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REVIEW OF SOLUTIONS USED IN HIGH-SPEED INDUCTION MOTOR DRIVES OPERATING IN HOUSEHOLD APPLIANCES*

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Abstract: The paper presents a high-speed induction motor drive as an alternative for household appliances. A short comparison was made between standard and high-speed motors. The solutions that use three-phase induction motors were taken into consideration with different types of rotors: solid or squirrel-cage. The assumed power of drive was up to 1 kW. As the power source, a single-phase voltage source has been adopted, which was indirectly converted to a three-phase output voltages with the fundamental frequency up to 667 Hz.

Keywords: *high speed induction motor drives, household appliance drives, power electronic converters*

1. INTRODUCTION

High-speed electric drives are important components of numerous up-to-date technical solutions. This is connected with high power density and small dimensions of these high-speed machines and also the possibility of controlling rotational speed within a wide range. Solutions with high-speed motors are employed in electric vehicles and, first of all, in power tools (saws, drills, etc.) as well as household appliances (vacuum cleaners, juice extractors, etc.) [4], [15]. Such choice is justified considering benefits that high-speed drives with 2- or 3-phase motors provide, especially induction machines that are reliable, have a simple and compact design and their windings as well as magnetic circuits are utilized better. The torque produced by induction machine is a function of its geometrical dimensions as well as its magnetic- and current-carrying capacity [3]. This can be expressed by the following equations [10]

$$T = f(\mathrm{c_e}, \phi, i), \tag{1}$$

$$P = T\omega, \tag{2}$$

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where T – electromagnetic torque, c_e – machine constant (containing information about its dimensions), ϕ – magnetic carrying capacity, i – current-carrying capacity, P – output power on motor shaft, ω – angular speed.

The paper is focused on a review of solutions employed in household appliances (HA). Requirements imposed on the drives of that type include, among other things, the need to keep the power factor, representing the energy drawn from the power supply grid in the form of purely sinusoidal wave, as high as possible [5], [6]. Any control system for high-speed electric drive powering a HA has to meet two fundamental requirements. The first consists in full control of motor currents. The second requirement concerns the motor speed control, although in appliances of that type, speed values are not particularly important. Exceeding allowable current values can result in destruction of semiconductor switches. Therefore, the structure of the control circuit must include a block that imposes a limit on output current value.

In drives designed to be used in HA, a criterion of fundamental importance is the cost effectiveness, which in practice means reduction to the minimum of the number of components used such as sensors of electric and non-electric quantities and capacitors. Speed sensor is also eliminated. The absence of any speed measuring components affects inevitably precision of the speed control. A scalar control method provides constancy of u/f ratio.

2. TOPOLOGY OF A HIGH-SPEED ELECTRIC DRIVE SYSTEM FOR HOUSEHOLD APPLIANCES

The present study started with an analysis aimed at selecting a topology for high-speed drive system designed for HA drives. The available topologies of power electronic converters, different designs of high-speed motors, and drive control methods suitable in view of the specific function were considered.

2.1. A REVIEW OF INDUCTION MOTOR PROPERTIES

A drive system typically comprises a power supply source, a converter, a motor, a transmission, and a load [2]. Household appliances are usually equipped with AC commutator motors operating at speeds as high as 4300 rad/s. Nowadays, induction motors are the most common sources of mechanical energy. They are reliable, inexpensive, and easy to operate. Induction motors powered directly from 50 Hz or 60 Hz electric power grid can achieve maximum rotational speed of 314.16 rad/s and 377 rad/s, respectively. Also motors with permanent magnets are becoming more and more popular. To obtain speeds higher than 377 rad/s in two- or three-phase induction machines, it is necessary, apart from employing special structural solutions, to use power electronic converters. The converter’s output voltage frequency is higher than the power supply line frequency and in the case of motors dedicated to vacuum cleaner suction units – operating at speeds of the order of 4191 rad/s – the frequency of voltage supplying a motor with one pair of poles is 667 Hz. To obtain supply voltage with such a high frequency, it is necessary to employ appropriate power electronic converters with topology adopted to specific control needs. To be able to supply electric motors from frequency converters, it is also necessary to develop new solutions in the area of motor structure designs. These requirements become more and more demanding with increasing supply voltage frequency. Inverters are controlled with the use of different techniques, decreasing distortion of voltage and current waveforms at converter input and output.

