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INVESTIGATION OF HIGH SPEED INDUCTION MOTOR DRIVE OPERATING IN HOUSEHOLD APPLIANCES*

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Abstract: The paper presents conclusions which are results of research on the use of high-speed drives operating in household appliances. The solutions that use three-phase or two-phase induction motors were taken into consideration. The assumed power of motors was up to 1 kW. The article describes the control process of power converters that is characterized by unity power factor and output voltages with the fundamental frequency up to 667 Hz. The requirements for control process were characterized and intelligent solutions were analysed, taking into account power outages, fluctuations, or accidental failures of supply voltage. The control functions of the controller elaborated, such as current and speed control, drive start-up and control circuit supply were described.

Keywords: *High speed drive, induction motor control, scalar control*

1. INTRODUCTION

In high-speed induction drives, either two- or three-phase, used in power tools and household appliances (HA), the control process must be realized in a specific way. The specificity comes from the need to meet requirements concerning operating conditions and energy conversion. Reliable operation of HA drive is expected to be resistant to emergency states resulting from improper use, e.g., accidental disconnection from the power supply source or temporary supply voltage fluctuations. At the same time, drive installed in a HA is required to interfere with the power supply grid as little as possible [1], [4], [5], [7], [9], [11]. Taking into account the specificity of a drive used, e.g., in power tools, it is possible to formulate technical requirements and expectations applicable to control circuits and energy converters:

– power factor (PF) equalling unity;
– current and voltage control;
– control depending on supply voltage value;
– recovery of energy from rotating masses;

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– common supply for power and control circuits;
– resistance to improper operation.

The above requirements can be met by a properly designed system of modulators cooperating with the control circuit. For laboratory tests of proposed solutions, a test stand was made (Fig. 1). It consist of a 3P-3W voltage source inverter (VSI) controlled using FPGA EP2C20F484 device. The digital controller executes the modulation tasks (Section 2), current and speed control (Section 3), drive start-up (Section 4) and control circuit supply (Section 5).

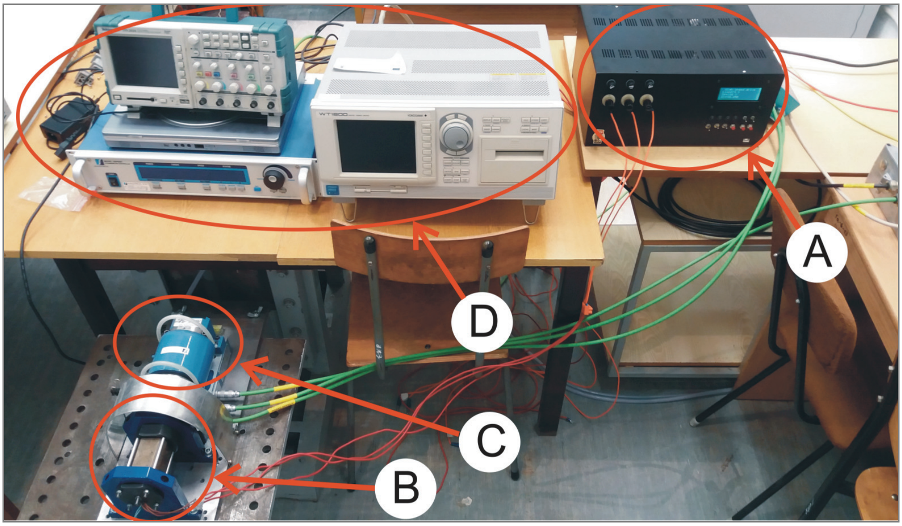

Fig. 1. Test stand of high speed drive: A – VSI with digital controller, B – induction motor drive, C – programmable load, D – measurement devices

2. INVERTER MODULATOR

High-speed induction motors operated at speeds up to 40,000 rpm require their supply voltages characterized with very high frequency of fundamental harmonic (up to 667 Hz) to be accurately synthesized. The voltages supplied by inverter are synthesized with the use of two- or three-phase modulators depending on the type of induction motor. Employing vector modulators seems to be unjustified in this case in view of the absence of any strict requirements concerning the precision with which the control circuits operate [6]. Taking into account versatility of methods used to modulate waveforms supplying the motor, two-phase modulation can be accomplished on the same converter, which is capable of supplying a three-phase motor. All that is to be done is connecting properly the two-phase motor to the three-phase inverter and changing the modulation functions.

