LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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LOW-VOLTAGE ASYNCHRONOUS-MOTOR FREQUENCY CONVERTERS' TECHNICAL FUNCTIONS

Thesis for the degree of the Master of Science (Technology)
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Examiners: Professor Juha Pyrhönen
Junior Researcher Hannu S. Kärkkäinen

ABSTRACT

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Keywords: Electric Drives, Frequency Converters, Asynchronous Motors, Synchronous Motors, Scalar Control, Vector Control, Direct Torque Control.

The electric drive is part and parcel of the industry. It is used to control the speed of an electric motor, to adjust the energy consumption to match just the demand. The frequency converter is a modern tool to improve the energy efficiency of different industrial equipment, ventilation systems, pump stations, vessels, transportation etc.

Nowadays, drives manufacturers offer a wide range of various technical features. On one hand, it becomes simpler to match functional requirements, but on the other hand an engineer has to know how to choose suitable technical functions for a certain application.

This work contains an overview of all diagnostic and technical features of frequency converters of various manufacturers available on Russian market and a statistical analysis of these functions for a better understanding the diversity between different brands. Besides, the experimental analysis was made to show an example of several programmable features one of the converters.

The paper has the practical value for engineers designing, installing, operating or maintaining electrical drives.

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LIST OF SYMBOLS AND ABBREVIATIONS

Roman letters

f	Frequency	[Hz]
I or i	Current	[A]
L	Inductance	[H]
n	Speed	[rpm]
P	Power	[kW]
R	Resistance	[Ohm]
s	Slip	
T	Torque	[Nm]
U or u	Voltage	[V]

Greek letters

ψ	Flux linkage	[Wb]
η	Efficiency	[%]
φ	Angle between voltage and current	
ω	Angular speed	[s^{-1}]

Subscripts

α	Direct component of the reference frame fixed to the stator
β	Quadrature component of the reference frame to the stator
d	Direct component of the rotor-flux-oriented reference frame
q	Quadrature component of the rotor-flux-oriented reference frame
s	Stator coordinates
r	Rotor coordinates
m	Magnetizing component of the inductance
σ	Leakage component of the inductance

Abbreviations

FC	Frequency Converter
IM	Induction Motor
PMSM	Permanent Magnet Synchronous Motor

1. INTRODUCTION.

The purpose of installing frequency converters as a component of an electric drive system is always to improve process controllability, save energy and make the technological process more effective. All of these are strongly related to the payback period. Therefore, manufacturers started to adopt frequency converters (FC) for specialized applications and to set the technical functionality accordingly by adopting the firmware and adding or removing features.

Electrical engineers working with drives equipment have to understand and be able to choose an appropriate product for a certain application. Moreover, to make a correct rationale of the choice is a sophisticated problem. That is why the purpose of the paper is to give an overview of technical and diagnostic capabilities of modern frequency converters and to present the data in a common table for convenient use.

The research is made to be useful for designers or engineers choosing equipment for different projects. Therefore, a description of the technical functions was made to support engineers. In most applications, simple scalar control can be applied and there is no necessity to buy an expensive frequency converter full of various features. But some technological processes must be controlled with high accuracy or high dynamics. In these cases, some additional macros or other features might be useful. Hence, the technical functions analysis was made to show the functional performance of each converter.

Firstly, it is important to consider two most common converter topologies, their pros and cons and basic principles of FC's control systems used nowadays. Secondly, technical features of the converter are discussed. And finally, as a demonstration of diagnostic functions' programming and trends analysis, some corresponding experiments were conducted.

Functional Schemes of Frequency Converters

The power circuit of an electrical drive containing a frequency converter (FC) which is supplied by the industrial network voltage U_{network}, network frequency f_{network} and an induction motor *M* supplied by this FC is show on Figure 1.1:

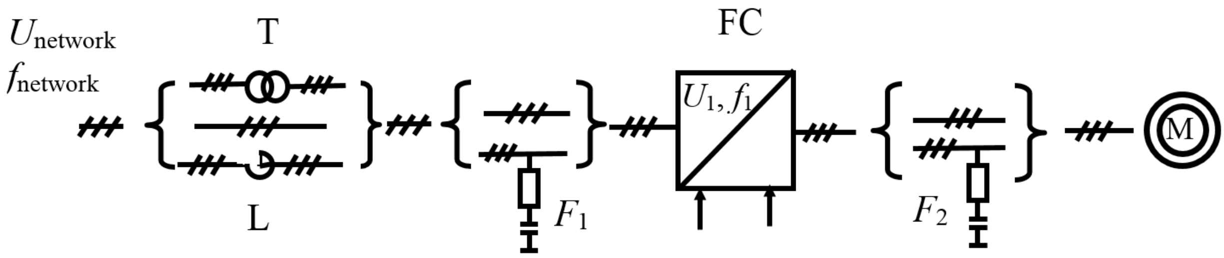


Figure 1.1. Principal description of a frequency converter drive.

Shortcuts:

T - Transformer matching voltage levels;

L - Reactor;

F_1 - RC filter;

FC - Frequency converter;

F_2 - RC filter;

There are different topologies of the frequency converter. Some of them are not used widely, like cycloconverter (direct frequency converter), therefore, just the most common topologies were described. The interest of the research is to consider the basic two-level industrial FC and to give an overview of its functionality.

The frequency converter's input parameters are coming from the grid side (power grid or a matching transformer): voltage U_1 and frequency f_1. Also, its controllable output parameters: phase voltage U_2 and frequency f_2 are determined respectively by control signals u_{u} and u_{f}. Induction motor control can be done by adjusting U_2 and f_2. By the phrase "induction motor control" one should understand the control of the main variables: current *I*, electromagnetic torque *T*, angular speed ω.

The frequency converter in a system FC-IM consists of three main blocks:

- IGBT-based Active Front-End (AFE) or diode-based Non-regenerative Front-End (NFE) rectifier;
- DC-link filters: C- or LC-filter;
- Voltage Source Inverter (VSI) or Load Commutated Inverter (LCI);

Commercially, the VSI based convert is more widespread than other types of drives. Its topology is presented in *Figure 1.2.* Note, that the picture has a general presentation of the frequency converter topology. For AFE rectifiers an IGBT bridge must be shown instead of the diode bridge.

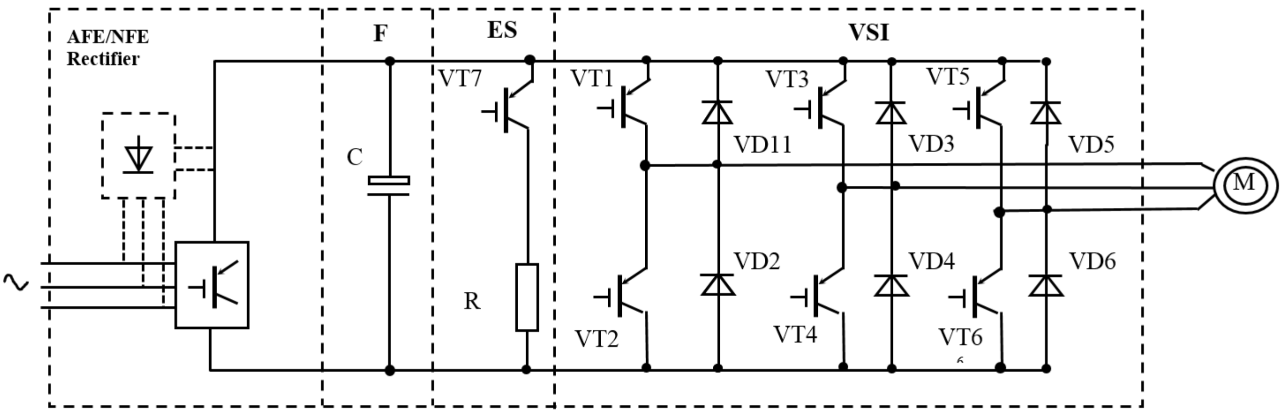


Figure 1.2. VSI based frequency converter primary circuit.

The output voltage is modulated by a pulse-width-modulation voltage control. The IGBTs' switching is modulated by a signal of certain switching frequency and by a reference voltage. The modulation principle is shown in *Figure 1.3.*

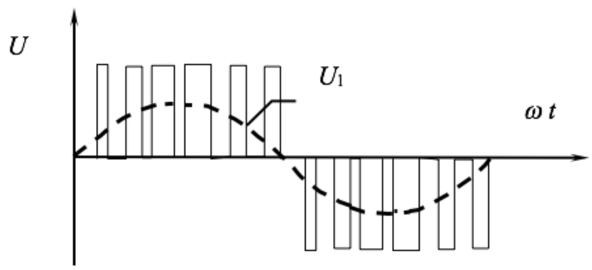


Figure 1.3. Pulse-Width-Modulation.

The main difference between an AFE and an NFE is that the first one is a bidirectional active rectifier, what means a possibility to transmit energy back to the grid in case of the generator mode of IM. Such a mode is normally used when fast motor braking should be made. If there is an NFE instead of an AFE, a braking unit (BU) should be used. It absorbs the braking energy. The BU turns ON when DC-link voltage exceeds certain limits and provides the capacitor discharge through a resistor.

Surprisingly, Russian grid managing companies do not allow the user to transmit energy back to the grid. A fine will result of generating. But in autonomous energy systems like ships, isolated settlements AFE drives are widely used.

Besides, there are different alternatives of the inverter topology, e.g. LCI converters. These inverters are not that much common nowadays, therefore, they are left out of the scope.

To summarize, the pros and cons of the described frequency converters' topologies are listed below.

Advantages of inverter technology drives:

- High range of the VSI drive output frequency from ~0 Hz to 1500 Hz limited just by switching frequency and switching losses. For the LCI drive maximum output frequency is 100–125 Hz;

- High power factor (0.95–0.98) for DFE converters. For AFE converters the power factor is adjustable between capacitive and inductive values depending on the current handling capacity of the AFE;

- Less number of switches compared e.g. to cycloconverter drive and simpler control system not requiring synchronization with the grid;

- Possibility to recuperate energy back to the grid;

Shortcomings of inverter technology drives:

- 2-level energy conversion topology what deceases the drive's efficiency to 94-96 % compared to a DOL drive;

- In case of LCI attention should be payed to the coupling of load rate, $\cos\varphi$ and thyristors commutation conditions;

- In case of VSI drives the AFE rectifier is costly, but with DFE rectifier the energy efficiency of the system is low if BU should be used;

- DC-link filters in some cases are quite large and significantly increase the dimensions of the FC;

General cons of all kinds of frequency converters:

- Decreasing value of electromagnetic torque due to output current (voltage) high-frequency harmonics;

- Increasing additional losses in the motor due to output current (voltage) high-frequency harmonics. As a result, around 10 ^{o}C of higher operating temperature compared to DOL drive;

- Due to speed control, at lower speed values worsening of the motor cooling (applicable to standard motors);

- Overvoltage at stator windings increase due to switches commutations. An output filter or additional stator winding isolation is required;

- Additional actions preventing bearings from high frequency flux components are required in the magnetic circuit of the motor;

- In case of a long cable (normally: >200 m) between FC and IM an output sine-filter is often required;

- Additional noise and high frequency electromagnetic fields affect the environment;

Control Systems of Frequency Converters

Modern voltage source frequency converters have various motor control systems suitable for different process requirements and providing different electrical drive performance. All control systems can be divided into three basic types: scalar control, vector control and Direct Torque Control (DTC). All these control types are well known theoretically from uncountable number of books, but particular mathematic models, observers and coordinates controllers are already patented and kept as private company's data.

Therefore, this chapter contains just a theoretical information about basic electrical drive control principles.

Scalar control system

Scalar control is based on voltage amplitude and frequency control and steady-state motor data. The motor voltage to frequency ratio *u/f* ratio is held constant by default. The IM starting process is made by changing the amplitude and frequency simultaneously from 0 to 50 Hz. Also, the system may have a loop with the speed feedback, thus, during the motor running the supplying voltage can be adjusted to perform the steady state speed control. As the same time, the precise torque or position control cannot be made in the classical scalar control system. (Pyrhönen et al. 2016)
Many applications can be based on IM scalar control technology, for example, fans and pumps. These tasks are simple and do not require any sophisticated cycle, do not demand a high dynamics level and do not suppose torque control.

Figure 1.4A schematic of the scalar control system is shown *Figure 1.4*. The control system has frequency f_{ref}, torque T_{ref} or speed n_{ref} as reference signal. In case of frequency reference the input signal goes straight to the voltage reference block and then to the space vector modulator. In case of speed or the torque reference the input signal first goes to the sum block to deduct a feedback signal, then the signal delta goes further to a controller (usually digital PI-controller is used) which sets a new reference signal.

The frequency reference f_{ref} may cause an overcurrent, that is why there is a limitation block which prevents it by analyzing current sensors actual values and comparing them with I_{max}.

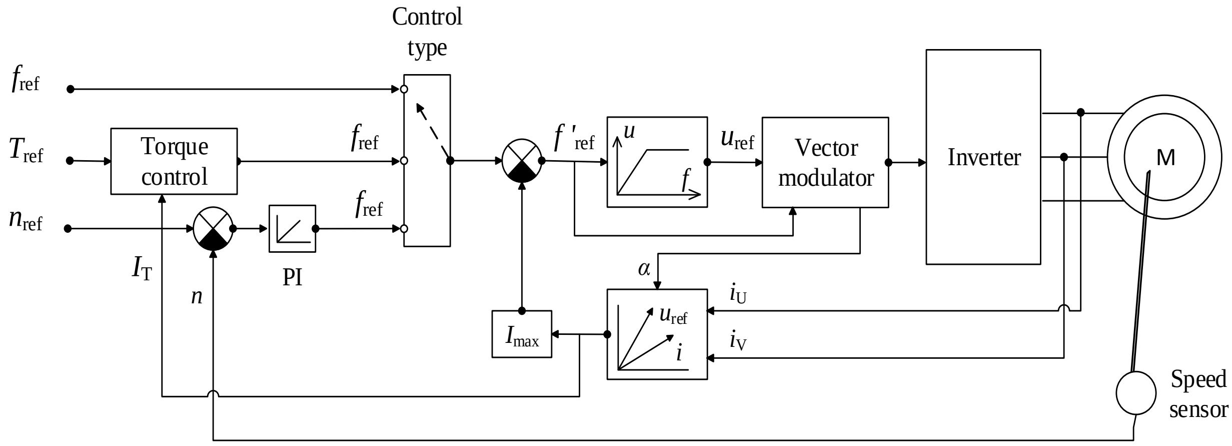


Figure 1.4. Block diagram of the scalar control system.

The voltage reference block has a set for a voltage curve: the constant *u/f* ratio (set by default), S-curve, root-mean-square curve or IR-compensation. For example, the S-curve is normally used when a smooth start/stop is required (e.g. in a conveyor application). The root-mean-square curve is used with purpose to improve energy efficiency in fan applications: low voltage feed motor at low speed. The IR-compensation should be used in case of high starting torque: an extra voltage at low speed provides full flux linkage (to be used e.g. in mass pump applications: because of the mass high viscosity high torque is required to start the pump).

The inverter modulator provides IGBTs with the final switching references. Modulator uses the sine triangle comparison technique. Modern inverters use asynchronous pulse width modulation (PWM). Nevertheless,

*Figure 1.*4 shows a more sophisticated technique: space vector modulation which allows analyzing the torque producing current i_T. The modulator can estimate the current voltage vector position and then calculate the vector’s angle. The current vector position can be found in the same way. Then the angle between voltage and current vector has to be calculated and finally active current can be obtained.

However, without a proper IM model by using the scalar control the torque can be roughly estimated. This control technique cannot provide high level of dynamics, but the motor gradually changes its states (by tenths of seconds). More sophisticated control system which provides significantly higher dynamics will be described below. (Pyrhonen et al. 2016)

<u>Vector control system</u>

It is an IM magnetic field control which in fact controls the motor flux linkage (for IM it is normally a rotor flux linkage). In the control system the stator current in monitored and a certain mathematical model analyses the stator and/or rotor flux. In fact, the current vector is divided in two parts (axis d, q): the flux producing and the torque producing current. Thus, it is called two-axis IM model which is presented in *Figure 1.5.*

One of the most important parts of the control system is the IM model, which act as a rotor EMF estimation block which is also based on the two-coordinate equivalent circuit. The circuit's parameters can be transformed to the rotor coordinates. The rotor flux linkage estimation block can operate with an encoder or a position sensor signal as well as without any sensors at all. If the technological process does not require the precise speed control, the sensorless vector control is preferable, because the sensor installation is much more expensive and it decreases the overall system reliability.