From numerous available solutions, the most popular electric motor is the squirrel-cage induction motor [12]. This is because the machine design is simple and easy to manufacture, which translates into low manufacturing cost and reliable operation. Speed control in squirrel-cage induction motor can be accomplished by:

– changing the number of pole pairs,
– changing the sliding rate,
– changing stator voltage,
– changing frequency.

With frequency-based control, motor speed can be changed smoothly from several rpm to a maximum speed depending on mechanical structure (bearings) and number of pole pairs. It should be remembered that above its rated speed, a motor controlled from frequency converter works at constant power level due to constant voltage, so the torque decreases approximately in proportion to frequency increase (Fig. 1).

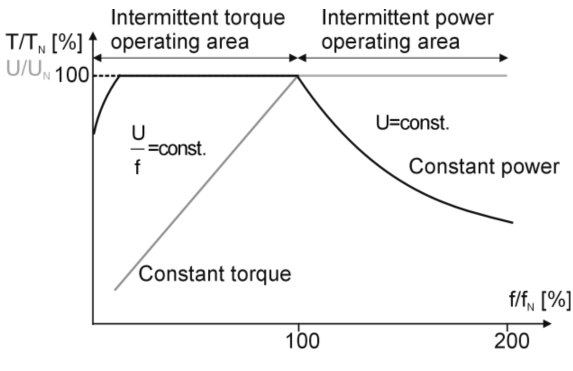

Fig. 1. Allowable change ranges for values of motor torque T and rms supply voltage U as a function of inverter output voltage frequency f (all quantities are related to their rated values)

To be able to control rotational speed at constant load torque for frequencies exceeding the rated frequency, it is necessary to adopt higher motor design frequency (depending on the required upper speed limit). The control of motor below its rated speed is determined mainly by ventilation conditions. A motor operated at constant load in a wide speed range must be provided with external cooling system. The use of external cooling is also recommended for motor operation in upper portion of its rpm range – mainly in view of air resistance and noise generated by a ventilator mounted on the motor shaft. Motors designed to operate with power electronic converters should have a reinforced insulation system resistant to significant steepness of voltage coming from inverter as well as reinforced bearing nodes that guarantee extended service life. The following structures of high-speed induction motors are used (Fig. 2):

– induction machines with squirrel-cage laminated rotor,
– induction machines with slip-ring laminated rotor,
– induction machines with squirrel-cage solid rotor,
– induction machines with copper tube solid rotor,
– induction machines with solid rotor.

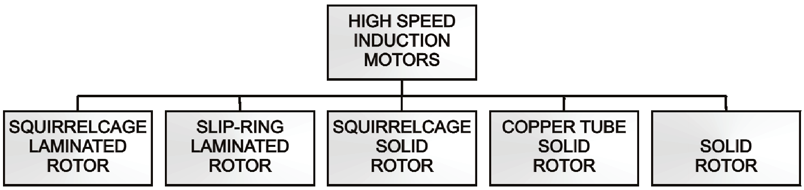

Fig. 2. General classification of high-speed induction motors

Each of the above-listed high-speed motor solutions implies the need to introduce significant design changes with respect to motors operated at power supply grid frequencies.

