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Start-up of large-power synchronous motor with the 6 kV voltage source inverter and microprocessor-controlled unit for excitation supply

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The paper presents idea and practical implementation of a medium voltage synchronous drive with a voltage source inverter in the stator circuit and a microprocessor controlled unit for excitation supply. Construction of both devices was presented, and methods of their cooperation were described. Selected start-up methods of large power synchronous motors were presented. Exemplary realization was discussed. Measurement results of the direct full-voltage start-up and frequency start-up of a real 1.25 MW 6 kV fan drive system were compared and discussed.

K e y w o r d s: synchronous motor, start-up methods, voltage source inverter, variable-frequency drive, excitation control

1 Introduction

Low-speed synchronous motors designed as salient-pole are used in drive systems of fans, pumps, compressors, *etc*. In the mining sector they are used, among others, for main ventilation fan systems in underground parts of coal mines.

Due to the weight of the fan rotor of up to a few dozen tons and a diameter of up to 9 m, this drive type is characterized by a high moment of inertia, which is about 10 times higher than the moment of inertia of the motor rotor [1]. The start-up of such a drive system is considered to be difficult due to the large power of the engine and a high moment of inertia.

Improper commissioning procedure can lead to the motor work at a speed lower than the synchronous speed, a long-term operation with a current greater than the rated current, rotational speed oscillation, electromagnetic torque pulsation, considerable mechanical overload on the motor shaft, and accelerated wear of bearings. After an unsuccessful start-up, due to the long-time of the coast-down, another attempt is possible, often after over a dozen or several dozen minutes. It should also be taken into consideration that the inrush current exceeds several times the nominal current, which causes significant heating of the motor windings. It is therefore necessary to limit the number of start-up attempts at a specific time interval. Given the above, the start-up of synchronous motors driving mine ventilation fans is one of the basic issues of operation in the mining industry.

Thanks to the dissemination of modular multilevel converters for medium voltage in recent years [2-10] it is possible to mitigate the start-up effects of large power motors [11-16].

The article presents a comparison of direct full voltage and the inverter start-up test results of large power motor used to drive the main ventilation fans operating in one of coal mines in Poland.

2 Large power AC motors start-up methods

Start-up of large power AC motors, including synchronous motors, carried out by various methods. The simplest method of starting is the direct full-voltage asynchronous start-up. It involves the direct connection of the motor to the power grid [11-14, 17, 18]. The disadvantage of this method is the fact that the high start-up inrush current causes voltage drops in the power supply grid. The voltage drop in the power supply grid causes the engine starting torque reduction in proportion to the square of the voltage.

The impact of the inrush current on voltage drops in the power supply grid can be limited by starting the motor with an additional capacitor in the supply circuit [11, 12, 14, 15]. The capacitor is the source of reactive current drawn by the motor. In this way it relieves the supply grid from the flow of such current. After reaching the appropriate rotation speed the capacitor is switched off. Capacitor circuits are able to compensate approximately half of the voltage drop caused by the motor inrush current.

In order to limit the impact of the inrush current on the power supply grid the stator starter in the form of a start-up reactor is also used [11, 12, 14, 15, 17, 18]. As a result of the reactor impedance, put in series with the stator windings, the inrush current of the motor is reduced, and the motor voltage is reduced by the reactor voltage drop. In the final stage of the start-up inrush current decreases, motor voltage and motor torque increase. At a speed close to the synchronous speed the reactor is short-circuited.