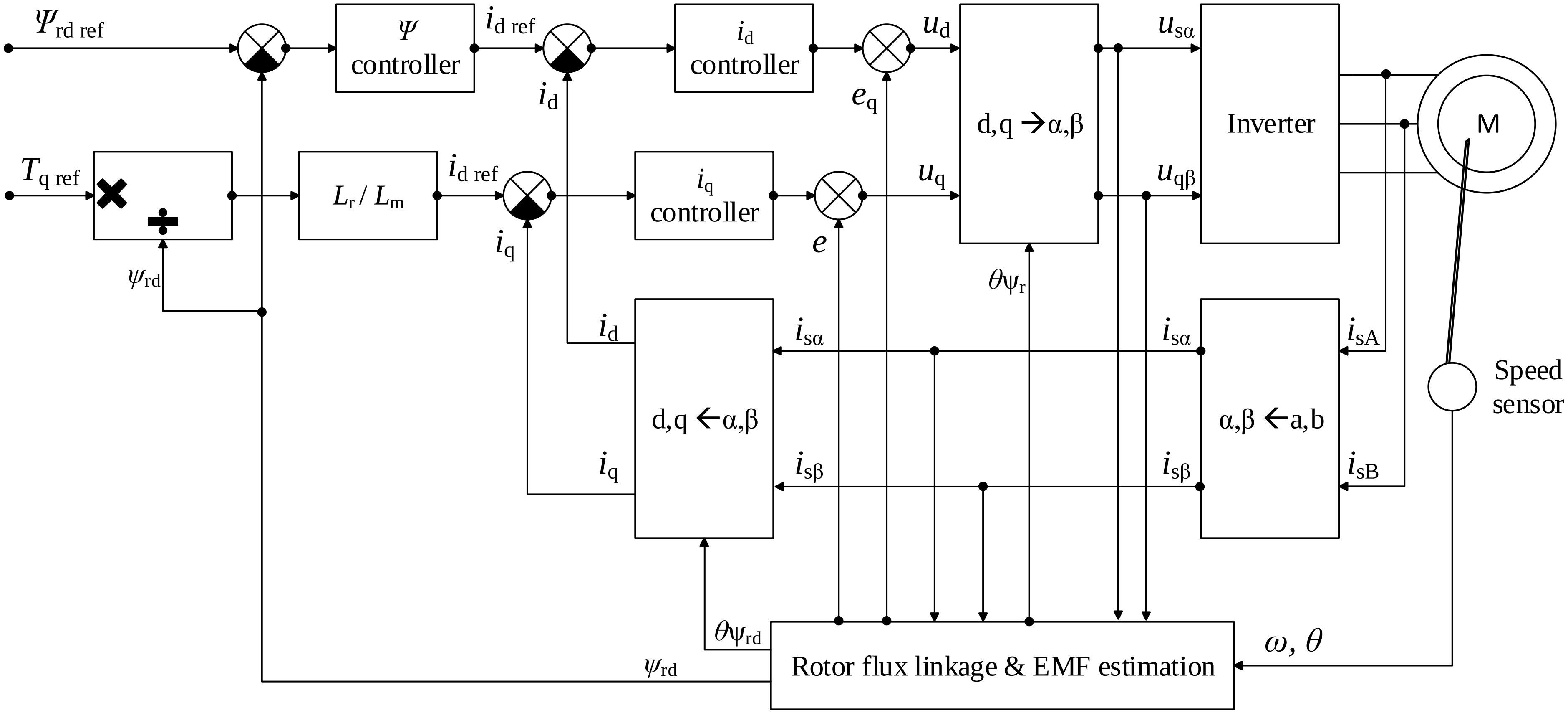


Figure 1.5. Block diagram of the vector control system.

The rotor angle estimation calculated in the observer (estimation block) is used for the coordinates transformation: from α, β to d, q and vice versa. The reference for the i_d current controller comes from the flux linkage (ψ) controller and for i_q from the torque reference signal $T_{q\ ref}$. The ψ controller is placed in the d-axis current circuit to magnetize the motor. It provides a better dynamic during the transient process.

$$0 = i_{rd} R_r + \frac{d\psi_{rd}}{dt} + \omega\psi_{rq} \tag{1}$$

$$\psi_{rd} = L_m i_{sd} + L_r i_{rd} \tag{2}$$

$$i_{rd} = -\frac{L_m}{L_r} i_{sd} \tag{3}$$

The q-axis current reference is determined by equation (3), which is obtained from equation (2). It should be mentioned that a transient process time is defined by the electromagnetic time constant. According to equation (3) can be seen that to decrease the transient process time the stator current should be boosted when the flux linkage is still 0. The same logic is in the rotor circuit equation (1) where the higher current i_{rd} creates the higher voltage drop in the rotor winding and therefore it leads to the higher $\frac{d\psi_{rd}}{dt}$ derivative and better dynamics during the magnetic circuit transient process.

As conclusion it should be mentioned, that the current defines the maximum allowed torque value. However, the DC-link voltage and total motor resistance define the current limit. (Anuchin 2015; Klutchev 2001)

Direct torque control system

The Direct Torque Control (DTC) initially was developed for asynchronous motors, but it can be used as well for synchronous machines control. ABB released frequency converters with DTC for the first time in 1988 (Pyrhönen et al. 2016). The simplified version of the control system containing flux & torque relay controllers and the adaptive motor model is shown in *Figure 1.6*. The use of this control system is to provide a required constant torque.

As can be seen in *Figure 1.6* the DTC system has to detect the phase currents (2 phases is enough), DC-link voltage and the current IGBTs' state and then send all this data to the motor model. Unlike the vector control, in DTC there is no need to know the actual motor angular speed. The control system can estimate the flux linkage and torque via the mathematical model which is independent from the speed. The relay controller compares torque and flux reference values with actual ones. Then optimal switching logic block selects a suitable IGBTs state and switches to it. Finally, the instantaneous flux linkage vector is increasing or decreasing the current flux linkage vector and, thus, it changes the torque as well.

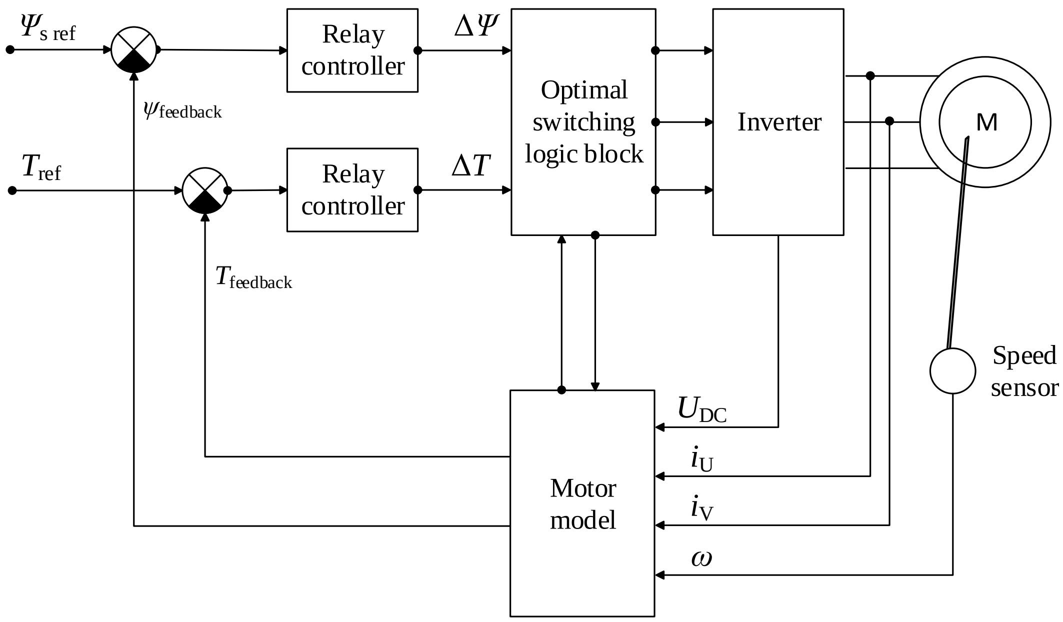


Figure 1.6. Block diagram of the direct torque control system.

Since the IM model is based on flux linkage equations 1-3, it is necessary to determine the inductances $L_{s\sigma}$, L_m, stator resistance R_s and stator phase currents i_U, i_V.

The accuracy increases if the magnetic circuit saturation is taken into account. The observer based on this effect can significantly increase the stator flux linkage estimation at low speed rates (Anuchin 2015).

Finally, the DTC has much higher dynamics compared to the vector control, but it is limited by the mechanical capabilities of the drive. However, some developers think that direct torque control offers lower overload capability than vector control. This issue was discussed in book of Anuchin A. “Sistemy upravlenia electroprivodov” (2015, pages 358-368).

General conclusions

Modern frequency converters do have all control systems described above. Therefore, the particular control method should be chosen according to the technological application’s requirements and the budget for the installation.

If there is no requirement related to dynamics, precise position or torque control the scalar control is normally good enough. This system does not contain a sophisticated motor model, it is stable, reliable and easy to setup.

For more demanding applications the vector or direct torque control are used. An application may require e.g. precise tension control: drives in metal sheet production, textile industry; accurate and high dynamic speed control: a conveyor strip, hoists or many other mechanisms may require also a speed sensor for the most precise control. But in fact, the encoder installation is quite costly and less reliable, so it has to be installed when sensorless control is not applicable at all. DTC control is used for a number of applications where the speed is not important, but a constant torque should be provided: a pusher drive, winches, paper machines, etc.

This chapter gives just an overview for a rough understanding of the control system variety. Of course, control techniques are much more complex, they consider more parameters and phenomena. It is worth noting that frequency converters’ technical options described in Chapter 2 are linked with different motor control methods that is why this chapter is placed in the introduction section.

2. MAX 1000 V FREQUENCY CONVERTERS' TECHNICAL PARAMETERS.

Different frequency converters' properties are compared. The converters have several important and some less important practical operating features. The converters observed are industrial type converters with power rates up to 100 kW. If the manufacturer offers different frequency converter models for the scalar and vector control, the latter one is selected for the survey. Also, some firms offer inverters with 3-level voltage source converters or matrix converters in addition to usual 2-level voltage source converters. In that case 2-level converters are chosen to be studied since they are most common nowadays.

The aim of the work is to compare frequency converters of the same type made by different manufacturers and provide a statistical analysis about their functions and faults diagnostic capabilities. This information may be useful for people who are choosing an inverter for a project, since all that data is presented in one place.

In *Tables 9-11* (Appendix 1.-3) numbers are used instead of the full title of inverters. It has been done with purpose to save some space in the page and let the table to be more compact. Detailed brand names and the inverter's model titles are given in *Table 1* below. Also, the table shows the converter application type given by the manufacturer.

In the current chapter, there is no other reference to any source of technical information because all the data related to the frequency converters functionality was collected by using documents available online, downloaded mostly from frequency converters manufacturers' websites. Therefore, it is not reasonable to put a reference each time mentioning a FC's feature, otherwise it will be complicated to read *Tables 9-11* (Appendix 1.-3). All utilized manuals (engineering guides) are placed in section References. According to the rules, with their correct titles, sources and release date.

Table 1. Frequency converters under the study

Converter's num.	Manufacturer & Title	Application Field
1	ABB ACS880	Industrial drives
2	Siemens SINAMICS	General purpose drives
3	Schneider Electric Altivar	Standard drives
4	Danfoss Vacon100	Industrial drives
5	Eaton 9000X	General purpose drives
6	Emotron VFX	High performance drives (demanding
7	Hyndai N700v	General purpose drives
8	Invertek Optidrive P2	High performance drives (demanding
9	Mitsubishi Electric FR-A800	General purpose drives
10	Omron RX	General purpose drives
11	Tecorp Electronics	General purpose drives
12	Toshiba TOSVERT VF-AS3	General purpose drives
13	Yaskawa A1000	General purpose drives
14	Hitachi SJ-700	General purpose drives
15	VESPER EL-9011	General purpose drives
16	TRIOL AT-24	General purpose drives
17	CHAEZ-ELPRI	General purpose drives

All possible messages shown on the inverter's screen are named according to the following logic:

- Technical functions *fxxx;*
- Warnings are called *Axxx;*
- Fatal errors are called *Fxxx;*

Technical features of frequency converters

Below, a statistical analysis of the technical parameters of the frequency converters is presented. The data was found from information provided by manufacturers. Technical manuals and user guides are available mostly on companies' web-sites which were studied for this research. Also, some documentation was provided by manufacturer's representatives after a request for it.

During the data collecting process some difficulties were faced. Some manufacturers have no detailed documentation for their converters and programming guides lack explanations. This issue is related more to Russian manufacturers which produce converters just for domestic market and, therefore, provide documentation only in Russian. Some brands limit the propagation of their manuals and do not publish them in the internet. For example, CHAEZ-ELPRI Ltd (Cheboksary, Russia) only provided the converter documentation after an email request.

In *Table 9* (Appendix 1.) below the technical parameters of 17 different inverters are shown. The list of parameters was created by combining some particular functions to a common function (without losing accuracy) to reduce the table's size and simplify the overall understanding. It should be kept in mind, that some of the functions contain several in-built parameters which can be adjusted in different ways depending on the user's purpose. For example, the drive's acceleration/deceleration ramp type can be set automatically with sample curve types or manually by setting some particular points.

Table 2 showing the distribution of FC's technical functions to several common groups (combined by type and usage) is presented below. It was made with aim to optimize the analysis by conducting it inside each group of functions.

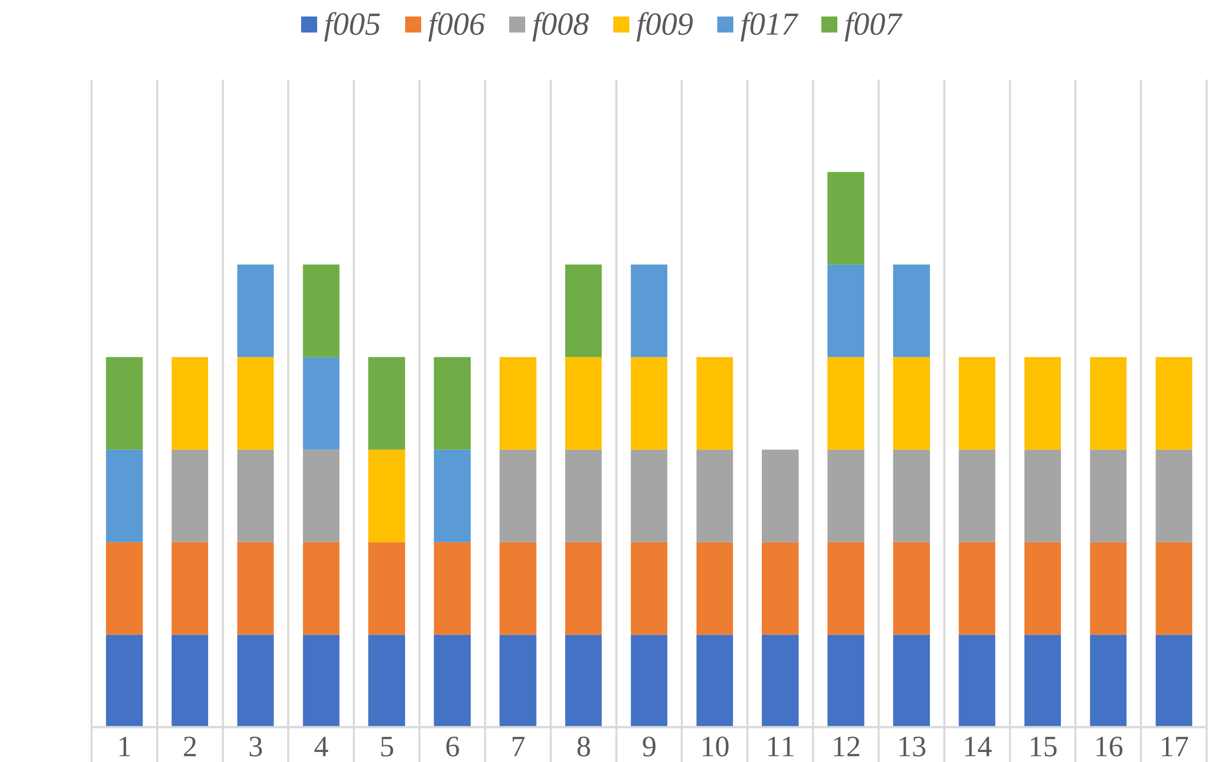
Table 2. Technical functions of frequency converters

Num.	**Title**	**Category**
f005	Scalar Control	Motor Control
f006	Adjustable IR-Compensation	
f007	Direct Torque Control (DTC)	
f008	Sensorless Vector Control	
f009	Vector Control (with encoder feedback)	
f017	Supporting PMSM Control	
f004	Master/Follower Functionality	Additional Features of Control System
f010	Linear Ramp Type (acceleration/deceleration)	
f011	S-Ramp Type (acceleration/deceleration)	
f012	Adjustable Acceleration/Deceleration Time	
f013	JOG Function	
f015	DC-Magnetization (pre-heating / lock the rotor)	
f016	Energy Saving Mode (flux optimization)	
f018	Macro Configuration (for a specific field of application)	
f019	PID-Control Macro	
f022	Positioning With Encoder or Limiting Switches	
f035	Free Function Blocks (math and logic operations)	
f037	Switch to Change The Motor Supply Source to The Network	
f038	Programmable Operating Mode (according to the day hours)	

Continuation of Table 2

Num.	Title	Category
f014	Prohibit Frequencies	Safety During Process Running or Human Safety
f020	Protection From The Load Loss	
f021	Programmable Actions After an External Event	
f023	Emergency Running Mode (forced running despite occurred fatal errors)	
f028	Oscillation Damping	
f029	Flying Start	
f030	Safe Torque Off (STO)	
f031	Protection From Rotating In Opposite Direction	
f032	Adjustable Automatic Restart	
f024	Password to Limit From Changing Parameters	System Functionality
f025	Load Analyzer (selection in %)	
f026	Maintenance Timers And Counters	
f027	Energy Saving Calculator	
f033	Software for Configuring And Monitoring The Frequency Converter	
f034	Smartphone Application	
f036	Removable Control Panel With a Memory Stick	
f001	Programmable Analog I/O	Additional I/O and/or External Modules
f002	Programmable Digital I/O	
f003	Programmable Relay Outputs	

The graph shown in Figure 2.1 presents the availability of control system functions (category: motor control) according to *Table 2* in each frequency converter (numbers from 1 to 17). Functions' codes from *Table 9* (Appendix 1.) are used in the figure instead of their titles. The graph should be understood by using an explanatory table below it. The presence of each function is defined as number 1 in the table and a certain color in the figure (according to the legend above it). All following graphs are made similarly.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
f007	1			1	1	1		1				1					
f017	1		1	1		1			1			1	1				
f009		1	1		1		1	1	1	1		1	1	1	1	1	1
f008		1	1	1			1	1	1	1	1	1	1	1	1	1	1
f006	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
f005	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 2.1. Motor control functions availability.