2.1.1. DESIGN OF HIGH-SPEED INDUCTION MOTOR

The efficiency level of high speed induction motors (HSIM) is nearly the same as the efficiency level of low speed motors (range up to 377 rad/s), but HSIM loss distribution may vary, of course, depending on design and control conditions (e.g., the magnetizing inductance might change due to the flux level variation in the field-weakening region. There have been some problems which considered this. Cooling surface of high-speed motors is smaller. It means that power losses of those motors are the same. This leads the problems to the cooling technique. The difference in loss distribution between conventional and high-speed induction motor is presented in [9]. HSIMs are supplied by frequency converters, so this influences the motor losses. Also, the converter's losses depend on the power electronics converter solutions. Stator of HSIM is similar to standard motor, but the important problem is to minimize the power losses. In addition to this, a thick lamination is used. A rotor is the most important part of the HSIM. The mechanical performance of high-speed induction motor is related to mechanical stress of laminations and squirrel-cage due to centrifugal force. The rotor balance is very important too, due to bearings life. Because of high friction losses the air gap construction has to be proper for air change and hit dissipation. Mathematically, the high-speed electric motor can be modelled by the means of standard three-phase induction machine equations. As the subject of considerations is a three-phase induction machine [11], the following simplifying assumptions have been adopted when developing the machine model: electric and magnetic symmetry of stator and rotor design; only first harmonics are taken into account in flows and magnetic induction; linearity of magnetization characteristics; and linearity of the electric circuit.

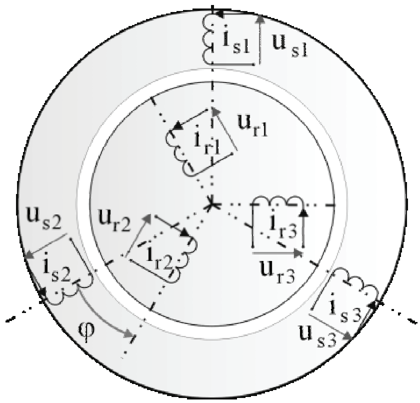

Fig. 3. Model of a three-phase induction machine

With the adopted simplifying assumptions, equations of voltage circuits can be expressed by means of the following equations

$$\mathbf{u}_s = \mathbf{R}_s \mathbf{i}_s + \frac{d}{dt}(\mathbf{L}_s \mathbf{i}_s) + \frac{d}{dt}(\mathbf{L}_{sr}(\varphi)\mathbf{i}_r), \tag{3}$$

$$\mathbf{u}_r = \mathbf{R}_r \mathbf{i}_r + \frac{d}{dt}(\mathbf{L}_r \mathbf{i}_r) + \frac{d}{dt}(\mathbf{L}_{sr}(\varphi)\mathbf{i}_s). \tag{4}$$

Equation of the mechanical system takes the form

$$\frac{2}{p}\mathrm{J}\frac{d\omega_r}{dt} + \frac{2}{p}\mathrm{F}\omega_r + T_L = \frac{p}{2}\mathbf{i}_s^T \frac{\partial}{\partial \varphi}(\mathbf{L}_{sr}(\varphi))\mathbf{i}_r, \tag{5}$$

where

$\mathbf{u}_s$ = col(u_{1s}, u_{2s}, u_{3s}) – stator voltages vector,
$\mathbf{u}_r$ = col(u_{1r}, u_{2r}, u_{3r}) – rotor voltages vector,

$\mathbf{i}_s = \mathrm{col}(i_{1s}, i_{2s}, i_{3s})$ – stator currents vector,
$\mathbf{i}_r = \mathrm{col}(i_{1r}, i_{2r}, i_{3r})$ – rotor currents vector,
$\mathbf{R}_s = \mathrm{diag}(R_{1s}, R_{2s}, R_{3s})$ – stator resistance matrix,
$\mathbf{R}_r = \mathrm{diag}(R_{1r}, R_{2r}, R_{3r})$ – rotor resistance matrix,
J – moment of inertia of mechanical structure,
F – coefficient of friction in rotational motion,
φ_r – rotor electric angular position,
ω_r – rotor electric angular velocity,
T_L – mechanical load torque,
p – number of stator pole pairs,
$\mathbf{L}_s$ – stator windings inductance matrix,
$\mathbf{L}_r$ – rotor windings inductance matrix,
$\mathbf{L}_{sr}$ – matrix of mutual inductances of stator and rotor windings depending on rotor angular position φ_r.