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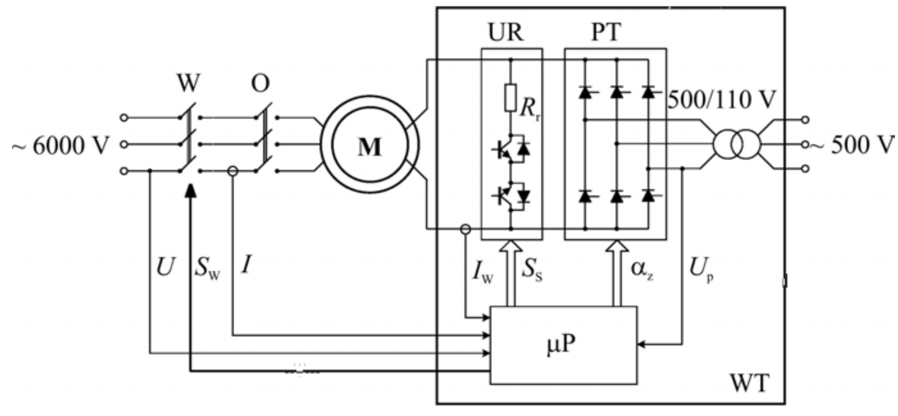

Fig. 1. Scheme of motor with ProgressPOWER microprocessor-controlled unit for excitation

Mitigation of the start-up effects by reducing the motor supply voltage is also performed by Korndorfer autotransformer system [11, 12, 14, 15, 17]. The motor takes the inrush current proportionally to the voltage reduced by the autotransformer. The current on the primary side of the autotransformer is dependent on the square of the ratio of the autotransformer. In the initial start-up phase the motor is supplied with reduced voltage by the autotransformer. In the next step, the autotransformer is opened, and part of its windings operates as a starting reactor. After reaching the proper speed the motor is switched to full voltage supply.

Another method to start-up is a partial stator winding supply, which is possible in machines with sectional windings. During the start-up part of the stator windings are supplied, and the other windings are in an open state or connected to the capacitors. The values of the inrush current and starting torque are reduced approximately in proportion to the number of supplied parallel branches of the stator windings [19]. After reaching the proper speed the windings are switched and full voltage is given to the stator winding.

The machines with the appropriate structure (two-speed motors with switchable windings), can be started-up by changing the number of pole pairs [1, 17]. Depending on the configuration of stator windings connection, there can be obtained a different number of pole pairs and different winding impedance which determines the inrush current. Start-up of the motor is held at a high impedance for the lower number of pole pairs of the magnetic field. After exceeding the rated synchronous speed, the motor is switched to a greater number of pole pairs. Synchronization is done from the over synchronous speed and with the current slightly higher than nominal.

Soft start is possible in drive systems with variable frequency power supply [11-16]. Systems based on inverters supplying the stator windings with appropriate control, e.g. constant volts per hertz (V/Hz) method, are able to execute start-up procedure with low inrush currents and slight drops in mains voltage. In the case of synchronous motors the added advantage is maintaining the synchronous state during the whole start-up process. It eliminates the need to synchronize the motors from the speed lower than the synchronous speed.

3 Microprocessor-controlled unit for synchronous motor excitation

Figure 1 shows a scheme of the ProgressPOWER microprocessor controlled excitation unit for synchronous motor [20].

The device developed in cooperation with the author is intended to supply the excitation of synchronous motors with continuous current up to 400 A. It allows to perform the direct asynchronous full voltage or a reactor start-up procedure [18]. The control of breakers in a 6 kV circuit and a thyristor rectifier in excitation circuit is performed by the microprocessor system. Autonomous operation mode or external master control mode is available. Reactive power or excitation current follow-up adjustment during the synchronous operation of the motor is also possible.

In autonomous mode, asynchronous start-up of a synchronous motor is done by switching-on the supply voltage to the stator without forcing the current in the excitation circuit. To prevent high voltage induced on the terminals of the excitation circuit at the start-up, the field winding is attached to the start-up resistor. For switching on and off the start-up resistor in the excitation circuit, in place of the commonly used contactor, transistors are used in a configuration which allows the flow of bidirectional current induced in the winding during asynchronous start-up of the motor [20]. As the motor reaches a speed close to the synchronous speed, when current induced in excitation winding is small and of low frequency, the supply of the excitation is switched-on [21].