One can notice in *Figure 2.1* that functions like Scalar Control (*f005*) and Adjustable IR-Compensation are available in all frequency converters, which are considered in the study. But the function *f017* of PMSM control (an additional to the asynchronous machine) is quite rare and exists just in 35% of FCs.

Also it should be mentioned, that each converter which is considered above has either the vector control function or, in case of ABB and Emotron, the Direct Torque Control (DTC) method. Both control systems are finally quite similar in performance, since both use the two-axis model of the asynchronous machine. In vector control the measured stator current is controlled by changing the flux-producing component and the torque-producing component.

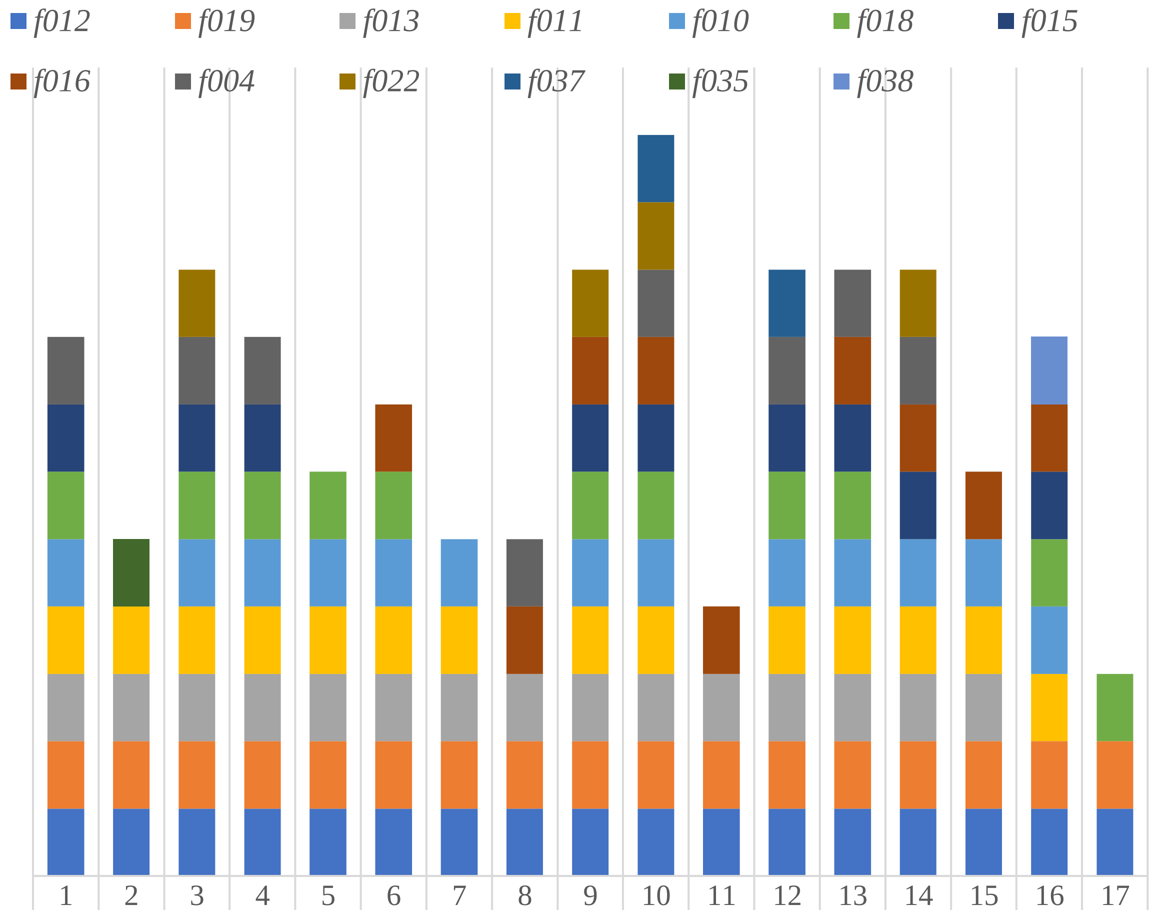
The classical DTC method operates with the same maximum value of switching frequency because similar IGBTs are used. But in DTC the optimal switching logic changes IGBT's operating frequency depending on the current electromagnetic state of the machine. Thus, on one hand, there is a benefit as the converter switches its state only on demand. Such a behavior might help optimizing the torque ripple and save energy losses caused during switching periods. But on the other hand, a variable switching frequency might also cause a higher torque ripple on the load side. It is quite a sophisticated issue and different specialists think diversely about this. (Anuchin 2015)

Nevertheless, the DTC approach can operate with a faster torque response than vector control, below 2 ms. But in that case, from the mechanical point of view there are usually some restrictions. Therefore, it should be taken into account and the torque response time should in many cases be decreased. (Pyrhönen et al. 2016).

Drives' applications can be completely different, therefore, for some, one should match the acceleration/deceleration ramp type and time, and for others to maintain a certain parameter at a determined level with a definite accuracy. A category of functions necessary for these kinds of applications was defined as Additional Features of Control System and it is presented in *Figure 2.2.* The most common functions are the following:

- Linear Ramp Type (acceleration/deceleration), *f010*, in 76% of FC;
- S-ramp Type (acceleration/deceleration), *f011*, in 82% of FC;
- Adjustable Acceleration/Deceleration Time, *f012*, in 100% of FC;
- JOG Function, *f013*, in 88% of FC;

- PID-Control Macro, *f019*, in 100% of FC;



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
f038																1	
f035		1															
f037										1		1					
f022			1						1	1				1			
f004	1		1	1				1		1		1	1	1			
f016						1		1	1	1	1		1	1	1	1	
f015	1		1	1					1	1		1	1	1		1	
f018	1		1	1	1	1			1	1		1	1			1	1
f010	1		1	1	1	1	1		1	1		1	1	1	1	1	
f011	1	1	1	1	1	1	1		1	1		1	1	1	1	1	
f013	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		
f019	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
f012	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 2.2. Additional control system functions availability.

As it was mentioned above, some frequency converters have inbuilt functions/macros, providing simplification of the drive's cycle control structure without using PLCs or equivalent logical devices. Probably, these converter's features can save additional money for the setting up a system and for buying a logical device in case of a standard application. Examples of these technical functions:

- Positioning With Encoder or Limiting Switches (*f022*);
- Free Function Blocks (*f035*);
- Switch to change the Motor Supply Source to The Network (*f037*);
- Programmable Operating Mode (*f038*);

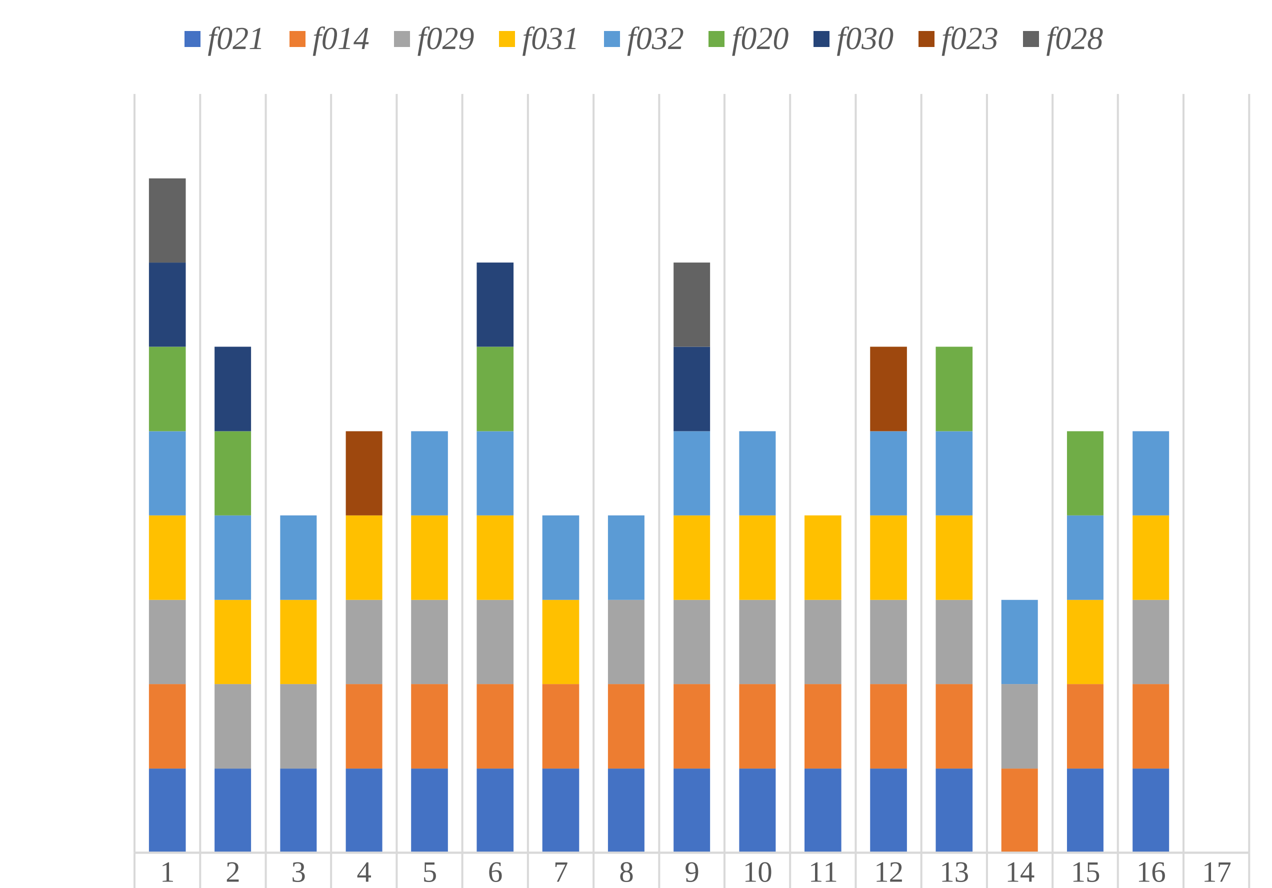
It should be mentioned that such a useful function as Free Function Blocks (*f035*) is presented just in Siemens frequency converter what offers a huge advantage among all considered converters. This feature makes it possible to do some mathematical and logical calculations for any signal without PLC and then send it to a control system controller or any other control device of the automation system.

In each electrical drive application it is required to provide the safe and uninterruptable operation as well as safe conditions for engineers working with the equipment. The next category in *Table 2* is analyzed in the following figure.

Functions providing safety for humans and the equipment itself are presented in Figure 2.3 and the most common ones are listed below:

- Prohibited Frequencies, *f014*, in 82% of FC;
- Programmable Actions After an External Event, *f021*, in 82% of FC;
- Flying Start, *f029*, in 82% of FC;
- Protection From Rotating In Opposite Direction, *f031*, in 82% of FC;
- Adjustable Automatic Restart, *f032*, in 82% of FC;

These functions ensure that the system will operate without any interruption. Nowadays, each unintentional stop of the electrical drive leads to more and more costs, therefore, it is so important to prevent them. For example, by adjusting the Automatic Restart (*f032)* and setting the number of attempts (or waiting time) provide the operation continuation without human involvement which significantly reduces the non-operating time of the drive.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
f028	1								1								
f023				1								1					
f030	1	1				1			1								
f020	1	1				1							1		1		
f032	1	1	1		1	1	1	1	1	1		1	1	1	1	1	
f031	1	1	1	1	1	1	1		1	1	1	1	1		1	1	
f029	1	1	1	1	1	1		1	1	1	1	1	1	1		1	
f014	1			1	1	1	1	1	1	1	1	1	1	1	1	1	
f021	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	

Figure 2.3. Safety functions availability (for human and the equipment).

For example, in some industrial machines only one rotational direction is allowed and a feature protecting from rotating the machine in opposite direction (*f031*) can increase safety and secure humans from an unpredictable risk. Also, the opportunity of programming a certain frequency converter's reaction on an external event, for instance, allowing stopping the drive on time just after a fault detection.

Not less important is the function skipping prohibited frequencies (*f014*). It helps avoiding mechanical resonances in the system, which can be critical for human as well as for the equipment.

There are functions which are not that common in modern converters, but also help improve drive safety. In case of several applications, the features listed below can provide an additional safety for the maintaining personnel:

- Protection From Load Loss (*f020*);

- Safe Torque Off (*f030*);

With the function “protection from the load loss” the converter monitors the output frequency and/or the motor speed. Frequency converter controls the signal coming from a sensor. If the signal is lost, it immediately determines a fault. This function may be used in applications controlling mechanical gears of elevating machines, a belt of the conveyer drive, protection of the pump lock (Siemens AG 2013)

With the function “Safe Torque Off (STO)” IGBT control signals can be blocked which action prevents the inverter from creating an electromagnetic torque without first switching off the whole drive. The idea of this feature to double the signal preventing the voltage in IGBTs to provide additional safety. After the activation of the STO function the converter immediately stops modulating (if it had been operating) and cannot be started again before the STO switch is opened. The second case where this function can be used is a quick maintenance work to prevent an accidental start, while keeping the frequency converter’s power supply ON (ABB Oy 2016). This function, however, cannot be used with permanent magnet motors in the field weakening area as it should endanger the converter voltage tolerance.

Quite large number of system functions are available in frequency converters which improve their usability. They can be seen in Figure 2.4.