2.1.2. HIGH-SPEED THREE-PHASE INDUCTION MOTOR WITH SOLID ROTOR

As an example, a three-phase induction motor with monolithic steel rotor and the following parameters were selected:

rated power	$P_n = 1000$ W,
rated current	$I_n = 2.76$ A,
rated speed	$n_n = 39{,}940$ rpm,
synchronous speed	$n_s = 40020$ rpm,
rated stator voltage	$U_n = 300$ V,
rated voltage frequency	$f_s = 667$ Hz.

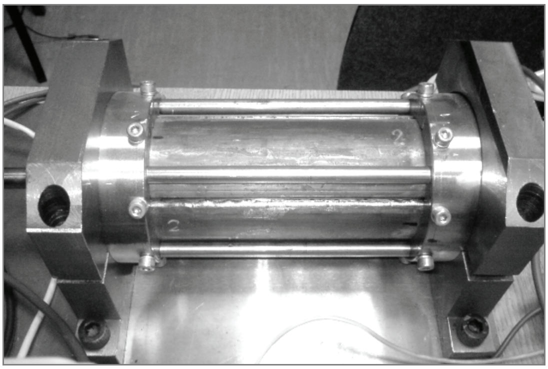

Fig. 4. High-speed three-phase induction motor on the laboratory test setup

The motor is characterized by a simple design of rotor manufactured out of a single piece of steel which translates into low manufacturing cost. The solid rotor outer diameter is 17.5 mm. Stator of the motor was made out of a 0.23-mm thick transformer strip ET-110-23. In the course of stator laminated steel core, neighbouring individual laminations were rotated by 90° to improve anisotropy. High-speed motors are characterized by higher rotor length to diameter ratio compared to standard solutions (designed to be supplied directly from power line). The motor under examination has the following dimensions: stator laminate length l_s = 125 mm, outer diameter d_z = 56 mm (Fig. 4). Such form adopted for rotor of a high-speed motor rotor is conditioned by the centrifugal force value which must not be larger than that in standard solutions.

Stator windings were made of copper wire with diameter d_{iz} = 0.3 mm. The current density assumed for the adopted diameter is j_s = 9 A/mm^2. The number of coils connected in series was 96, and the number of parallel conductors making a single coil was a_c = 8; this means that 368 needed to be placed in a slot. Total motor losses calculated at the design stage are ΔP = 163 W. In the course of laboratory tests, motors with external cooling were examined.

2.2. A REVIEW OF POWER ELECTRONIC CONVERTER DESIGN SOLUTIONS

One of the many electronic power converter topologies that can be used to feed high-speed induction motors are devices comprising: a AC/DC grid voltage rectifier, a DC-link, and a DC/AC voltage inverter [7], [8], [14]. Power electronic AC/DC converter must secure sinusoidal form of input current, which at the same time has the phase as the supply line voltage which can be obtained by using AC/DC circuits of PFC-type. The function of DC/AC circuits is done by voltage inverters with half-cycle switching of transistor switches (in the case of motors with 2 and more pole pairs) and voltage inverters with pulse modulation [8], [11].

Due to the simple structure and small dimensions, voltage inverters are most popular in the ranking of topologies. A converter comprising voltage inverter with half-cycle switching requires controlled voltage of DC/DC intermediate circuit. The control process in inverter with half-cycle switching consists in cyclical switching of transistor switches on and off according to a pattern comprising six pulses. Such pattern can be controlled by intermediate circuit voltage; in such a case, frequency at the circuit output will always follow changes of the intermediate circuit voltage average value. Converters comprising voltage inverters with pulse modulation in their structure do not require the intermediate circuit voltage amplitude to be changed. Inverters with pulse-based modulation are known as pulse width modulation (PWM) inverters. The PWM method consists in changing width of intermediate circuit voltage pulses according to an algorithm comparing two auxiliary voltages, e.g., a carrier voltage of triangular waveform with a sinusoidal modulating voltage. This enables the synthesis of voltage and current waveforms as well as the control of their rms values and fundamental harmonic frequencies.