Considering the natural modulation process consisting in comparing modulating waveforms with a carrier function waveform given by

$$u_{car}(t) = \frac{2}{\pi}\arcsin\left(\sin\left(\pi f_p t - \frac{\pi}{2}\right)\right), \tag{1}$$

where $u_{car}(t)$ is a triangular signal carrier with frequency f_p, the circular trajectory of inverter output voltages of the three-phase motor output voltages connected according to the diagram shown in Fig. 2a is obtained by means of using three-phase sinusoidal modulating signals

$$u_{sk}(t) = \cos(\omega t + 2\pi k/3), \tag{2}$$

where $k = -1, 0, 1$ for phases B, A, and C, respectively.

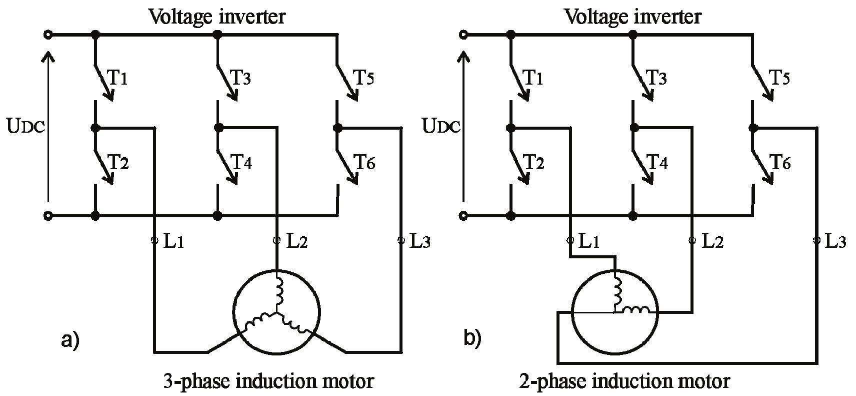

Fig. 2. Diagrams of two- and three-phase motor connected to a three-leg voltage inverter

Connecting a two-phase motor to the inverter according to diagram shown in Fig. 2b requires modulating functions in the natural modulator to be changed. One method of transforming three sine functions shifted symmetrically by 1/3 of the round angle with respect to each other into three functions modulating waveforms of a two-phase circuit supplied by a three-leg inverter, consists in using the following transformation

$$u_{\mathrm{AM}} = u_{\alpha} + u_0, \tag{3}$$

$$u_{\mathrm{BM}} = u_{\beta} + u_0, \tag{4}$$

$$u_{\mathrm{CM}} = u_0 = -(u_{\alpha} + u_{\beta})/2, \tag{5}$$

where u_{AM} and u_{BM} are waveform modulating functions for the two inverter legs to which motor windings are connected, and u_{CM} is the waveform modulating function for these inverter legs in which the motor's common point is coupled.

The formula needs to be subject to transformation from the system of natural coordinates (A, B, C) to the system of stationary coordinates (α, β) according to the Clarke transform. By changing the modulating functions, one obtains the circular trajectory of the voltage vector for the two-phase motor as well. Switching of the modulating functions by multiplexer (mux) may occur in the controller configuration stage or as a result of realization of superior processes, e.g., those connected with the number of motor phases auto-detection by state machine described in detail in [2] (Fig. 3).

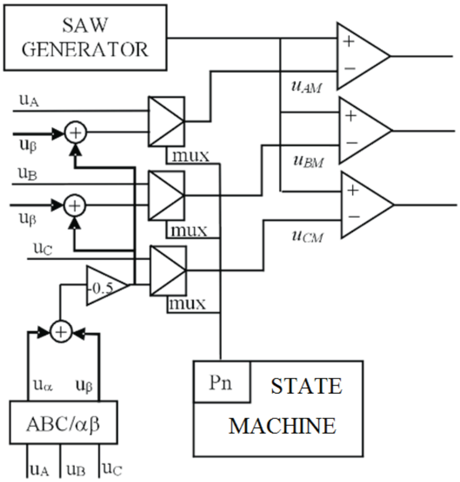

Fig. 3. A diagram of modulator realizing two- or three-phase modulation based on configuration bit Pn generated by state machine [2]