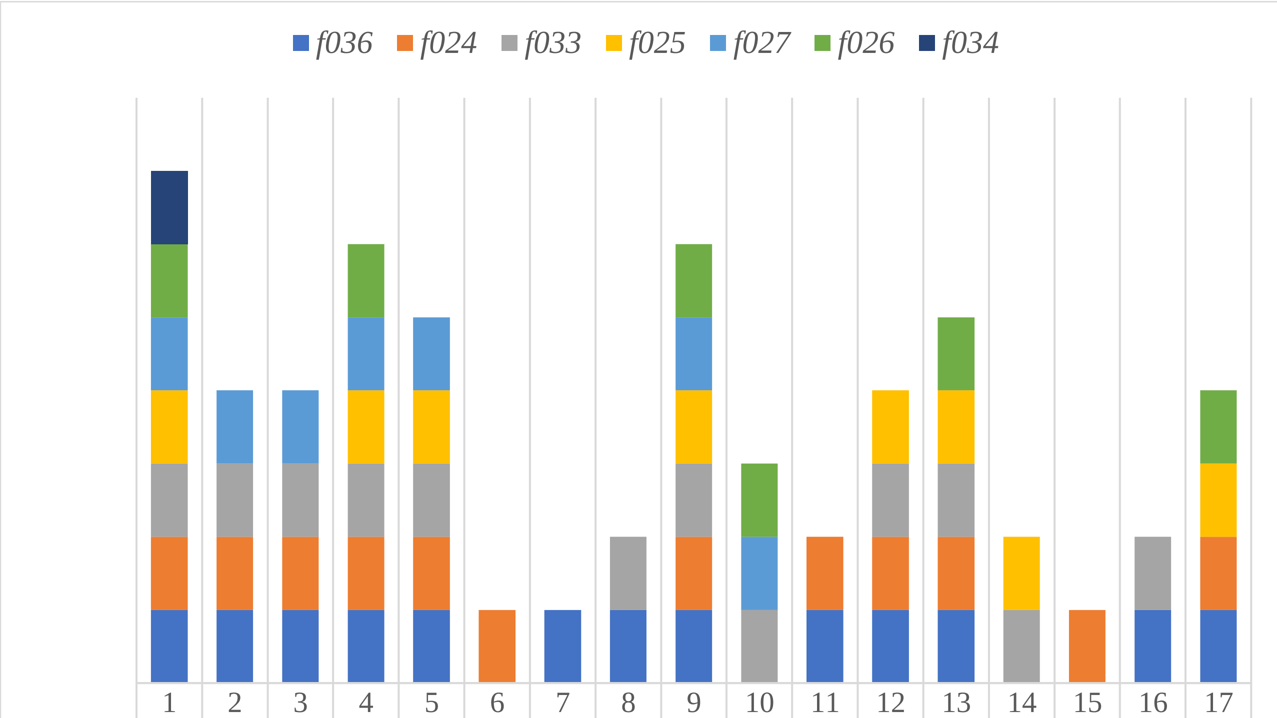
From these features the most common ones are:

- Removable Control Panel With a Memory Stick *f036* (in 76% of FC);

- Password to Limit From Changing Parameters *f024* (in 70% of FC);

- Software For Configuring And Monitoring The Frequency Converter *f033* (in 70% of FC);

It should be mentioned that features *f036* and *f033* reduce the setup time of the converter. All leading manufacturers can offer this option to the customer. But such firms as Vesper and Emotron do not have these features.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
f034	1																
f026	1			1					1	1			1				1
f027	1	1	1	1	1				1	1							
f025	1			1	1				1			1	1	1			1
f033	1	1	1	1	1			1	1	1		1	1	1		1	
f024	1	1	1	1	1	1			1		1	1	1		1		1
f036	1	1	1	1	1		1	1	1		1	1	1			1	1

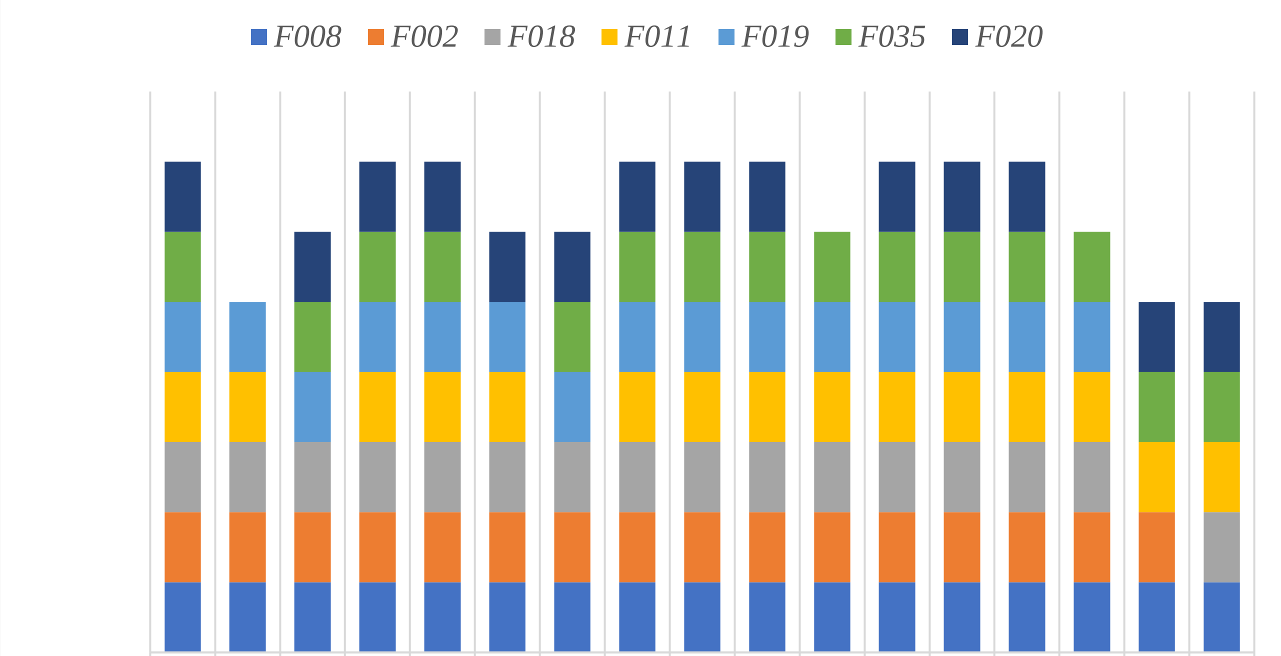
Figure 2.4. System functions availability.

Diagnostic functions of frequency converters (fatal errors)

In this section a list with fault messages is presented and analyzed. These messages should help the user to understand the diagnostic functionality of each converter. By this should be understood all functions which protect people, a motor and the converter itself. Fault messages inform the user about the fault type. Manuals offer more detailed failure description. Additionally, there could be found some reasons causing a fault and possible solutions how to fix it.

A full list of faults identified by inverter is presented in a *Table 10* (Appendix 2.). Some fatal errors are combined according to similar meaning (or a fault could be named generally), despite the fact that they could be separated messages/faults in the converter. It should be mentioned that in the *Table 10* particular faults diagnosed by the inverter are presented, which informs about a particular fault/event, but not about a possible reason which can lead to this fault. As a result, in the control panel's screen a fault message (with its code) can be seen.

Since the list of these messages is quite long (*F001..F056*), it was decided to present different analyses of different parts of the table, which can represent the biggest interest for potential users. *Figure 2.5* shows the availability of the most common diagnostic functions of fatal errors, which are present in 80% of frequency converters considered in the research. Similarly to the previous section, functions in the figure are presented in a different order compared to the *Table 10*; The most common diagnostic functions are shown first.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
F020	1		1	1	1	1	1	1	1	1		1	1	1		1	1
F035	1		1	1	1		1	1	1	1	1	1	1	1	1	1	1
F019	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		
F011	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1
F018	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1
F002	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
F008	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 2.5. The most common technical features (presented in 80% of FC).

Figure 2.5 shows that from all variety diagnostic functions (56 functions in the list) just a few basic are presented in 80% of frequency converters. It can be noticed, that among them there are functions protecting the converter: the input voltage control, output current control with aim to prevent overload, overtemperature of the FC, the DC link voltage control. Also, some functions protecting the motor are likely available: motor overload, braking resistor fault detection (also for thermistors).

It is necessary to mention, that fatal errors detected by the converter are not only securing the features for electrical devices like frequency converter or motor, but also in many applications providing safety for people working with that equipment. Consequently, it is worth analyzing these functions (*Table 3*).

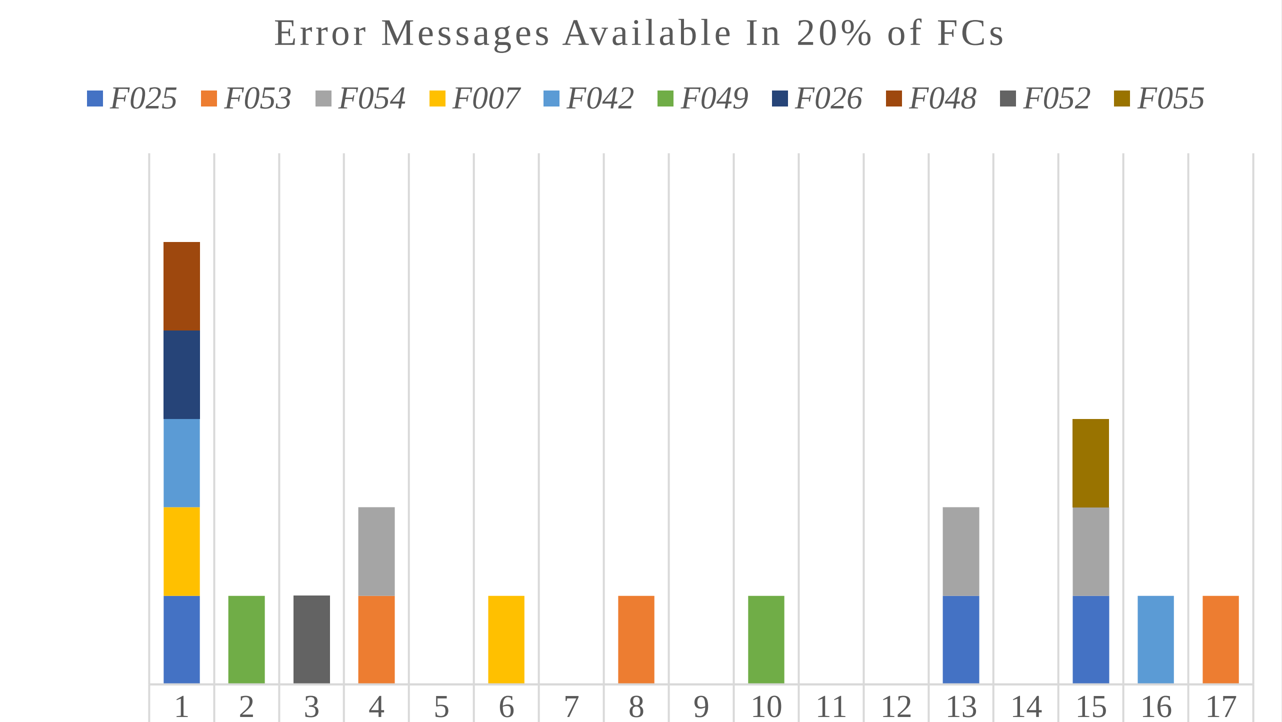
Table 3. List of functions providing human safety

Num.	Fault name	Availability in FC, [%]	FCs without this function	FCs with this function
F003	Load unbalance (earth leakage)	30%	- Siemens - Schneider Electric - Danfoss - Eaton - Hyndai - Inverter - Mitsubishi Electrics - Omron - Tecorp Electronics - VASPER - TRIOL - CHAES-ELPRI	- ABB - Emotron - Toshiba - Yaskawa - Hitachi
F005	Wiring/earth fault	70%	- Invertek - Tecorp - Toshiba - Hitachi - TRIOL	- ABB - Siemens - Schneider Electric - Danfoss - Eaton - Emotron - Hyndai - Mitsubishi Electrics - Omron - Yaskawa - VESPER - CHAES-ELPRI
F012	Output phase loss	76%	- Emotron - Hyndai - Invertek - Omron	- ABB - Siemens - Schneider Electric - Danfoss - Eaton - Mitsubishi Electric - Tecorp - Toshiba - Yaskawa - Hitachi - VESPER - TRIOL - CHAES-ELPRI

According to the obtained result, it can be concluded that not all of manufacturers take into account the safety functions. Functions *F003, F005* might be substituted by protective automatic switches, but to replace the feature *F012* would be a quite complicated task.

Continuing the analysis, it is important to mention that modern frequency converters have a large number of different self-condition diagnostic functions. The most important is the overload protection (55% of considered in the research FC have it) and the power unit overtemperature (rectifier, inverter, pre-charging circuit). Also, significant attention is payed to microcontroller software faults (70%), controlling the connection between different modules and external devices (76%), temperature sensors faults (24%), FC's modules fault (65%), faults during macro program running.

Also, it is interesting to present the analysis of uncommon diagnostic functions of the frequency converters. This study can be seen in the figure below:



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
F055															1		
F052			1														
F048	1																
F026	1																
F049		1								1							
F042	1															1	
F007	1					1											
F054				1									1		1		
F053				1				1									1
F025	1												1		1		

Figure 2.6. Error messages available in 20% of FCs.

Among other features, there are several functions for self-diagnostics (fault in ADC-circuit *F025*, inverter connection malfunction *F026*), running the main program control (connection with a follower drive is missing *F048*, fault during "flying" restart *F049*), also some minor functions (output contactor stuck *F052,* malfunction in the inverter's clock *F054*, fault caused by simultaneously pressed buttons "forward" and "backwards" *F055*). It should be mentioned, that "output contactor stuck" feature is related to the Output Contactor Command function of the frequency converter. According to manuals, just Schneider Electric converters have it: "This allows the converter to control a contactor located between the motor and the converter" (Schneider Electric 2015).

Based on the obtained results some conclusions can be made. Modern frequency converters have multiplicity of the diagnostic functions. Of course, not all of them are necessary for every kind of application, but for a particular task it might be helpful to have one of the above-mentioned "minor" functions such as connection with a follower drive control (and print on the control panel's screen the fault code about that).

Moreover, also as important features should be considered those, which appear during the running process of the frequency converter and indicate the malfunction of the control system software itself. Those faults help to react immediately on the fault and stop the drive if it is necessary to prevent it from operating with wrong parameters. For example, if a conveyer drive will continue operating with a wrong speed, it might cause a defect in the output product. Among the whole list of functions may be allocated as follows:

- *F034*, Motor Stall (in 35% of FC);
- *F037*, PID-Controller Failure/Feedback Missing (in 40% of FC);
- *F038*, Overspeed (in 60% of FC);
- *F039*, Encoder Failure (in 60% of FC);
- *F045..F046*, Analog/Digital Signal Fault (in 60% of FC);

The diagnostic functions mentioned above can provide the additional safety for people as well as for the proper operation of the drive.

Warning messages of frequency converters (preventing the fault)

Warning signals appearing during the initialization and the operation process of the drive are presented in this section. This message can prevent from the fatal error and inform the user about reaching some limit. Usually, these warnings could be found and fixed by a user according to the instructions in the converter's technical manual.

The full list of warning messages is presented in *Table 11* (Appendix 3.). It should be mentioned that not all manufacturers divide faults messages into two groups: fatal errors and warnings. For example, in inverter brands below there are just one type of the fault:

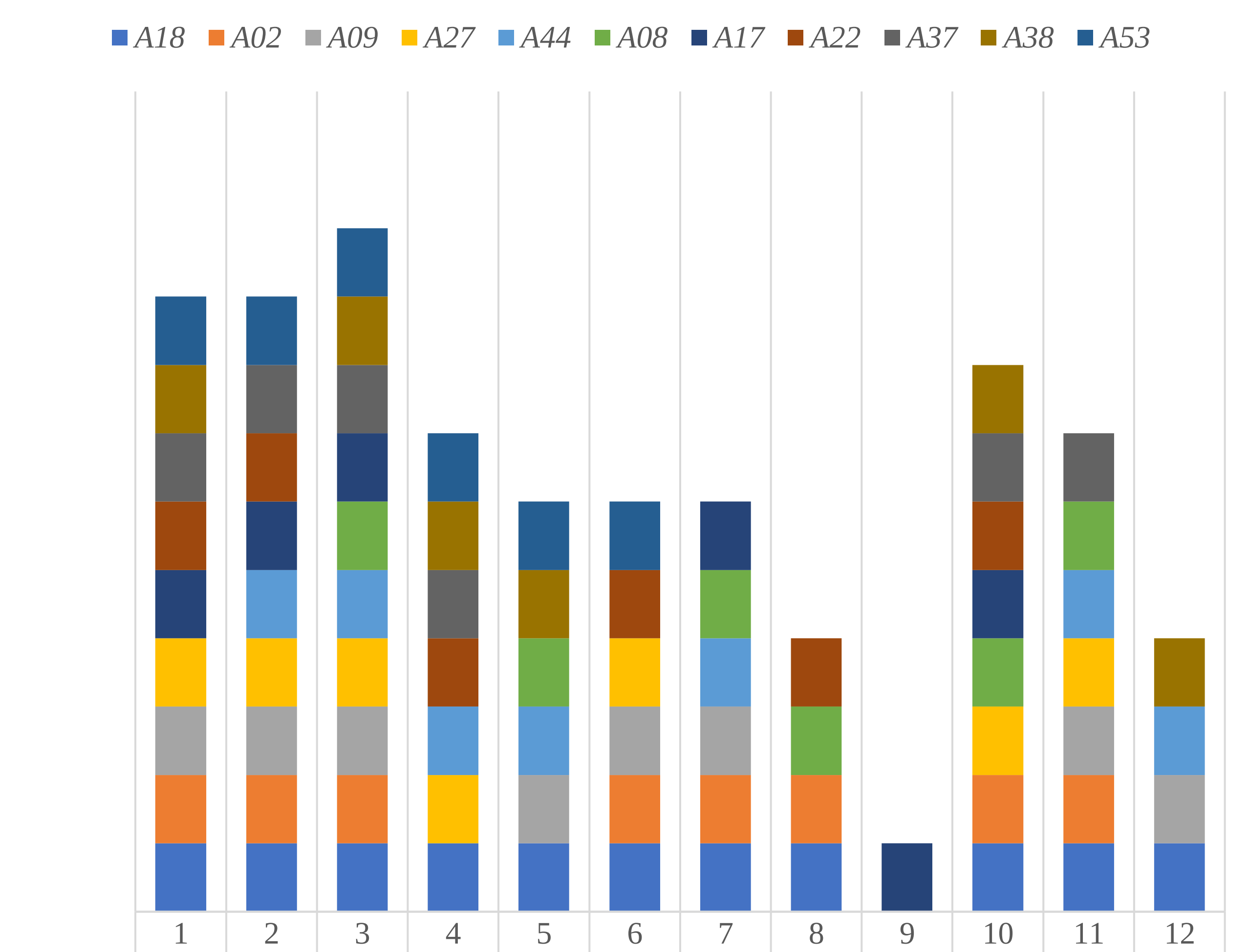
- Invertek Optidrive P2;
- Tecorp Electronics A1000;
- Hitachi SJ-700;
- VESPER EL-9011;
- TRIOL AT24;

For this list of manufacturers there is no information about warning messages in technical manuals. For these converters, the column related to the availability of the warning function is painted in the grey color. Also, some manufacturers like Schneider Electric Altivar 71 offer to set manually the frequency converter's reaction for each external event (whether a warning or a fatal error).