After supplying the excitation circuit of DC current the microprocessor controls its value, and after exceeding the value pre-set by parameter turns off the start-up circuit transistors and disconnects the start-up resistor. The final stage of the start-up process is field forcing procedure which allows to reliably pull in the rotor for synchronous operation.

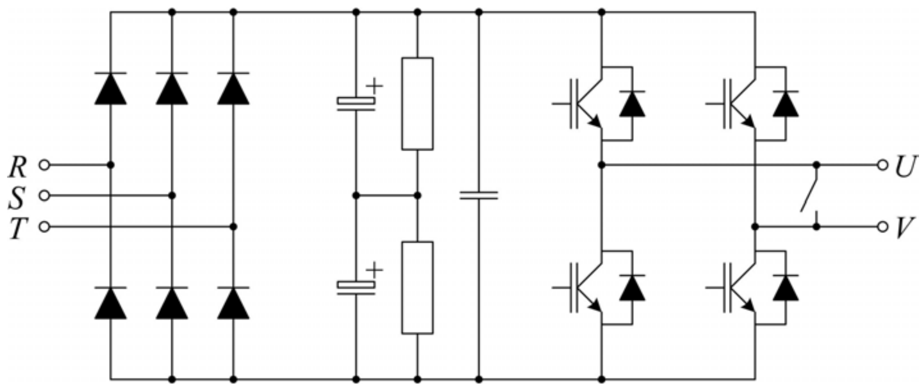

Fig. 2. Scheme of a single power cell [22, 23]

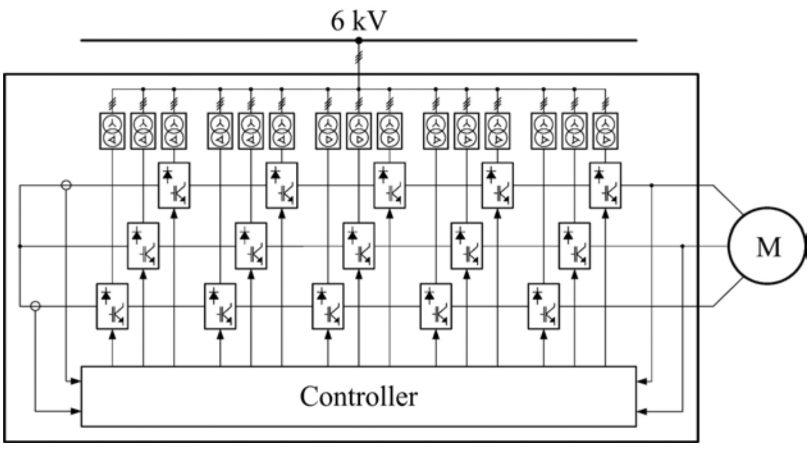

Fig. 3. Block diagram of converter for 6 kV supply voltage [22, 23]

Turning off the current in the excitation winding is performed by actuating thyristor rectifier to the inverter operation. This allows to quickly discharge energy of the excitation winding by returning it to the grid without the start-up resistor load [21]. Re-connection of the resistor, in order to prepare the drive for the re-start, is done after the field current completely off.

4 Voltage inverter for vfd

One of the producers of inverters designed for VFD is a Chinese company Harvest, which is currently part of Schneider Electric. The HARVEST series VFD devices are designed for voltages in the range of 3-13.8 kV, power in the range of 280-8000 kW and current in the range of 25-800 A [22, 23].

Converters are based on the modular construction [9, 24]. A scheme of a single power cell with a diode rectifier and voltage inverter based on the IGBT transistors [22, 23] is shown in Fig. 2. The power cell includes a three-phase 6-pulse rectifier and two-level voltage inverter.

The complete converter consists of an appropriate number of cascade-connected power cells [3-5, 8] with possibility to automatic bypass of defective cell.

Each power cell is supplied from a separate transformer block with an appropriate transformer vector group to ensure proper phase shift of voltage [4, 5].

Depending on voltage the device is composed of 12 (3 kV) to 33 (13.8 kV) power cells. The device is controlled by a microprocessor system. Fig. 3 shows a block diagram of the converter for 6 kV supply voltage [22, 23].