2.2.1. A REVIEW OF CONTROL METHODS AND TOPOLOGIES OF INVERTERS FOR HIGH-SPEED DRIVE SYSTEMS

The progress in the field of semiconductor power electronic devices determines the possibility of constructing high-power inverters characterized by high output voltage frequencies and small overall dimensions. Up-to-date semiconductor devices can be operated at high switching frequencies, however, in combination with high powers this may result in significant commutation-related losses. Therefore, apart from PWM inverters enabling favorable voltage waveform to be obtained on a receiver, also inverters with half-cycle switching, which together with controlled DC/DC converter constitute a converter used to supply the motor. The waveform of receiver current can be obtained, with a small number of switchings, by selecting appropriate topologies and inverter control methods. Inserting LC filters between inverter and receiver may also have favorable effect on reduction of distortion components in voltage and current waveforms, which results in an increase of weight and cost of the solution. In devices such as power tools and household appliances, precise control of speed and torque is not required in most applications. The cost of the control circuit is expected to be a small fraction of the finished product price [14]. Overload protections can be introduced in the form of mechanical couplings or bimetal components which usually makes voltage inverters with simple control circuits quite sufficient. Figure 5 shows a power circuit comprising a single-phase pulse-controlled rectifier with sinusoidal power line current and three-phase voltage inverter.

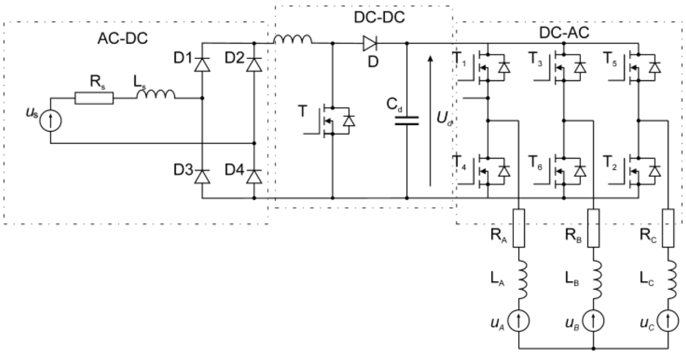

Fig. 5. A diagram of rectifier and inverter with marked measuring signals

In the course of analysis, attention was focused on economical converters with a limited number of power electronic components. One of the analyzed circuits with three-phase induction motor is shown in Fig. 6. In the solution presented, transistors T1, T2 and capacitors C_P, C_N constitute a single-phase voltage doubling rectifier. This allows voltage to be changed in the intermediate circuit, with the power factor value being kept close to unity (sinusoidal converter input current in phase with power supply line voltage). The other transistors T3, T4, T5, and T6 and capacitors C_P and C_N form an asymmetrical inverter (V-connected inverter) supplying induction motor. The circuit of Fig. 6 offers the possibility of energy backflow to single-phase supply line when motor is operated in the power-generating mode.

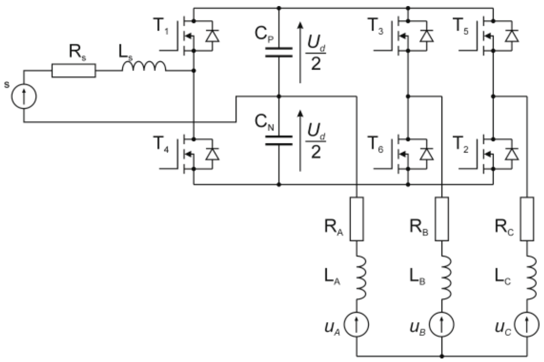

Fig. 6. An economical drive system with half-bridge voltage multiplying rectifier and V-connected inverter supplying an induction motor

2.2.2. THE CONTROL METHOD

For the application example presented, torque, speed and position precision are not important. In the application used in this study, the most important criteria are cost effectiveness and efficiency. From this point of view, the voltage waveform should be selected so that the harmonic content of the current is the smallest. The proposed system contains a rectifier with unity power factor (Fig. 7). For such topologies adopted in order to stabilize the output voltage – voltage feedback was applied. Next, a voltage is measured by voltage probes SU and compared in signal comparator S with the reference voltage $k_u U_{d\text{ref}}$. As a result of this comparison the control error $k_u \Delta u_d$ is obtained which is entered to a *PI* voltage regulator $RegU_d$. The output of the PI controller is multiplied in the K*A*B module by scaled power line voltage waveform. This multiplication result generates a signal proportional to the current needed to stabilize the voltage capacitor.