Figure 2.7 shows the distribution of features (warning messages) which are available in more than 50% of frequency converters considered in the research. It can be noticed that the majority of them have the same meaning as the fatal errors from the previous section *Diagnostic functions of frequency converters (fatal errors)*. It should be understood that warning messages notify about exceeding pre-limits and the fatal error message occurs when limits are already overstepped. Some of these features are allocated below:

- *A18*, Motor Overtemperature (92% of all considered FC have it);
- *A02*, Overcurrent (66%);
- *A09*, DC Link Voltage Fault (67%);
- *A27*, Communication Error of Some Interface (58%);

- *A44*, Too High/Low Torque (58%);



	1	2	3	4	5	6	7	8	9	10	11	12
A53	1	1	1	1	1	1						
A38	1		1	1	1					1		1
A37	1	1	1	1						1	1	
A22	1	1		1		1		1		1		
A17	1	1	1				1		1	1		
A08			1		1		1	1		1	1	
A44		1	1	1	1		1				1	1
A27	1	1	1	1		1				1	1	
A09	1	1	1		1	1	1				1	1
A02	1	1	1			1	1	1		1	1	
A18	1	1	1	1	1	1	1	1		1	1	1

Figure 2.7. Warning messages available in more than 50% of FCs.

In numerous of frequency converters, which have the technical function *f021* (Programmable Actions for an External Event, Appendix 1.), there is the possibility to set a certain warning after an external event and to set the frequency converter's action for it, as it was mentioned above.

The overview of retail prices for the list of chosen drives

For the more detailed analysis, it is worth mentioning also the price for each considered converter since during the project's designing process there are so many issues which should be kept in mind. Nowadays, a large number of companies produce frequency converters and the majority of them are quite similar. Furthermore, the electrical drive is not a cheap system and that is why also the converter's price matters.

The aim of this study was to present visually the economical part of the designing process and give engineers the first sight of the matter. For that purpose, prices were provided by official distributors via email after an individual request. All data was collected just for Russian frequency converters market; prices are valid for Moscow area, but probably some retailers also ship devices to different regions. In the email request were 5 FC of different power values: 3 kW, 11 kW, 30 kW, 55 kW, 90 kW. All of them supposed to be supplied by 400 V AC. As an additional equipment an EMC-filter was chosen (some FCs may have more options by default). The list of converters, prices and their options are presented in *Table 4.*

During data collecting process a certain problem was faced, some distributors (or even manufacturers) did not provide any information about prices for their converters. The request was made by a private person. Unfortunately, not every company's policy allows sharing the price info to private customers. Following companies (or distributors) did not send any information: Tecorp Electronics, Yaskawa, Triol, CHAES-ELPRI.

Russian market has the evident pattern of flexible discount system. Some manufacturers may give even 50% discount from the initial price. Therefore, it should be well understood that during communication with distributors a different behavior was met. Some of them gave a discount for that request, but in the Figure 2.8 full prices are presented. Nevertheless, the value of each discount is listed below:

- Eaton (33%);
- Invertek (20%);
- Hitachi (30%);
- Danfoss (20%);

Table 4 FC Retail prices

FC Title	Power, kW	Price, €	Options
ABB ACS880	3	967.6 €	IP 21; EMC-filter, braking chopper, LCD-screen;
	11	1 506.9 €	
	30	2 839.1 €	
	55	4 937.1 €	
	90	7 291.2 €	
Siemens Sinamics G120 + CU250	3	1 260.8 €	IP 20; EMC-filter;
	11	2 578.0 €	
	30	5 099.6 €	
	55	8 214.6 €	
	90	9 757.2 €	
Schneider Electric Altivar 71	3	830.0 €	Up to 75kW IP 21, then IP31; EMC-filter, reactor in the DC-link, LCD-screen;
	11	1 604.2 €	
	30	2 861.9 €	
	55	4 871.8 €	
	90	7 668.9 €	
Danfoss Vacon100	3	924.7 €	IP 21; LCD-screen; no EMC-filter, no braking chopper;
	11	1 836.3 €	
	30	3 544.6 €	
	55	5 754.8 €	
	90	8 128.8 €	
Eaton DG1	3	718.1 €	IP 21; EMC-filter, braking chopper, LCD-screen, reactor in the DC-link;
	11	1 327.1 €	
	30	2 673.5 €	
	55	4 162.2 €	
	90	5 274.3 €	
Emotron VFX	3	436.0 €	IP 20; EMC-filter, braking chopper;
	11	1 451.0 €	
	30	2 224.2 €	
	55	3 803.4 €	
	90	5 567.1 €	
Hyndai N700v	5.5	793.5 €	IP 00; up to 22kW there is a braking chopper; no EMC-filter, no reactor in the DC-link;
	11	919.0 €	
	30	2 392.3 €	
	55	3 338.7 €	
	90	4 856.1 €	
Invertek Optidrive P2	4	545.0 €	Up to 11kW IP20, then IP55; EMC-filter, braking chopper, LCD-screen;
	11	943.0 €	
	30	2 148.0 €	
	55	4 147.0 €	
	90	5 414.0 €	

The continuation of Table 4

FC Title	Power, kW	Price, €	Options
Mitsubishi Electric FR-A800	3.7	762.2 €	Up to 22kW IP20, from 30kW IP00; EMC-filter, braking chopper, PLC, STO function;
	11	1 482.4 €	
	30	3 423.0 €	
	55	5 677.0 €	
	90	8 641.9 €	
Omron RX	3	369.2 €	Up to 55kW IP20, from 75kW IP00; EMC-filter, in-built PLC;
	11	547.6 €	
	30	2 042.4 €	
	55	2 795.5 €	
	90	4 675.3 €	
Toshiba TOSVERT VF-AS1	3.7	909.6 €	Up to 15kW IP20, from 18,5kW IP00; EMC-filter;
	11	1 351.1 €	
	30	3 319.1 €	
	55	4 925.5 €	
	90	8 031.9 €	
Hitachi SJ-700	4	1 028.7 €	Up to 55kW IP20, from 75кВт IP00; EMC-filter, Up to 22кВт braking chopper;
	11	1 607.4 €	
	30	3 451.1 €	
	55	5 280.9 €	
	75	7 492.5 €	
VESPER EL-9011	3.7	722.6 €	IP20; (no options are available)
	11	1 158.1 €	
	30	2 411.3 €	
	55	4 006.4 €	
	93	6 445.2 €	

According to the data presented in *Table 4* the graph showing the price diversity was built. It is presented in *Figure 2.8.*

Obviously, different manufacturers and their retailers set various prices, but also the discount scale is not the same. Since companies have various price policies related to the private request it cause a certain inaccuracy of the graph. But the basic image of the retail price still can be seen in *Figure 2.8*.

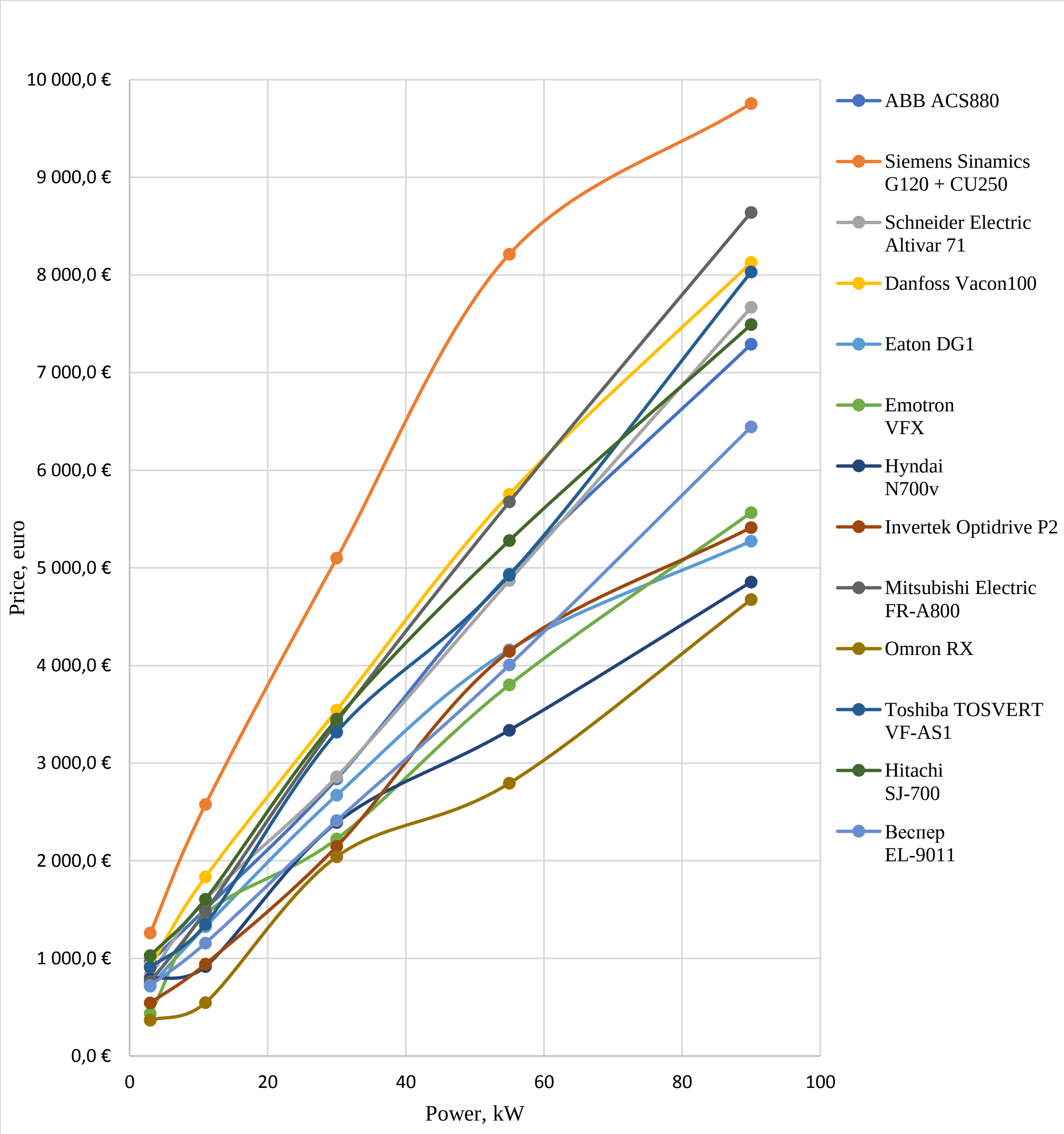


Figure 2.8. Frequency converters' prices.

For the obtained data some calculations were made: the mean value (for each FC power rate) and the deviation from it. Results are presented in *Table 5*. For each power rate the deviation from the mean value is about 20%. Considering the inaccuracy effect can be assumed even lower deviation.

Table 5. Converters average prices

Power Rate	**Mean Value**	**Deviation From The Mean Value**	**Deviation in %**
3kW	789.8	182.5	23%
11kW	1408.6	339.4	24%
30kW	2956.2	624.1	21%
55kW	4762.7	972.8	20%
90kW	6865.0	1378.1	20%

To conclude the retail price analysis, it should be mentioned that the final price for the frequency converter highly depends on the business relations with the distributor and the final decision should be made considering this point.

One more point to be considered for each manufacturer is price per kilowatt. The statistical data is shown on *Table 6*.

Table 6. Converters prices per 1 [kW]

Num.	**FC Title**	**Average price per 1 [kW]**
1	ABB ACS880	145.0 €
2	Siemens SINAMICS	216.5 €
3	Schneider Electric Altivar	138.3 €
4	Danfoss Vacon100	157.7 €
5	Eaton 9000X	116.7 €
6	Emotron VFX	96.5 €
7	Hyndai N700v	84.4 €
8	Invertek Optidrive P2	85.8 €
9	Mitsubishi Electric FR-A800	130.8 €
10	Omron RX	68.7 €
11	Toshiba TOSVERT VF-AS3	131.6 €
12	Hitachi SJ-700	142.9 €
13	VESPER EL-9011	104.6 €

Conclusions

In the chapter low voltage converters’ (< 1000 V) technical possibilities were considered using 17 different manufacturers’ products as examples. All the collected data about technical and diagnostic functions was gathered in Appendixes 1-3.

By studying technical manuals released by manufacturing companies which are available for downloading a statistical analysis was conducted. As a result, some basic functions were obtained which all modern converters have and also rare functions present just in a few FCs, but which are still useful for certain responsible applications.

The analysis was made with purpose to give an overview of modern frequency converters and to simplify the decision making process when designing the electrical drive system. A design engineer should keep in mind that the system should be optimal and should not contain useless features. Normally, that approach helps to save costs and increase the reliability of the system. The modern frequency converter can be purchased with different optional features sets.

3. EXPERIMENTAL ANALYSIS OF THE FREQUENCY CONVERTER'S BEHAVIOR.

The experimental part of the work is made with purpose to demonstrate a real frequency converter's (and drive's in general) reaction to a system malfunction and to analyze the disadvantages (or limitations) of the diagnostic functions of different manufacturers. Since the equipment for the experiment was provided by Danfoss Drives Russia, there were several limitations related to the equipment safety issues.

As long as the experiment work should be made to create emergency conditions for the drive, there is a risk of damage for the equipment. Thus, the experiment had to be conducted carefully; the laboratory equipment should not be broken. In Danfoss there is a laboratory with different frequency converter models, but access was provided just to one: Vacon NXP.

According to the FC's technical documentation, the converter is monitoring and diagnosing possible faults in the system during the operating process. The frequency converter can be programmed for a certain reaction on an external event. There are basically three types of reactions:

- tripping and showing a message containing a fault code;
- continuing operation, but showing a warning message;
- the converter does not react at all;

Obviously, the reaction must depend on the frequency converter application. In case of the drive system fault could harm human or destroy equipment, the process must be stopped. Thus, the frequency converter has to prevent the damage. But there are some cases, where a drive system fault (e.g. cable fault) should not lead to an immediate interruption of the operation process. For example, a fire extinguishing system must work as long as possible, even if one of supplying cables should be lost.

The aim of the following experiment is to demonstrate typical problems during frequency converter operation on a site, and programming methods of their prevention. Therefore, it has been decided to check the following emergency cases:

- breakage of a cable connecting the FC's output and the motor's stator terminals – the motor cable (during operation without load);

- breakage of the motor cable (during operation with load);

- breakage of a cable connecting the power supply and the FC's input – network cable (during operation without load);

- breakage of the network cable (during operation with load);

Technical Data About The Laboratory Equipment

The functional scheme of the FC-IM drive system built in the Danfoss laboratory is presented in Figure 3.1. The drive's technical parameters are shown in *Table 7*.

The provided lab's equipment has no additional filters (d*u*/d*t* filter or choke), so that the stator windings of an induction motor (IM) are connected to frequency converter output. And the FC input is connected directly to the grid via a protecting device (circuit breaker or similar) which is placed in an electrical cabinet. There is no matching transformer between the FC and the grid. Moreover, there is no further data about extra protecting equipment.

The load on the motor's shaft is obtained by using an electromagnetic break. The electrical drive control can be done by a control panel of the frequency converter or by Vacon software NCDrive. There is no speed sensor in the system. All measurements were made by frequency converter itself and all trends were recorded by the NCDrive.