The use of multiple power blocks in each phase of the inverter allows to construct the multi-level inverter. The multi-level inverter, through appropriate control of the PWM signal [2-10], allows to obtain output current with a harmonic content below 2.5%.

The configuration shown in Fig. 3 corresponds to the 30-pulse rectifier and 11-level voltage inverter by overlapping 5 grade PWM waveforms.

Rectifiers of power cells can be made in the form of a diode or transistor rectifiers, which enables operation with energy return to the grid.

The HARSVERT converters can be used in power supply systems of asynchronous or synchronous motors. Control can be implemented by the constant volts per hertz method or vector control [2, 5, 8, 24-27]. Table 1 shows the rated data of HARSVERT-S06 converter for synchronous motors drives.

Table 1. Rated data of HARSVERT-S06/130 converter

Parameter	Value
Nominal power	1250 kW
Input current THD	< 3 %
Input power factor	0.95
Output voltage	6000 V
Output frequency	0.5 – 120 Hz
Output current	130 A
Output current THD	< 2.5 %
Frequency resolution	0.01 Hz
Torque pulsation	< 0.1 %
Efficiency	> 96 %

The start-up procedure of a synchronous motor with a frequency converter is different from the asynchronous start-up.

During synchronous motor frequency start-up, the angle between the vector of stator voltage and the starting position of the rotor pole should be within a certain acceptable range. In the initial moment of start-up, this angle is unknown and should be set by an appropriate synchronization.

At the first start-up phase the excitation current control device force a current in the excitation winding, which builds a magnetic field in the rotor. Next, the frequency converter supplies the motor winding armature of DC voltage forcing DC stator current flow. This current builds a strong magnetic field on the stator of the motor.

The rotor starts to rotate due to the electromagnetic force between the rotor and stator. The direction of rotation may be the same as the direction of rotation during normal operation or can be reversed.

After stabilizing the rotor position relative to the stator field the inverter starts rotating which generates magnetic field in the stator windings rotated at low speed in the direction of the normal operation of the motor drive. Rotor pole is pulled by stator pole.

After several oscillations with slight damping caused by the inertia of the rotor, the angle between the rotor and stator pole is fixed. At this moment, the motor is entering the synchronous speed operation state.

After the synchronization is complete the frequency converter controls the output voltage of the inverter based on a pre-set acceleration and volts per hertz characteristic gradually increasing the frequency to the desired value.

The above procedure is performed by a microprocessor system, which controls the start-up process of the HARSVERT inverter.

5 Cooperation of the excitation supplying device and frequency inverter in the stator circuit

Figure 4 shows a block diagram of power and control system of synchronous motor with microprocessor controlled excitation unit and voltage inverter in the stator circuit. Cooperation between the excitation control device and converter in the stator circuit is performed by a group of analogue and digital signals indicated in Fig. 4 with symbol S_c.

The start-up procedure is initiated by the excitation control device, which switches on the breaker in the 6 kV switching station. The appearance of the supply voltage causes notification from the inverter to the excitation device through the "ready" digital signal.

The excitation device sends a start signal to the inverter. The inverter starts to operate, confirming this by the proper digital signal, and activates the signal to start the operation of thyristor rectifier in the excitation supply circuit. The operation of the excitation current forcing device is confirmed to the inverter. The inverter announces to the analogue input of the excitation device the field current that must be produced by the thyristor rectifier.

Similarly, the excitation device informs the inverter about the present field current value. The inverter, on the basis of this signal, determines whether the excitation current has reached the minimum value required for start-up. Next, the inverter forces the current in the motor stator windings, which sets the rotor position in synchronous relation to the stator field.