3. INDUCTION MOTOR CURRENT AND VOLTAGE CONTROL

The control process in a high-speed electric drive used in HA and power tools has to meet two fundamental requirements. The first and unquestionable condition to be fulfilled consists in exercising full control of motor currents. The second requirement pertains to motor speed or motor supplying voltage control. Exceeding allowable or critical current values results in most cases in damage of semiconductor switches. Therefore, the current regulation circuit must contain in its structure an integrating block with a restriction for output value. In HA and power tools, the speed value is not of particular importance. As a consequence, a voltage controller may not include the integrating element. The experiments included attempt to implement a control system comprising an integrating element in the voltage controller. Increasing the order of transmittance of the closed circuit resulted in appearance of strong current beating observed for frequencies close to 450 Hz. Ultimately, it is possible to dispense of the integrating element and select settings for the other controllers heuristically. The current regulator should then be tuned based on the gain selection rule to keep gain value lower than 1 and the integration constant 2–3 times larger than the largest period of the motor supplying voltage variable component. The adopted voltage regulator gain should be large, e.g., of the order of 40. In most cases, heuristic selection of settings for drives installed in HA, where the impact of control parameters is not so important, turns out to be sufficient. In other cases it is necessary to make selections based on criteria that are widely addressed in literature. Among design criteria applicable to HA, cost minimization is one of the most fundamental issues. This economical criterion makes it necessary, among other things, to minimize the number of expensive components, including sensors of electric and non-electric quantities and capacitors. The controlled quantities which are not measured can be reconstructed by using e.g., the state variable estimation methods [9]. Striving to minimize the number of measuring sensors, the option to eliminate the speed and/or motor voltage sensor by using internal feedback was considered. A block diagram of an example control system is shown in Fig. 4. The absence of speed measurement affects precision of speed control, which is not a priority in the assumed domain of applications. Failure conditions (e.g., rotor lockup) can be taken into account by employing a block tracking operation of the controller, e.g., in the saturation range or using other means cooperating with sensors, represented symbolically in the diagram by the "Emergency breakdown" block. Output value of the control parameter m is scaled in the range from 0 to 1. As a result of such scaling, it equals directly the value of inverter's voltage gain. Based on the value of m, the controller calculates the output waveform frequency. The frequency results from the adopted scalar control method maintaining constant u/f ratio. Taking into account the effect of motor resistance, the characteristic has been modified (Fig. 5) by introducing a shift for discrete measurement points. The shift value depends on motor parameters, therefore they should be determined, preferably by means of experiment, increasing the voltage rms value for characteristic supply voltage frequencies.

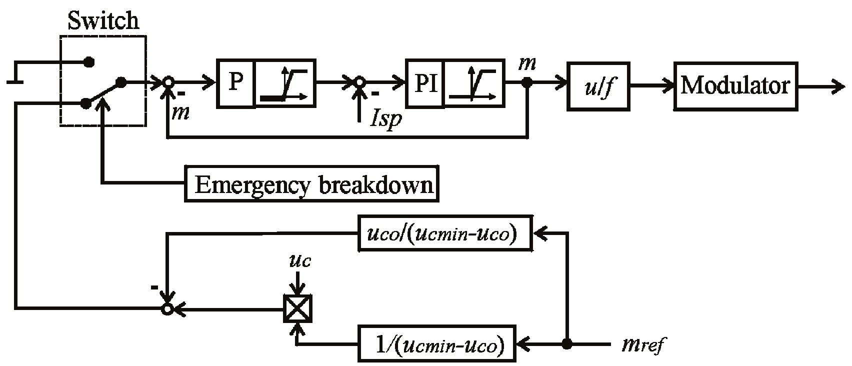

Fig. 4. A block diagram of the control system: I_{sp} – measured current, m – current controller output, m_{ref} – set inverter voltage gain, u_{co} – DC-link voltage, u_{cmin} – minimal controller supply voltage

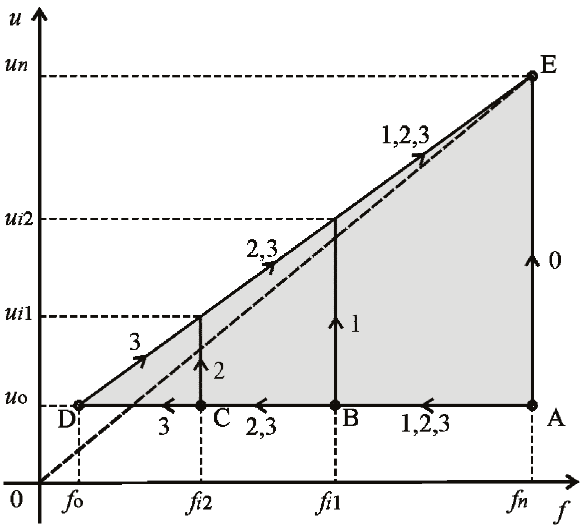

Fig. 5. Characteristic u/f = const with start-up process taken into account for different cases: (0) – AE path for motor at nominal speed, (1) – ABE path for non-zero motor speed (at f_{i1} frequency), (2) – ACE path for non-zero motor speed (at f_{i2} frequency), (3) – ADE path for stopped drive