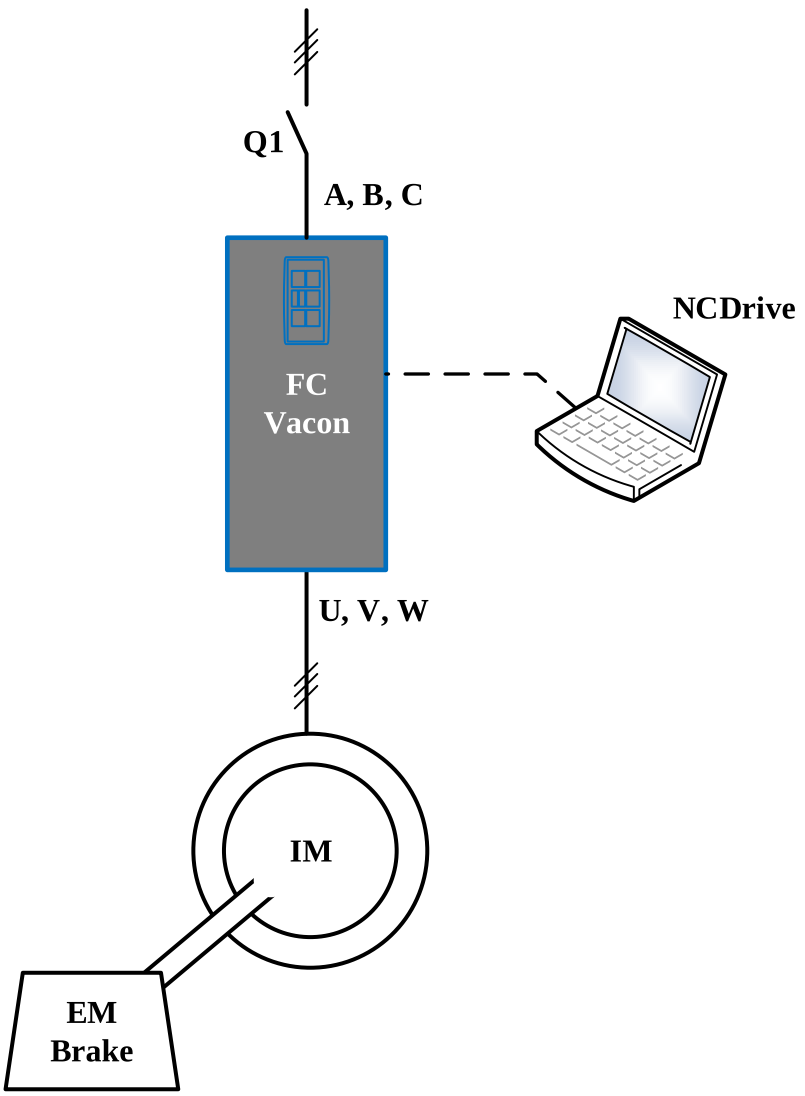


Figure 3.1. Electric drive functional diagram.

Technical parameters of the lab equipment are presented in *Table 7:*

Table 7. Drive system parameters

Num.	Parameter	Value
Parameters of the IM (ATB 212997501H0008)		
1	Rated power, P_N, kW	0.55
2	Rated line-to-line stator voltage, $U_{1\ \text{line-to-line}}$, V	380
3	Rated stator currrent, I_{1n}, A	1.7
4	Rated speed, n_n, rpm	1480
5	Rated fundamental frequency, f_1 , Hz	50
6	Power factor, cos φ_n	0.69
Parameters of the frequency converter (Type: Vacon NXP00035A2H1SSSA1A2000000)		
16	Rated power, P_n, kW	1.1
17	Rated line-to-line voltage, U_n, V	380
18	Input frequency, f_{in}, Hz	50
19	Rated current, I_n, A	3.3
Parameters of the electromagnetic break: ELFA electromagnetic powder break type P12H,		
20	Rated torque T, Nm	20
21	Supply voltage U_n, Vdc	24

The Drive Setup

The schematic of the control system is presented in *Figure 3.2.* All blocks presented in the figure are realized inside the converter’s software. During all tests the frequency converter worked in a scalar control mode. In Vacon NXP as in majority of modern FCs there are many additional features to program, but it was out of the scope of this study. A basic parametrization was made: motor data, acceleration/deceleration time, input signals, start/stop logic, etc. All basic programming and trend capturing was made in Vacon NCDrive software.

The simplified scalar system block diagram is shown in *Figure 3.2*. Just those features which were parametrized, are presented here. Below each block there is an index of a corresponding parameter.

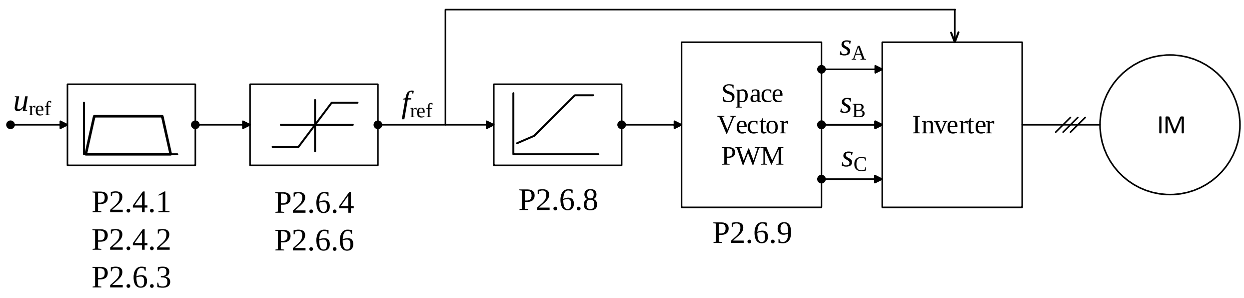


Figure 3.2. Block diagram of the scalar control (with parameters codes).

A table below shows a brief description of main control parameters. These parameters are explained to give the better understanding of the schematics in *Figure 3*.2. The main idea of these blocks is to setup a suitable *U/f* curve including its ratio, limits and other features.

Motor parameters such as voltage, frequency, current, power factor were set according to the *Table 7*, therefore, they are not included there. Also, some other minor parameters were not added to the table. They were set by default.

Parameters' settings which were used in further experiments, are shown in *Table* 8 by the grey text highlight.

Table 8. Control system parameters

Index	Parameter	Min	Max	Unit	Description
P2.4.1	Ramp 1 shape	0	10	s	Smooth ratio for S-curves
P2.4.2	Ramp 2 shape	0	10	s	
P2.6.1	Motor control mode	0	4		0: Frequency control 1: Speed control 2: Open loop torque control 3: Closed loop speed control 4: Closed loop torque control
P2.6.3	*U/f* ratio selection	0	3		0: Linear 1: Squared 2: Programmable 3: Linear with flux optimization
P2.6.4	Field weakening point	8	320	Hz	This parameter was set to 50 Hz level
P2.6.6	U/f curve midpoint frequency	0	P2.6.4	Hz	This parameter gives the middle point frequency of the curve
P2.6.8	Output voltage at zero frequency	0	40	%	This parameter gives the zero frequency voltage of the *U/f* curve
P2.6.9	Switching frequency	1	varies	kHz	This parameter was set to 3.6 kHz level
P2.7.4	Input phase supervision	0	3		0: no response 1: Warning 2: Fault, stop according to a logic 3: Fault, stop by coasting
P2.7.6	Output phase supervision	0	3		

Experiment Execution

No Load Operation Test

First of all, before conducting the experiments listed above, it is necessary to capture the drive's performance without load and fault in the system. NCDrive has a Monitoring Window, where several different signals can be recorded. It was decided to capture the stator phase currents (I_U, I_V, I_W), the RMS stator current I_{RMS} and the motor's shaft speed n. It should be mentioned, that the FC's switching frequency was set by default to 3.6 kHz, the sample interval in NCDrive was set to 100 ms.

Thus, in *Figure 3.3* the no-load drive operation at 50 Hz is presented. On the right and left sides of the graph colored scales (blue, black, green, pink, red) can be seen. Each color corresponds to a certain signal:

- blue:	*U*-phase current	I_U
- black:	shaft speed	n
- green:	stator RMS current	I_{RMS}
- pink:	*U*-phase current	I_W
- red:	*U*-phase current	I_V

Also, attention has to be paid to the zero point of each scale, every signal has its own scale with its own zero point. Time scale is looks opposite, zero is placed on the right side of the scale. In result, the no-load stator current 1.35 Amps looks reasonable compared to the rated current 1.7 Amps (see *Table 7*). During this and all following tests, all curves were recorded via RS232 cable and Vacon NCDrive.

In *Figure 3.3* the stator phase current curves' shape is uneven by a reason of drive system topology. As it is written above, the frequency converter is connected to the grid without any input filter and the matching transformer. It is not clever to use the motor in these conditions. The reason of it is that the current trend has a harmonic distortion which affects the stator flux linkage. In result, it is harmful for the motor bearings. But this topic is out of scope of this work.

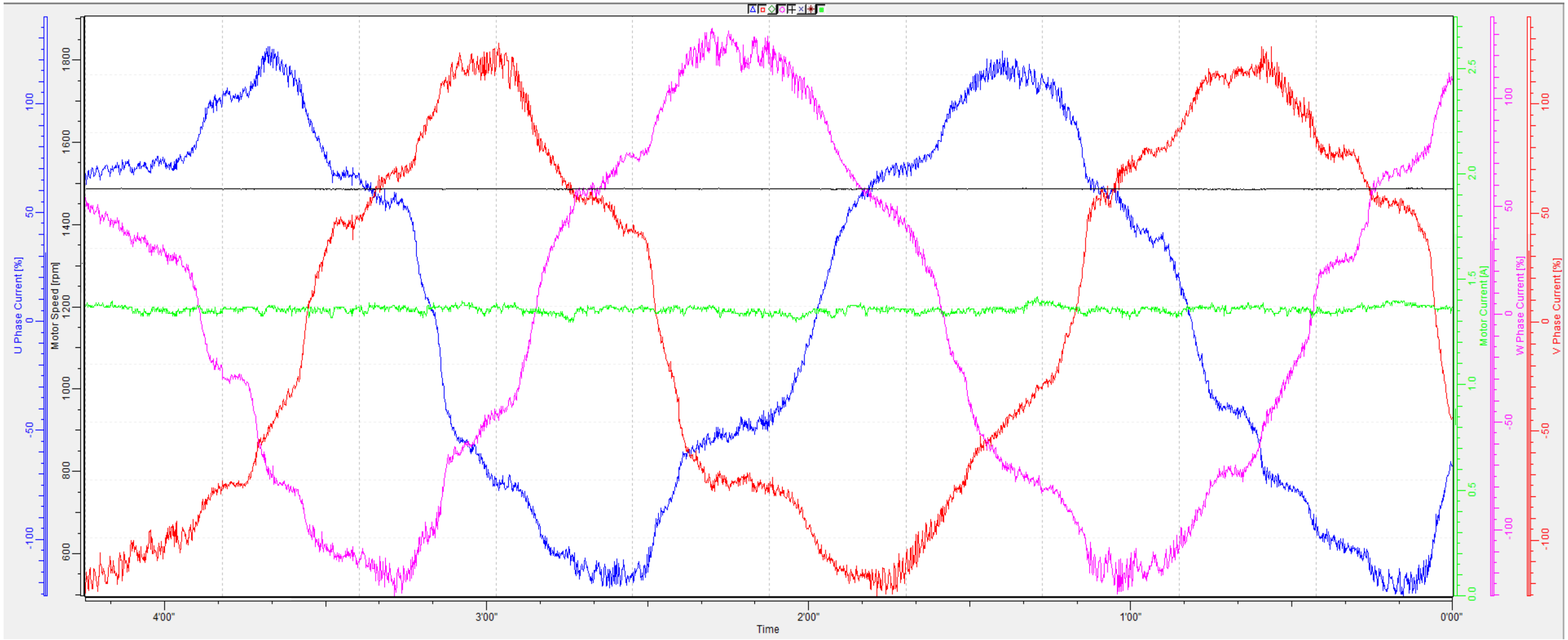


Figure 3.3. No load currents curves.

Now, all parameters of the frequency converter during its operation without a load are captured, and above-mentioned tests can be conducted.

Test 1: the breakage of the motor cable (T_{load} = 0 Nm)

For the following test an additional programming action was made. A frequency converter's reaction on the accident was set. It is parameter *P.2.7.6* which determines the converter's behavior, if the motor cable accident happens. For the test 1 and test 2 *P2.7.6* was set to 0 (no response), because it will allow the FC to continue operation and current & speed trends could be captured.

During the operation at the rated speed 1480 rpm with no load, the *W*-phase motor cable was disconnected. The drive was stopped after a few seconds. *Figure 3.4* shows the process where a reaction of the system can be seen.

Figure 3.4 should be understood in the following way. At the time equal to 35 s the cable connection failure occurs, then at the time equal 11 s (right point) the drive was stopped.

Test results.

As it can be seen in Figure 3.4 after the accident the speed slightly dropped down and started oscillate with the same frequency as the stator phase current. Moreover, one can hear a louder sound than before, which is coming from the motor side. Phase current increased a little, but is was limited by the frequency converter's software at 150 % of its rated point.

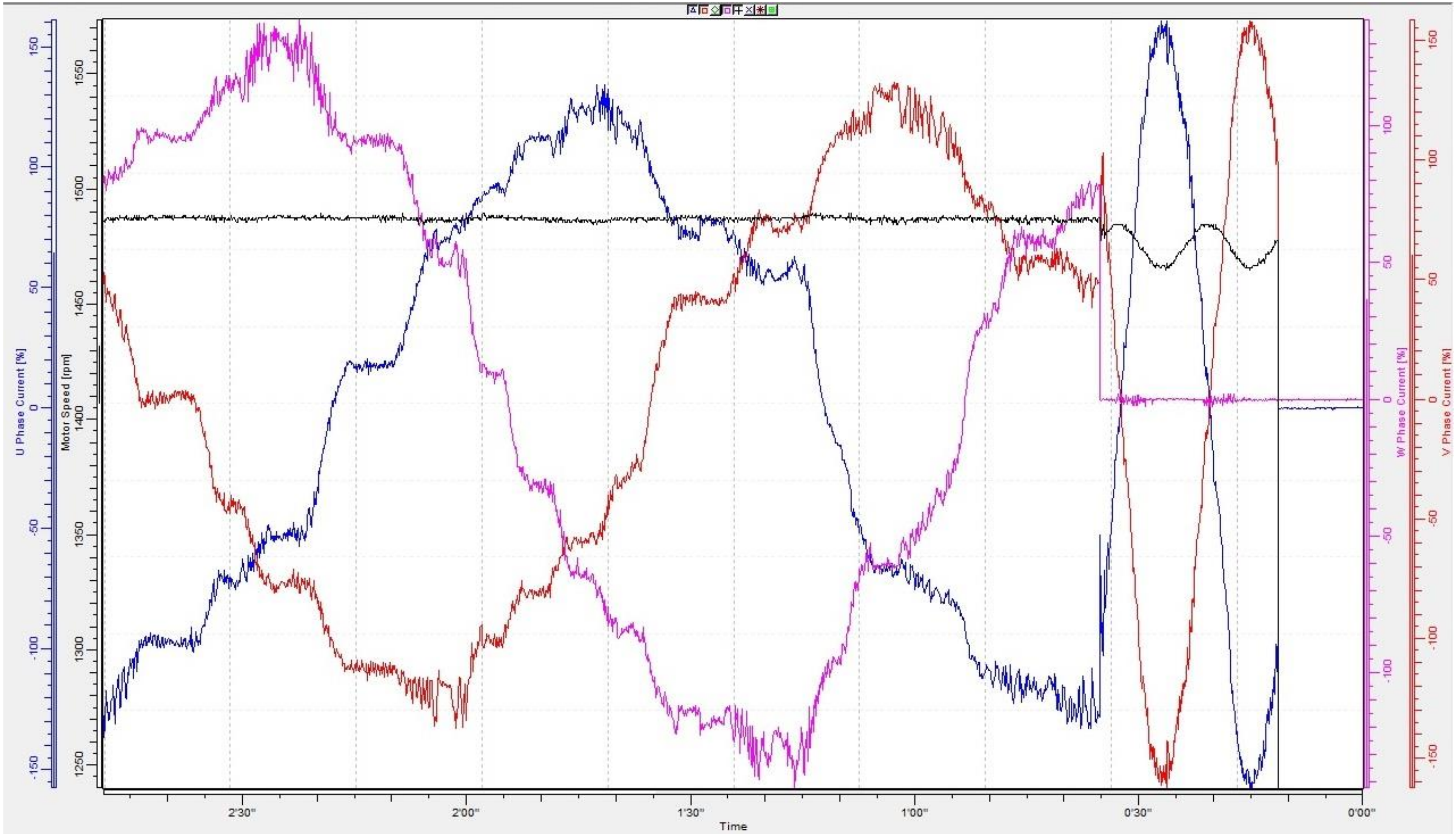


Figure 3.4. Test #1 curves.

Test 2: Breakage of motor cable (T_{load} = 0.5 Nm)

In the second test a similar action was made. While the drive was running at the rated speed 1480 rpm with a 0.5 Nm load, the *W*-phase motor cable was disconnected. The drive was stopped after a few seconds. *Figure 3.5* shows the process where a reaction of the system can be seen.

Figure 3.5 should be understood in the following way. At the time equal to 40 s the cable connection failure occurs, then at the time equal 19 s (right point) the drive was stopped.

Test results.

In *Figure 3.5* a similar frequency converter's behavior can be seen: the speed slightly dropped down and started to oscillate. Also, a sound coming from the motor was louder than during the first test. The phase current increased as before.

Motor cable fault. Conclusions

Obviously, the motor could carry on with a just two-phase supply, as it was shown during tests 1-2. But it would be still emergency conditions for it. In both tests speed oscillations which are seen in *Figure 3.4-Figure 3*.5 cause significant vibrations in the motor. This phenomenon negatively affects bearings' lifetime significantly damaging them. The second possible oscillation consequence is the overtemperature which is caused by the increased current. The temperature's rise may lead to the windings insulation fault. But those are theoretical issues, because normally the frequency converter prevents the overcurrent fault.