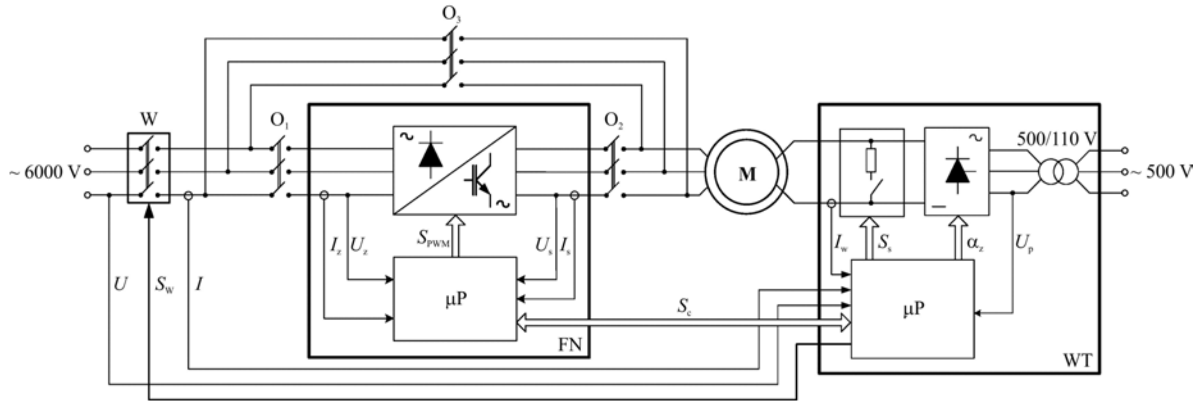

Fig. 4. Block diagram of the system: M synchronous motor, WT ProgressPOWER device for excitation, FN HARSVERT frequency converter

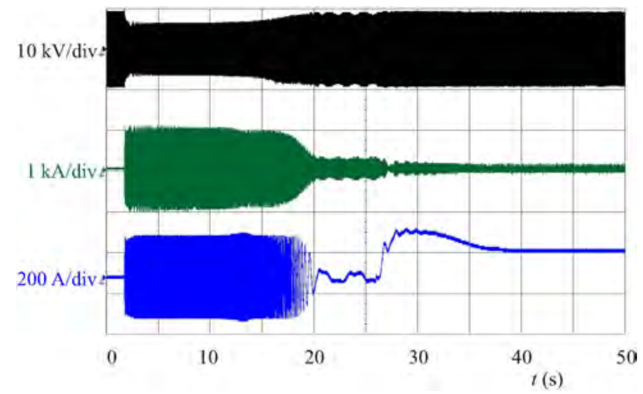

Fig. 5. Measured waveforms during direct full-voltage start-up: 1-current of excitation circuit, 2-stator current, 3-voltage at the power switching station supplying the motor

The inverter goes into operation, confirms this by sending digital signal to the excitation device and controls the set value of field current, increasing simultaneously the frequency of the voltage supplying the stator of the motor. After reaching the desired frequency the inverter sends to the excitation device a signal indicating the end of the start-up procedure. Then the inverter starts to measure the power factor of the motor and sends to the excitation device the field current set value signal so, as to achieve the power factor close to 1.

Drive stoppage procedure is initiated by the excitation device by sending a stop signal to the inverter. The inverter reduces the frequency until the motor stops. Next, the supply voltage from the stator is turned off and the set value of field current is reduced to a value close to zero. After the motor has stopped the inverter sends a digital signal to the exciter. The excitation device switches off the 6 kV breaker and executes the procedure for discharging the energy remaining in the excitation circuit.

6 Industrial implementation

The presented concept of cooperation of the microprocessor-controlled excitation unit for synchronous motor with voltage inverter in the stator has been realized with the participation of the author with the JJA Progress and OPA-ROW companies, using the drive systems of the main ventilation fans in one of the coal mines in Poland.

To drive the WPK 3.3 type fan the synchronous motor GAe1510t/01 type was used. Rated data of WPK 3.3 fan is presented in Table 2, and rated data of GAe1510t/01 motor is presented in Table 3.