The voltage source converter in V system can be used to supply two- or three-phase induction motors. An example with three phase is discussed (Fig. 8). In the system presented, the output current stabilization introducing a feedback current in the two phases of the motor was done. The third current phase is calculated on the basis of two measured in the other phases. The measured current signals in SI probes are compared with the reference waveforms of currents in the two adders. Then as a result of current error that goes to the current regulators about the structure of PI is compared.

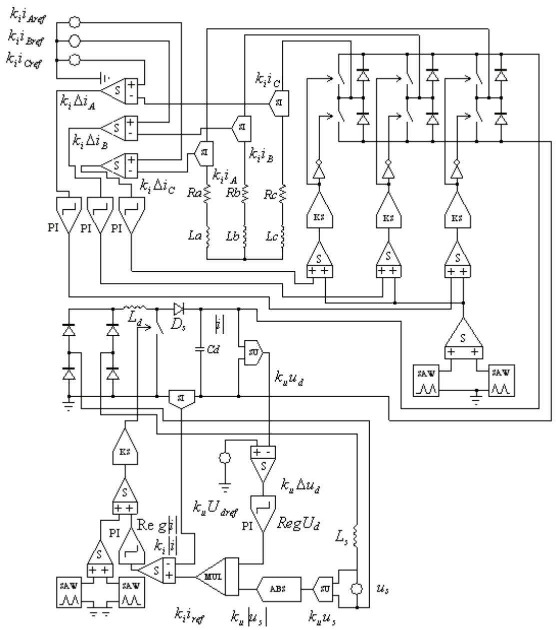

Fig. 7. Diagram of single-phase pulse-controlled rectifier with sinusoidal power line current and three-phase voltage inverter with control circuit

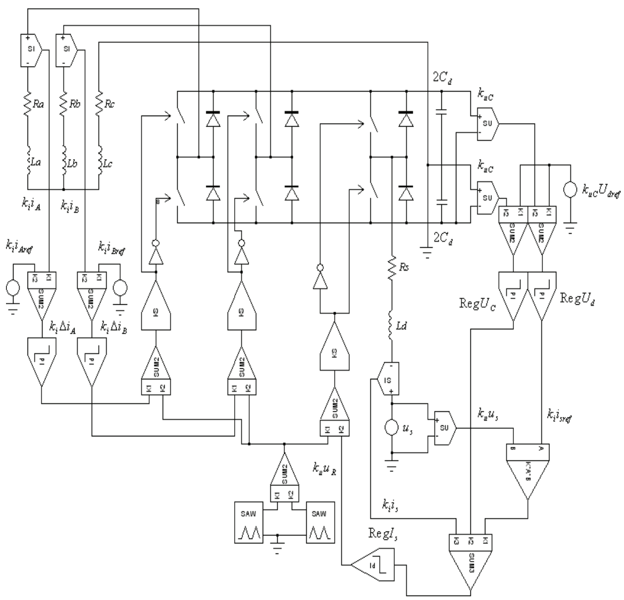

Fig. 8. An economical drive system with half-bridge voltage multiplying rectifier and V-connected inverter supplying an induction motor