To conclude the above written, it should be noted, that in those frequency converters, which have advanced programming features, like different reaction settings, it is better to choose the reaction, which prevents from the emergency drive operation, if there are no special process requirements.

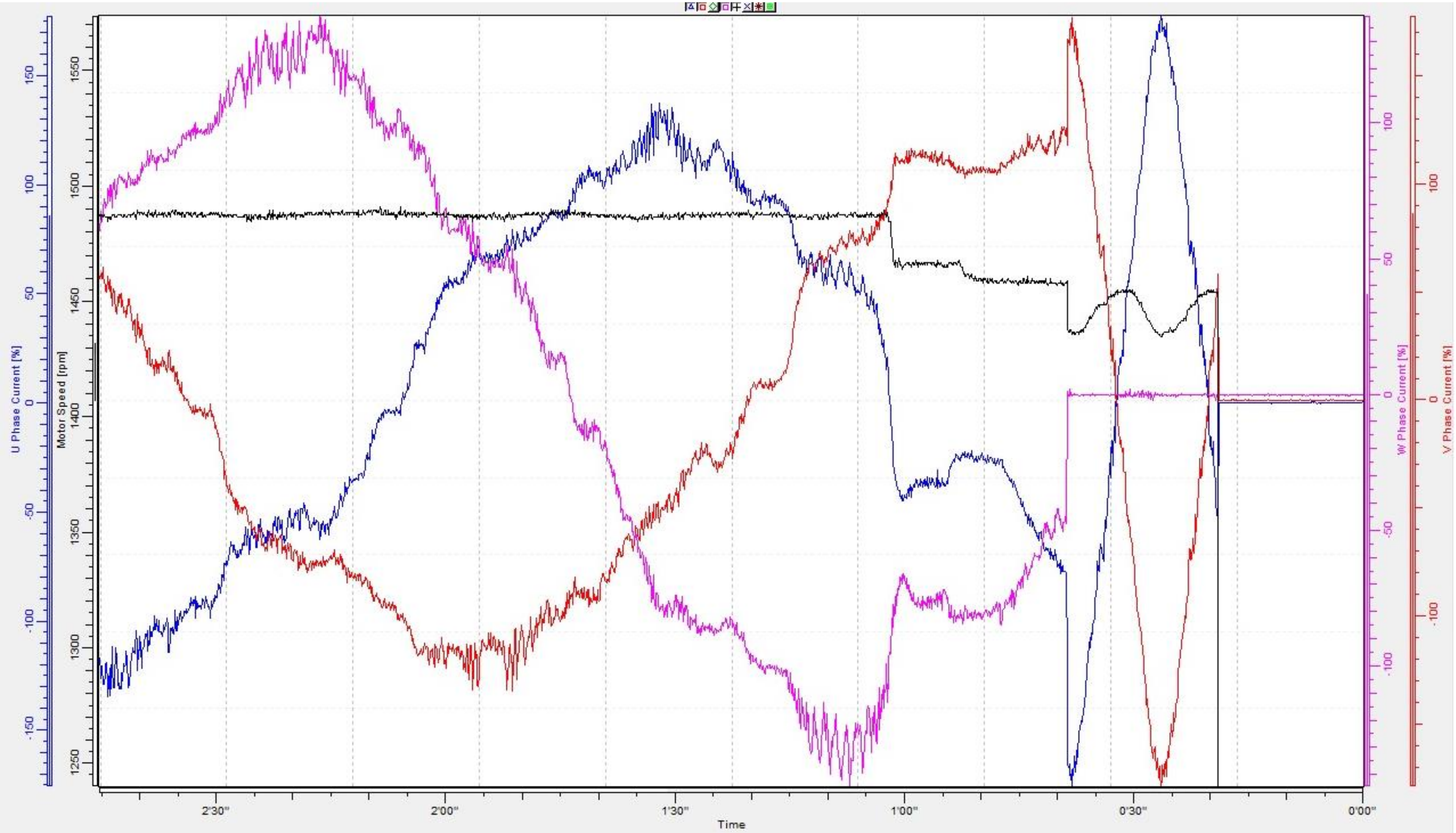


Figure 3.5. Test #2 curves.

Test 3: Breakage of network cable (T_{load} = 0 Nm)

The test introduces the experimental analysis of the network cable accident. From the theoretical point of view, the 2-phase power supply coming to the 6-pulse diode rectifier will have a similar DC voltage waveform. The line-to-line voltage will stay the same, therefore, the DC-link voltage will be close to 540V, as with the 3-phase power supply. The difference is related to the power, which reduces square root of 3 times, in case of 2-phase power supply.

In the third test, during the drive's operation at the rated speed 1480 rpm with no load, the *A*-phase network cable was disconnected. The drive was stopped after a few seconds. *Figure 3.6* shows the process where a reaction of the system can be seen. Thus, at the time equal to 60 s the cable connection failure occurs.

Test results.

When the accident occurs, one can see (*Figure 3.6*) that the stator phase current frequency increased. Nevertheless, the stator RMS current value stays same. Also, according to *Figure 3.6* there is no difference in the motor shaft speed (torque). Compare to the previous two tests, there are no hearable or visible changes in drive's operation.

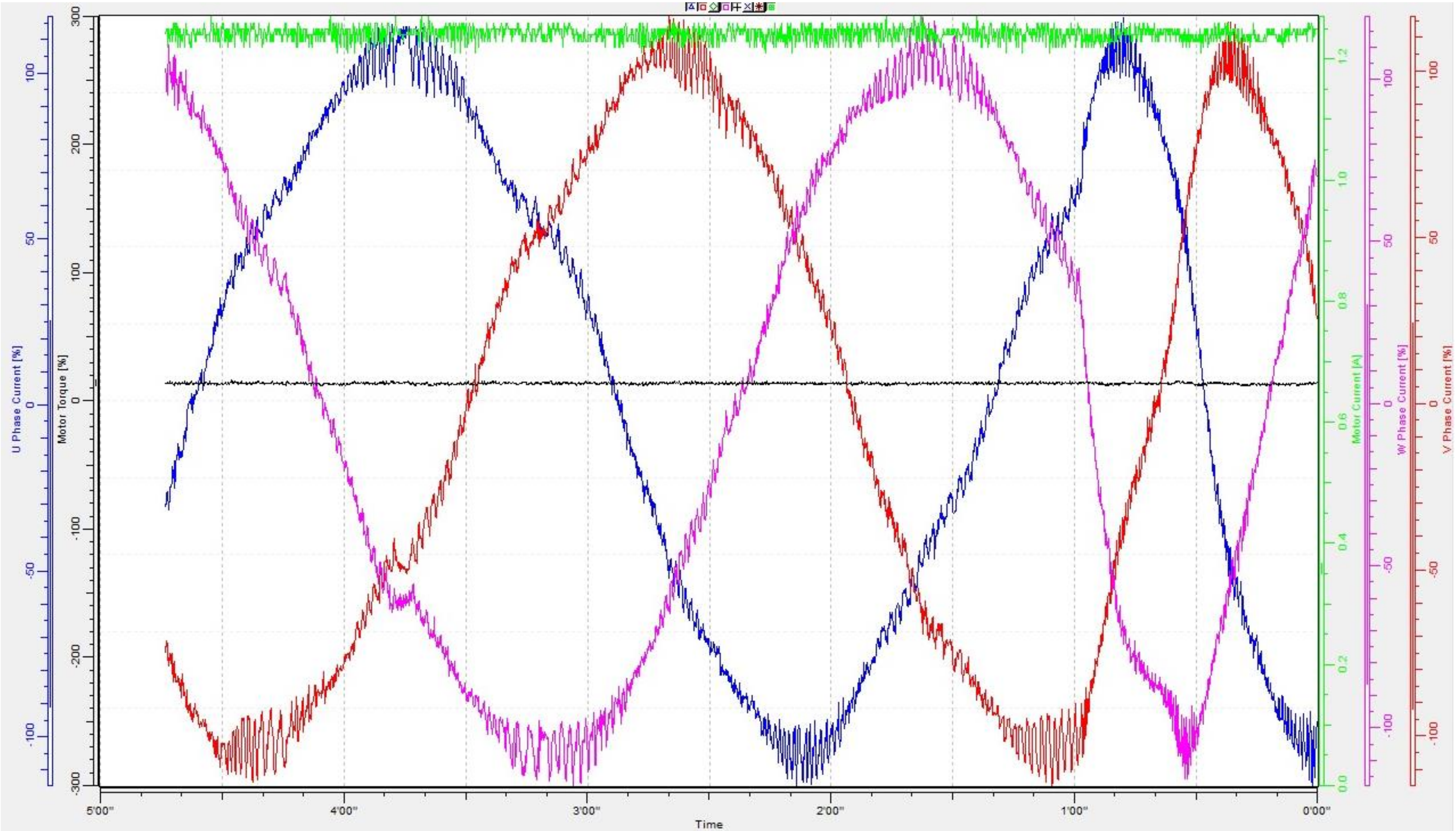


Figure 3.6. Test #3 curves.

Test 4: Breakage of network cable (T_{load} = 0.5 Nm)

A similar test was made, but in this case a load was attached to the motor. During the operation at the rated speed 1480 rpm with the load 0.5 Nm, the *W*-phase motor cable was disconnected. The drive was stopped after a few seconds. *Figure* 3.*7* shows the process where a reaction of the system can be seen. Thus, at the time equal to 48 s the cable connection failure occurs.

Test results.

Because of the load added to the motor, some principal changes happened. At this time, trends show even more increased the stator current frequency and a little decreased the RMS current value. Also, there is a small speed drop around 20 rpm.

Network cable fault. Conclusions.

The accidental disconnection of the network cable leads to the 2-phase power supply. As it was shown during tests 3-4, it does not affect directly the stator power supply.

Test 3 showed, that without any load, the stator current had the quite normal waveform, which looked like the pure sine. It means that the 2-phase supply does not affect the IGBT circuit operation. Later, during the fourth test the stronger deviation was seen. The drive has less input power available, but the same voltage in the DC-link, therefore, the RMS stator current also decreased. Thus, it is more challenging for the 2-phase supplied frequency converter to overcome the load. Meanwhile, without any load the decreased current (and power) value is enough to run the motor.

In conclusion, the 2-phase power supply causes difficulties when there is a load attached to the motor. If the load is less than its rated value and the process allows operate at the lower speed level, it will not be a problem for the converter to run the motor. One more issue should be pointed out. If the frequency converter is a bit oversized, it performs better in such emergency conditions as described above, because the motor current in % is lower compared to its own rated value.

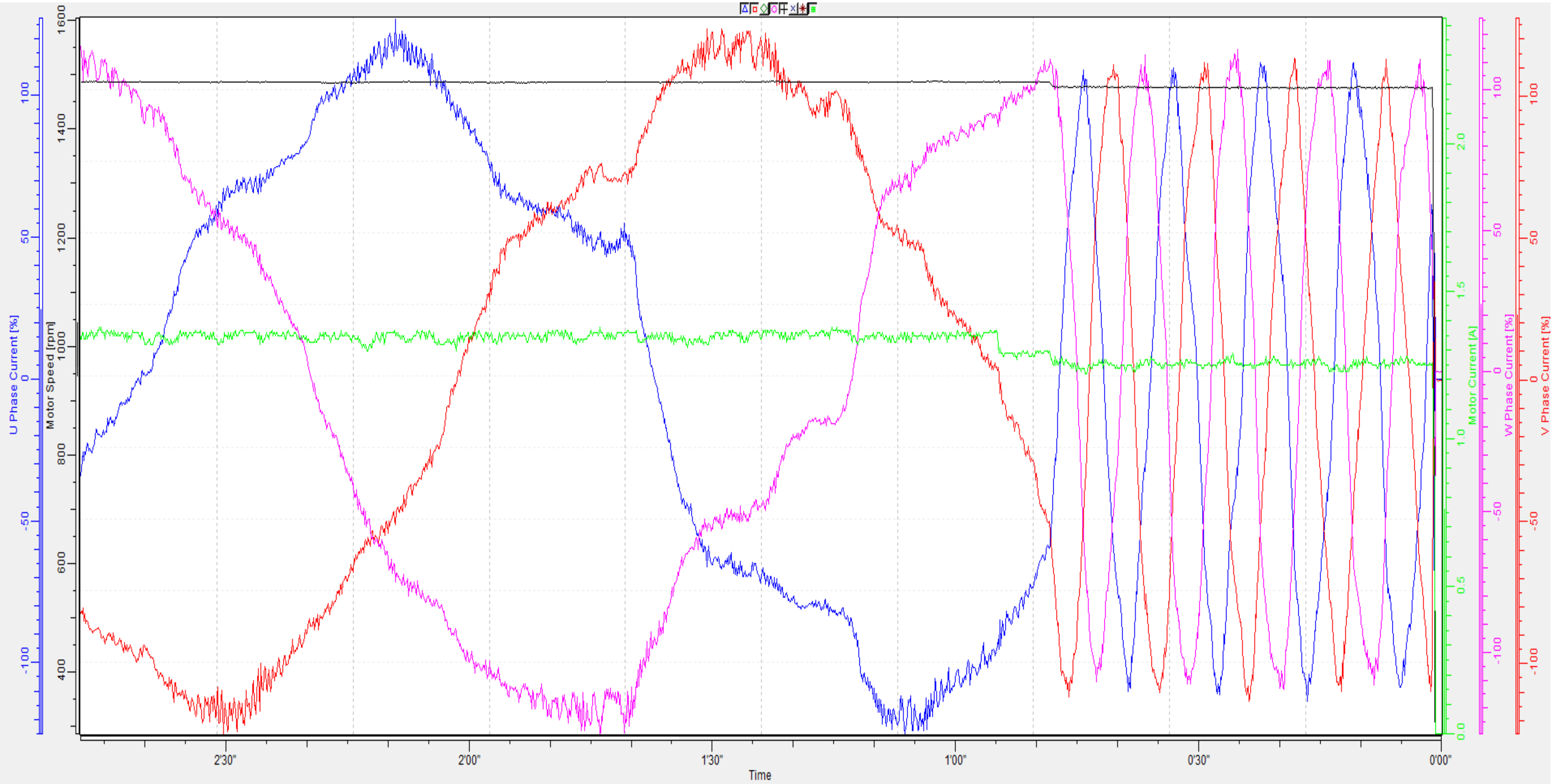


Figure 3.7. Test #4 curves.

Conclusions

These tests are aimed to show frequency converters' capabilities from the programming and from the hardware points of view. It was shown in *The Drive Setup* section that the frequency converter's reaction on emergency conditions described above could be set by changing a certain parameter via NCDrive software.

The first two tests show the drive's and converter's behavior in such an emergency case as the motor cable fault. Also, several possible consequences after the operating at emergency conditions were described.

Last two experiments present the system's behavior in the network cable accident. Captured trends show the normal operation without load, which could be suitable for low demanding drives like fans. Meanwhile, a higher load value causes difficulties for the converter. In scalar control mode it cannot provide the required speed level with the reduced input power.

In conclusion, the engineer must understand all possible drive operation conditions including emergency ones. According to the safety operation rules, it is recommended to use the input/output phase loss detection, if possible according to the process requirements. But for demanding applications, some of FC manufacturers allow commissioning engineer to program the converter's reaction for an accident. This section was made as the example, how it could be done from the practical side.

4. OVERALL CONCLUSIONS.

The goal of this work was to perform an overview of various frequency converters of different manufacturers and provide the statistical analysis. Moreover, in the work few experimental tests of several features and dynamical characteristics were conducted.

In the introduction section the theoretical explanation of the frequency converter's hardware, working principles and basic control systems was given. Later, in the second part of the paper, by using data from online sources, three structured tables with all technical and diagnostic FCs' features were presented. Under the study was the majority of drives available on the Russian market. Then, the statistical analysis was conducted based on user guides and manuals. It helps to get the understanding which inverter might be more suitable for the certain application. To give the full picture for the FC selection and rationale, retail prices were presented in the graph.

The experimental part presents the example of the converter's operation under emergency conditions. During tests it was shown how to set several parameters and adjust the drive to a required application by programming the frequency converter's reaction on an accident. It worth mention that the converter's behavior should strongly depend on the process.

The overview of quite large number of FCs of various manufacturers has the significant practical mission – to help engineers to work with that equipment. As a future prospective of this work, several professors from Moscow Power Engineering University already proposed to enlarge this frequency converters list and create an online database with all drives technical features to support electrical engineers with the actual data which might help them to match application requirements in the best way and save costs at the same time.

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Appendix 1.

