.</i>	<i>Арк.</i>	<i>№ докум.</i>	<i>Підпис</i>	<i>Дата</i>		<b>55</b>