Table 2. Rated data of WPK 3.3 fan

Outer blade diameter	3.3 m
Weight	21705 kg

Table 3. Rated data of GAe1510t/01 synchronous motor

Excitation voltage	77 V
Field current	230 A
Frequency	50 Hz
Rotation speed	600 rpm
Power factor	0.9
Rotor weight	3980 kg

Frequency converter configuration shown in Fig. 3 with the volts per hertz control implementation was applied. Figs. 5 and 6 show the measured waveforms during the direct asynchronous start-up of the motor without an inverter in the stator. The motor was powered from 6 kV, 36.8 MVA short-circuit power switching station. The start-up was carried out by a microprocessor-controlled excitation unit.

During the asynchronous start-up of the synchronous motor, the rotating armature field induces voltage and current flow in the rotor winding shorted by start-up resistor. Frequency of this voltage depends on the slip and decreases with increasing speed, which can be seen in Fig. 5.

Registered by excitation device, atypical waveform of excitation current in the initial phase of motor start-up

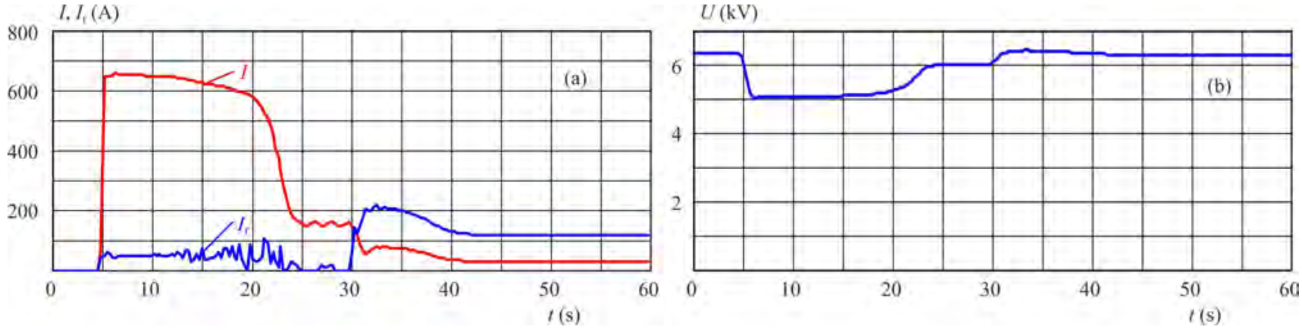

Fig. 6. Measured rms waveforms registered by the microprocessor of excitation device during direct full-voltage start-up: I_f-current of excitation circuit, I-stator current, U-voltage at the power switching station supplying the motor

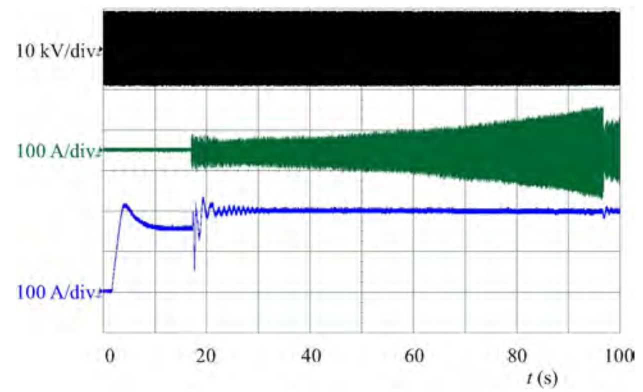

Fig. 7. Measured waveforms during start-up with a voltage inverter: 1-current of excitation circuit, 2-current in the switch bay supplying the inverter, 3-voltage at the power switching station supplying the motor

shown in Fig. 6 is caused by use of unidirectional LEM type current converter and caused by signal sampling period for measurement procedure of the microprocessor system.

Direct full voltage motor start-up causes a significant inrush current, repeatedly exceeding the rated value. Impedance of the power supply grid limits to some extent the inrush current. However, this results in the voltage drop on the switching station that supplies the engine, which can be seen in the presented measured waveforms.