The appearance of a distortion close to extreme values of current waveforms, and thus also higher harmonics of load currents, is the evidence of magnetic core saturation. The share of ohmic potential drop in motor resistance in the supply voltage vector depends on frequency, therefore it is admissible to apply approximation by using two different slope coefficients of the characteristic $u = u(f)$ depending on the frequency value.

The assumed range of supply voltage frequency change can be divided into three intervals. In the first interval, the supply voltage value is zero. This sub-range includes frequencies with values from zero to the value resulting indirectly from the supply voltage exceeding the voltage drop on the motor's resistance. In the second interval, characteristics $u = u(f)$ pertains to start-up processes. It is selected based on results of voltage and frequency measurements in the motor saturation limit. Moreover, the limit imposed on current in this interval allows a current value higher than the one in the assumed range of voltage frequency change corresponding to normal operation of the drive. Such an approach to determining characteristic $u = u(f)$ results in an increase of motor torque in dynamic states of the drive, at the expense of current distortions. The last, third sub-range of u/f characteristics, pertains to voltage frequency changes allowable in normal operating conditions. In this interval, the drive is considered to be in the start-up phase, moreover frequency changes, and thus also the motor speed variations, are connected with allowable changes following from correct operation of controllers. The characteristic in this very region is the steepest, and the current limiting value input to the controller is the smallest.

4. DRIVE START-UP

One of the problems needed to be solved in high-speed drive designs is to ensure correct realization of the start-up procedure. With the scalar control assumed, this is to occur at constant value of voltage-to-frequency ratio. Segment 0E in Fig. 5 represents the classical form of scalar control. The control process taking into account ohmic potential drops on resistances of motor windings should be continued over segment DE but only when the start-up occurs at zero motor speed.

In case of the drive being temporarily switched off, the start-up process starts at non-zero speeds. In such a situation, controllers start usually the control process from zero initial values, which can cause undesired behaviour resulting in disrupted operation of both the motor and the converters. The proposed start-up procedure reduces these undesired effects to a minimum. The start-up process needs a signal identifying actual value of motor speed. The occurrence of such a signal triggers switching to the appropriate characteristics. Example start-up processes are shown in Figs. 6 and 7. The start-up process always starts from the point E. Modulators are then set to synthesizing waveforms with decreasing frequency.

Starting from the rated value f_n, frequency is decreased during time t_2 until it reaches value f_0. This occurs at small amplitudes of modulating functions which should be selected with sensitivity of the measuring system used taken into account. If the process reaches the frequency f_0 (point D), the motor is halted.

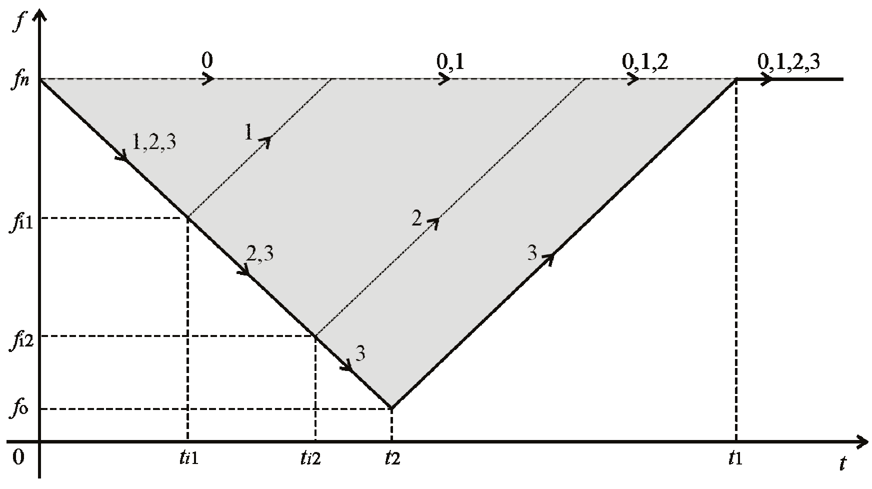

Fig. 6. Profiles representing changes in motor supplying waveform frequencies during start-up for different cases: (0) – path for motor at nominal speed (at frequency f_n), (1) – path for non-zero motor speed (at frequency f_{i1} during $2t_{i1}$ start-up time), (2) – path for non-zero motor speed (at frequency f_{i2} during $2t_{i2}$ start-up time), (3) – ADE path for stopped drive during t_1 – maximum start-up time