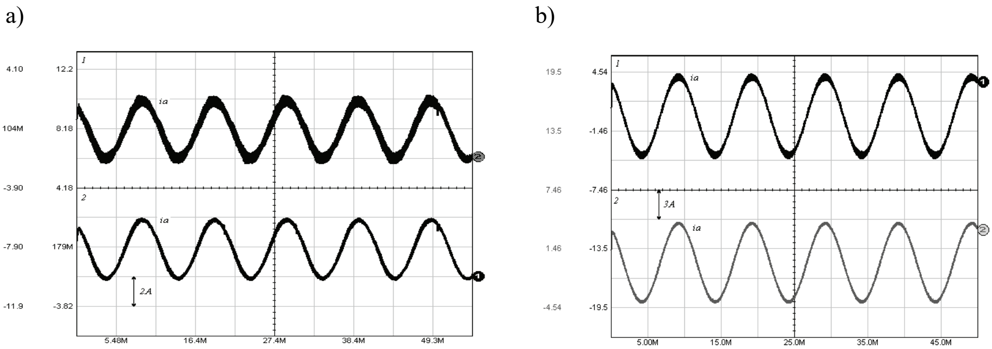

Fig. 9. The current waveform of phase A for two switching frequencies of voltage generator ($1 - f_c = 8.33$ kHz; $2 - f_c = 16.66$ kHz): (a) an economical drive system with half-bridge double voltage rectifier and V-connected inverter supplying 3-phase induction motor; (b) single-phase pulse-controlled rectifier with sinusoidal power line current and three-phase voltage inverter supplying induction motor

Simulation examinations were conducted in the ICAP/4 program. The waveforms of the given converter were appointed on the change of parameters of the load as well as a set of individual elements of the regulation responsible for the work of the structure. A rectifier is stabilizing the DC link voltage, that is increased with regard to the maximum value of line voltage, which provides correct work of the converters and stabilization of the output voltage.

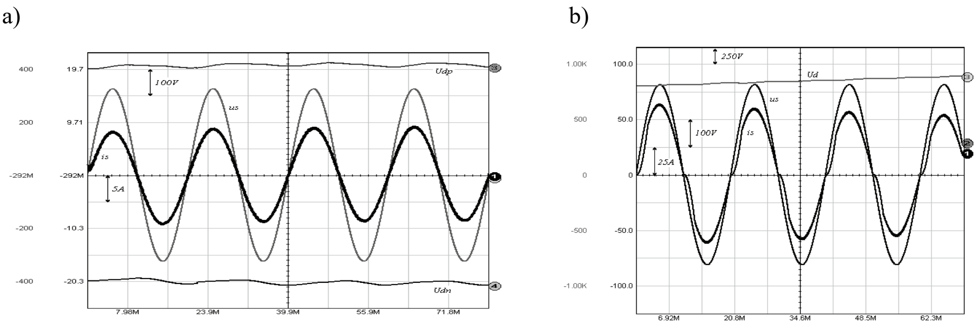

Fig. 10. Voltage waveforms u_s, a single-phase line current i_s, DC voltage U_d: (a) an economical drive system with half-bridge double voltage rectifier and V-connected inverter supplying 3-phase induction motor; (b) single-phase pulse-controlled rectifier with sinusoidal power line current and three-phase voltage inverter supplying 3-phase induction motor

The simulations performed lead to the conclusion that increasing the switching frequency has great influence on the currents shape of the motor (Fig. 9). Moreover, the current consumed from the power line by the converters is sinusoidal and in phase with the line voltage. The input current of boost type converter has a slight deformation at zero crossings. There are no such disadvantages in a model of V-converter with the half-bridge double voltage (Fig. 10).

3. CONCLUSION

The motivation and aim of this paper was to review drives with high-speed induction machines. Another goal was to find control system appropriate for a high-speed induction machine supplied by power electronics converter. The paper is focused on high-speed induction motor with special attention given to the solid rotor and two types of power electronics converters. Based on the analyzes performed it can be concluded that converter topologies shown in Fig. 7 and Fig. 8 realize requirements for high-speed motor drives. The inverters output currents are similar to sinusoidal waveforms and input power factor of the whole system is close to unity. Especially interesting is an economical V type converter. This system is characterized by a smaller number of semiconductor elements in relation to the other solutions discussed. One power module composed of six transistors is a complete circuit of this converter. This solution is advantageous in relation to the inverter topology supplied from the voltage boost converter, because of a smaller number of switching elements. So, with this solution the power losses and cost reduction of the system are associated. The presented knowledge is based on the own experience in the field of high speed drives. Also a study of literature was done.

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