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Start-up time from the moment of switching on the stator power supply to the moment of obtaining speed close to synchronous speed was 21 seconds, and the time needed to obtain a stable synchronous state was 28 seconds with 3 seconds procedure of field current forcing.

Figure 7 and 8 show the start-up process with use of the frequency inverter in stator circuit. There may be noticed the process of rotor magnetic field creation by the excitation current, the initial synchronization as the excitation current oscillations, the real start-up process as the stator current increasing, and the end of the motor shaft acceleration at the moment of stator current reduction.

Decreasing the motor supply voltage during start-up results in reduced starting torque, which increases the start-up time. In the presented case, the entire start-up procedure was 94 seconds, including 72 seconds engine speed increase process.

Start-up process dynamics is limited by the permissible value of inrush current and speed acceleration. Too fast speed increase can lead to a break of synchronism.

Significant reduction of inrush current allowed to eliminate the adverse impact on the power supply grid.

After the acceleration is complete, there is no need for a synchronization procedure because the start-up process is carried out in a state of synchronism of the rotor relative to the stator rotating field.

Application of a voltage inverter in synchronous motor stator circuit, in addition to the soft start of the drive, allows to adjusts the engine speed during the synchronous operation. In the presented solution the efficiency of the fan is controlled by a remote master speed reference engine or via the operator panel of the inverter.

7 Summary and conclusions

The paper presents the practical implementation of the ProgressPOWER microprocessor-controlled unit for synchronous motor excitation and HARSVERT voltage–frequency converter in stator of 6 kV voltage synchronous motor.

Use of voltage inverter in the stator circuit allows the start-up of the motor with significantly reduced inrush current. In the presented case, the inrush current does not exceed the rated value, which allows to eliminate adverse effects on the supply grid.

Ensuring effective start-up allows to automate the process, to simplify handling, to reduce failures, and to use the device in the automatic reserve systems in case of failure of the primary fan assembly.

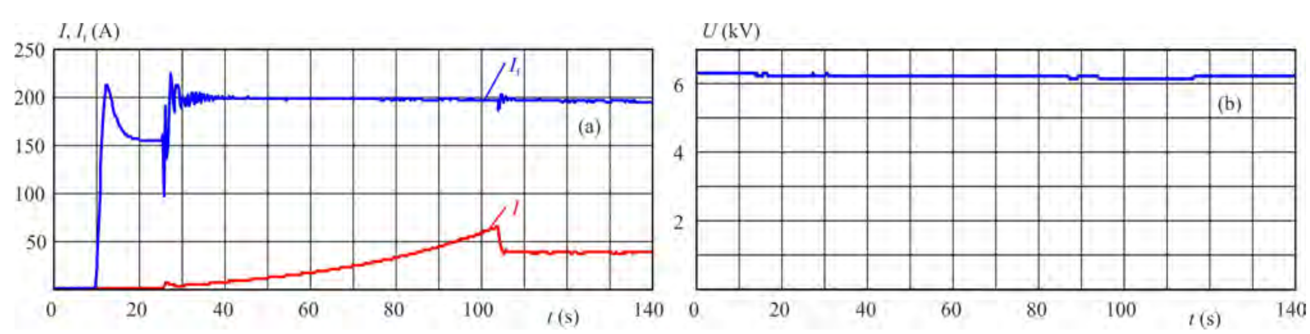

Fig. 8. Measured rms waveforms registered by the microprocessor of excitation device during start-up form a voltage inverter: I_f-current of excitation circuit, I-current in the switch bay supplying the inverter, U-voltage at the power switching station supplying the motor

Possibility of the supply voltage frequency adjustment allows to control the ventilation system productivity during synchronous operation of the motor. This makes it possible to reduce energy consumption needed to power the fan drive.

Verification measurements carried out at the real object confirm the validity of the concept and the implementation of the microprocessor-controlled excitation unit for synchronous motor with special software developed by the author and the voltage frequency converter in stator circuit co-operation.

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