Table 9. Technical features of frequency converters

Num	Name of the function	Inverter's number (according table 1)									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
f001	Programmable analog I/O	+	+	+	+	+	+	+	+	+	+
f002	Programmable digital I/O	+	+	+	+	+	+	+	+	+	+
f003	Programmable relay outputs	+	+	+	+	+	+	+	+	+	+
f004	Master/follower functionality	+		+	+				+		+
f005	Scalar control	+	+	+	+	+	+	+	+	+	+
f006	IR-compensation	+	+	+	+	+	+	+	+	+	+
f007	Direct Torque Control (DTC)	+			+	+	+		+		
f008	Sensorless vector control		+	+	+			+	+	+	+
f009	Vector control (with encoder feedback)		+	+		+		+	+	+	+
f010	Linear ramp type (acceleration/deceleration)	+		+	+	+	+	+		+	+
f011	S-ramp type (acceleration/deceleration)	+	+	+	+	+	+	+		+	+
f012	Adjustable acceleration/deceleration time	+	+	+	+	+	+	+	+	+	+
f013	JOG function	+	+	+	+	+	+	+	+	+	+
f014	Prohibit frequencies	+			+	+	+	+	+	+	+
f015	DC-magnetization (pre-heating / lock the rotor)	+		+	+					+	+
f016	Energy saving mode (flux optimization)						+		+	+	+
f017	Supporting PMSM motors	+		+	+		+			+	
f018	Macro configuration (for a specific field of application)	+		+	+	+	+			+	+
f019	PID-control macro	+	+	+	+	+	+	+	+	+	+
f020	Protection from the load loss	+	+				+				
f021	Programmable actions for an external event	+	+	+	+	+	+	+	+	+	+

Continuation of Table 9

Num	Name of the function	Inverter's number (according table 1)							
		11	12	13	14	15	16	17	
f001	Programmable analog I/O	+	+	+	+	+	+	+	
f002	Programmable digital I/O	+	+	+	+	+	+	+	
f003	Programmable relay outputs	+	+	+	+	+	+	+	
f004	Master/follower functionality		+	+	+				
f005	Scalar control	+	+	+	+	+	+	+	
f006	IR-compensation	+	+	+	+	+	+	+	
f007	Direct Torque Control (DTC)		+						
f008	Sensorless vector control	+	+	+	+	+	+	+	
f009	Vector control (with encoder feedback)		+	+	+	+	+	+	
f010	Linear ramp type (acceleration/deceleration)		+	+	+	+	+		
f011	S-ramp type (acceleration/deceleration)		+	+	+	+	+		
f012	Adjustable acceleration/deceleration time	+	+	+	+	+	+	+	
f013	JOG function	+	+	+	+	+			
f014	Prohibit frequencies	+	+	+	+	+	+		
f015	DC-magnetization (pre-heating / lock the rotor)		+	+	+		+		
f016	Energy saving mode (flux optimization)	+		+	+	+	+		
f017	Supporting PMSM motors		+	+					
f018	Macro configuration (for a specific field of application)		+	+			+	+	
f019	PID-control macro	+	+	+	+	+	+	+	
f020	Protection from the load loss			+		+			
f021	Programmable actions for an external event	+	+	+		+	+		

Continuation of Table 9

Num	Name of the function	Inverter's number (according table 1)									
		1	**2**	**3**	**1**	**5**	**6**	**1**	**8**	**9**	**1**
f022	Positioning with encoder or limit switches			+						+	+
f023	Emergency running mode				+						
f024	Limitation the parameter’s change	+	+	+	+	+	+			+	
f025	Load analyser (selection in %)	+			+	+				+	
f026	Maintenance timers and counters	+			+					+	+
f027	Energy saving calculator	+	+	+	+	+				+	+
f028	Oscillation damping	+								+	
f029	Flying start	+	+	+	+	+	+		+	+	+
f030	Safe Torque Off (STO)	+	+				+			+	
f031	Protection from rotating in opposite direction	+	+	+	+	+	+	+		+	+
f032	Adjustable automatical restart	+	+	+		+	+	+	+	+	+
f033	Software for configuring and monitoring the drive	+	+	+	+	+			+	+	+
f034	Smartphone application	+									
f035	Free function blocks	+	+	+			+				
f036	Removable control panel with memory stick	+	+	+	+	+		+	+	+	
f037	Switch to change the motor supply source to the network										+
f038	Programmable operating mode (according to the day hours)										

Continuation of Table 9

Num	Name of the function	Inverter's number (according table 1)							
		11	**12**	**13**	**14**	**15**	**16**	**17**	
f022	Positioning with encoder or limit switches				+				
f023	Emergency running mode		+						
f024	Limitation the parameter’s change	+	+	+		+		+	
f025	Load analyser (selection in %)		+	+	+			+	
f026	Maintenance timers and counters			+				+	
f027	Energy saving calculator								
f028	Oscillation damping								
f029	Flying start	+	+	+	+		+		
f030	Safe Torque Off (STO)								
f031	Protection from rotating in opposite direction	+	+	+		+	+		
f032	Adjustable automatical restart		+	+	+	+	+		
f033	Software for configuring and monitoring the drive		+	+	+		+		
f034	Smartphone application								
f035	Free function blocks								
f036	Removable control panel with memory stick	+	+	+			+	+	
f037	Switch to change the motor supply source to the network		+						
f038	Programmable operating mode (according to the day hours)						+		

<u>Appendix 2.</u>

<u>Table 10. Diagnostic functions (fatal errors)</u>

Num	**Name of the function**	**Inverter's number (according table 1)**									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
F001	Current sensor fault	+		+							
F002	Overcurrent	+	+	+	+	+	+	+	+	+	+
F003	Load unbalance (earth leakage)	+					+				
F004	Short circuit	+	+	+	+	+	+		+		
F005	Wiring of earth fault	+	+	+	+	+	+	+		+	+
F006	IGBT fault	+		+	+						+
F007	Current deviation between the IGBTs of different phases	+					+				
F008	Input phase (or cable) loss	+	+	+	+	+	+	+	+	+	+
F009	Charge switch fault	+	+	+	+	+				+	
F010	Deviation/fault of the input source		+	+	+	+	+	+		+	+
F011	DC link voltage fault	+	+		+	+	+		+	+	+
F012	Output phase loss	+	+	+	+	+				+	
F013	Autorestart fault	+	+							+	+
F014	Autophasing	+	+							+	
F015	IGBT overtemperature	+		+	+	+					+
F016	Temperature sensor fault		+	+			+			+	
F017	Power unit module overtemperature	+	+								
F018	Overtemperature in the converter	+	+	+	+	+	+	+	+	+	+
F019	Motor overload	+	+	+	+	+	+	+	+	+	+
F020	Thermistor overtemperature/fault	+		+	+	+	+	+	+	+	+
F021	Fan fault	+	+		+	+	+		+		+

Continuation of Table 10

Num	Name of the function	Inverter's number (according table 1)							
		11	**12**	**13**	**14**	**15**	**16**	**17**	
F001	Current sensor fault	+	+						
F002	Overcurrent	+	+	+	+	+	+		
F003	Load unbalance (earth leakage)		+	+	+				
F004	Short circuit		+	+		+	+	+	
F005	Wiring of earth fault			+		+		+	
F006	IGBT fault	+	+		+		+		
F007	Current deviation between the IGBTs of different phases								
F008	Input phase (or cable) loss	+	+	+	+	+	+	+	
F009	Charge switch fault					+	+	+	
F010	Deviation/fault of the input source	+	+	+	+				
F011	DC link voltage fault	+	+	+	+	+	+	+	
F012	Output phase loss	+	+	+	+	+	+	+	
F013	Autorestart fault								
F014	Autophasing						+		
F015	IGBT overtemperature	+				+	+	+	
F016	Temperature sensor fault								
F017	Power unit module overtemperature	+	+						
F018	Overtemperature in the converter	+	+	+	+	+		+	
F019	Motor overload	+	+	+	+	+			
F020	Thermistor overtemperature/fault		+	+	+		+	+	
F021	Fan fault		+	+	+			+	

Continuation of Table 10

Num	**Name of the function**	**Inverter's number (according table 1)**									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
F022	Safe Torque Off (STO) hardware failure	+			+					+	
F023	Power unit module fault	+	+	+							
F024	Internal hardware failure	+		+	+	+		+		+	+
F025	Measurement circuit ADC	+									
F026	Reduced run (inverter modules connection fault)	+									
F027	Control unit (internal failure)	+	+	+	+	+			+	+	+
F028	Communication error of some interface	+	+	+	+	+	+		+		+
F029	Memory unit failure	+	+						+	+	
F030	Parameters loading/saving error	+								+	
F031	Communication with external module failed	+	+	+	+			+	+	+	+
F032	Communication with control panel failed	+		+	+	+				+	+
F033	Motor locked		+			+	+				
F034	Motor stall	+	+		+	+	+			+	
F035	Fault/overtemperature/loss of the breaking resistor	+		+	+	+		+	+	+	+
F036	Mechanical brake failure	+		+	+		+	+		+	+
F037	PID-controller failure / feedback missing	+		+	+					+	
F038	Overspeed	+	+	+			+	+		+	+
F039	Encoder failure	+		+		+	+		+	+	+
F040	Load feedback loss	+		+	+						
F041	Stop failed	+		+	+						
F042	Overfrequency	+									

Continuation of Table 10

Num	**Name of the function**	**Inverter's number (according table 1)**							
		11	**12**	**13**	**14**	**15**	**16**	**17**	
F022	Safe Torque Off (STO) hardware failure		+						
F023	Power unit module fault			+	+				
F024	Internal hardware failure		+	+	+			+	
F025	Measurement circuit ADC			+		+			
F026	Reduced run (inverter modules connection fault)								
F027	Control unit (internal failure)			+	+	+		+	
F028	Communication error of some interface		+	+	+		+	+	
F029	Memory unit failure			+					
F030	Parameters loading/saving error	+	+	+				+	
F031	Communication with external module failed	+	+	+		+		+	
F032	Communication with control panel failed		+	+		+			
F033	Motor locked		+					+	
F034	Motor stall		+	+				+	
F035	Fault/overtemperature/loss of the breaking resistor	+	+	+	+	+	+	+	
F036	Mechanical brake failure	+	+		+				
F037	PID-controller failure / feedback missing	+		+		+			
F038	Overspeed		+	+		+			
F039	Encoder failure			+		+		+	
F040	Load feedback loss			+					
F041	Stop failed		+	+					
F042	Overfrequency						+		

Continuation of Table 10

Num	Name of the function	Inverter's number (according table 1)									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
F043	Communication between drive's modules lost	+	+	+	+					+	+
F044	Rectifier failure/overtemperature	+	+	+			+				
F045	Analog signal fault/deviation	+	+	+	+	+			+	+	
F046	Digital signal fault/deviation	+	+	+	+	+	+				
F047	Motor ID was not completed	+		+	+				+		
F048	Follower drive has tripped	+									
F049	Flying start failure		+								+
F050	Generating power exceeded its boundary		+				+	+		+	
F051	Too high/low torque		+	+	+	+	+		+		+
F052	Output contactor stucked			+							
F053	Under/over-temperature of the air (surrounding drive)				+				+		
F054	Clock failure				+						
F055	Simultaneously pressed both buttons for «front» and «back» rotation										

<u>Continuation of Table 10</u>

Num	Name of the function	Inverter's number (according table 1)							
		11	12	13	14	15	16	17	
F043	Communication between drive's modules lost	+	+	+				+	
F044	Rectifier failure/overtemperature						+		
F045	Analog signal fault/deviation		+				+	+	
F046	Digital signal fault/deviation								
F047	Motor ID was not completed	+	+	+		+			
F048	Follower drive has tripped								
F049	Flying start failure								
F050	Generating power exceeded its boundary	+	+	+	+	+		+	
F051	Too high/low torque		+	+	+	+		+	
F052	Output contactor sticked								
F053	Under/over-temperature of the air (surrounding drive)							+	
F054	Clock failure			+		+			
F055	Simultaneously pressed both buttons for «front» and «back» rotation					+			

Appendix 3.

Table 11. Diagnostic functions (warning messages)

Num	**Name of the function**	**Inverter's number (according table 1)**									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A01	Current sensor fault	+									
A02	Overcurrent	+	+	+			+	+		+	
A03	Load unbalance (earth leakage)	+				+					
A04	Short circuit	+						+			
A05	IGBT fault	+		+							
A06	Input phase (or cable) loss					+		+			
A07	Charging in process	+									
A08	Deviation/fault of the input source			+		+		+		+	
A09	DC link voltage fault	+	+	+		+	+	+			
A10	Output phase deviation			+		+					
A11	Autophasing will be processing	+									
A12	Motor ID in process	+									
A13	IGBT overtemperature	+		+							
A14	Temperature sensor fault	+	+								
A15	Power unit module overtemperature	+									
A16	Overload of the converter		+								
A17	Overtemperature in the converter	+	+	+				+			+
A18	Motor overtemperature	+	+	+	+	+	+	+		+	
A19	Deviation from user's load curve	+		+							
A20	Thermistor overtemperature/fault	+		+		+					
A21	Fan fault	+	+							+	

Continuation of Table 11

Num	Name of the function	Inverter's number (according table 1)							
		11	12	13	14	15	16	17	
A01	Current sensor fault								
A02	Overcurrent		+	+					
A03	Load unbalance (earth leakage)							+	
A04	Short circuit								
A05	IGBT fault								
A06	Input phase (or cable) loss							+	
A07	Charging in process								
A08	Deviation/fault of the input source		+	+					
A09	DC link voltage fault			+				+	
A10	Output phase deviation			+				+	
A11	Autophasing will be processing								
A12	Motor ID in process								
A13	IGBT overtemperature								
A14	Temperature sensor fault								
A15	Power unit module overtemperature								
A16	Overload of the converter			+					
A17	Overtemperature in the converter		+						
A18	Motor overtemperature		+	+				+	
A19	Deviation from user's load curve								
A20	Thermistor overtemperature/fault			+				+	
A21	Fan fault			+					

Continuation of Table 11

Num	**Name of the function**	**Inverter's number (according table 1)**									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A22	Safe Torque Off (STO) hardware failure	+	+		+		+			+	
A23	Power unit module fault	+									
A24	Internal hardware failure	+	+	+							
A25	Measurement circuit ADC	+									
A26	Adding/removing the extention module		+			+					
A27	Communication error of some interface	+	+	+	+		+				
A28	Communication with external module failed	+	+	+	+						
A29	Communication with control panel failed	+									
A30	Fault/overtemperature/loss of the breaking resistor	+		+						+	
A31	Mechanical brake failure	+					+	+			
A32	PID-controller failure / feedback missing	+						+			
A33	Speed deviation		+					+		+	+
A34	Encoder failure	+									
A35	Autorestart is active		+								
A36	Stop failed			+						+	
A37	Communication between drive's modules lost	+	+	+	+						
A38	Analog signal fault/deviation	+		+	+	+					
A39	Motor ID was completed with errors	+	+	+							
A40	Output contactor failure			+							
A41	Generating power exceeded its boundary			+							
A42	DC braking is active		+								

Continuation of Table 11

Num	Name of the function	Inverter's number (according table 1)						
		11	**12**	**13**	**14**	**15**	**16**	**17**
A22	Safe Torque Off (STO) hardware failure		+					
A23	Power unit module fault							
A24	Internal hardware failure			+				+
A25	Measurement circuit ADC							
A26	Adding/removing the extention module							+
A27	Communication error of some interface		+	+				
A28	Communication with external module failed			+				
A29	Communication with control panel failed		+					
A30	Fault/overtemperature/loss of the breaking resistor			+				+
A31	Mechanical brake failure		+					
A32	PID-controller failure / feedback missing			+				
A33	Speed deviation			+				
A34	Encoder failure							
A35	Autorestart is active							
A36	Stop failed							
A37	Communication between drive's modules lost		+	+				
A38	Analog signal fault/deviation		+					+
A39	Motor ID was completed with errors		+	+				
A40	Output contactor failure							
A41	Generating power exceeded its boundary							
A42	DC braking is active		+					

Continuation of Table 11

Num	Name of the function	Inverter's number (according table 1)									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A43	Motor stall is probable	+			+					+	
A44	Too high/low torque		+	+	+	+		+			
A45	Motor locking is highly probable					+					
A46	Drive has stopped after external signal	+								+	
A47	Warning: bearing ran-out	+									
A48	Warning: drive's on-time timer	+	+					+		+	
A49	Warning: device cleaning	+									
A50	Warning: fan's on-time timer	+									
A51	Warning: DC link capacitor's on-time timer	+									
A52	Warning: switches' on-time timer										
A53	External programmable warning	+	+	+	+	+	+				

Continuation of Table 11

Num	Name of the function	Inverter's number (according table 1)							
		11	**12**	**13**	**14**	**15**	**16**	**17**	
A43	Motor stall is probable								
A44	Too high/low torque			+				+	
A45	Motor locking is highly probable							+	
A46	Drive has stopped after external signal		+	+					
A47	Warning: bearing ran-out								
A48	Warning: drive's on-time timer								
A49	Warning: device cleaning								
A50	Warning: fan's on-time timer			+					
A51	Warning: DC link capacitor's on-time timer			+					
A52	Warning: switches' on-time timer			+					
A53	External programmable warning								