Identification of the frequency corresponding to the motor speed after time t_i results in the control circuit continuing operation represented by the segment DE of the characteristic with constant voltage-to-frequency ratio. In the frequency and voltage change profiles shown in the figures, detection of motor speed after time t_{i1} corresponds to a non-zero value of motor speed higher than the one which could be observed in the case of occurrence after time t_{i2}.

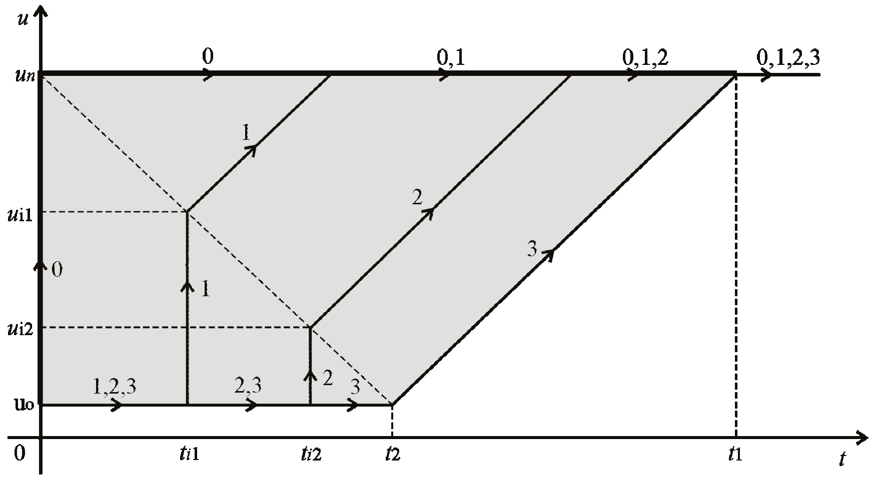

Fig. 7. Profiles representing changes in motor supplying voltage during start-up for different cases: (0) – path for motor at nominal speed (at voltage u_n), (1) – path for non-zero motor speed (at voltage u_{i1} during $2t_{i1}$ start-up time), (2) –path for non-zero motor speed (at voltage u_{i2} during $2t_{i2}$ start-up time), (3) – ADE path for stopped drive during t_1 – maximum start-up time

4.1. MOTOR SPEED DETECTION

Any control system for high-speed drive with induction motor must anticipate failure conditions connected with undesired supply voltage fadeouts. The above-described start-up procedures function correctly provided that the correct value of current motor speed is known. Economic criteria indicate that installing additional sensors should be avoided. In such a situation, the problem of speed identification should be solved by implementation of a properly selected algorithm undemanding as far as the computing power is considered. To estimate motor speed, it is possible to use the state observers technique, Kalman filtering, or similar algorithms [10]. It is assumed that the moment when the actual speed is detected initializes the classical start-up, beginning from the detected speed value. Such solution involves complex calculations and requires knowledge of some variables defining engine state (e.g., currents). In the case of powered rotating induction motor (e.g., after power failure), the phase currents cease. In such a situation it is not possible to estimate speed without prior forcing a current flow. The state variables, in the form of motor supplying currents, are sometimes forced by supplying the motor windings with short voltage pulses. This process is often accompanied by acoustic interference. The proposed solution makes use of identification of the motor operation state. It was assumed that switching from power- to torque-generating operation mode determines the instant of time (marked t_i on the characteristics) of switching to the portion of characteristic corresponding to u/f = const. Energy return to the source occurs for supply voltage frequencies less than the frequency corresponding to the current rotor speed. The value of the frequency can be a multiple of the supply voltage frequency depending on the number of motor pole pairs. This results in an increase of voltage on the intermediate circuit capacitor C_p. The capacitor voltage increase in dynamic states is taken into account in the power electronic converter circuit design and can result in the necessity of increasing its capacity and/or voltage. This leads to an increase of the inverter manufacturing cost. A schematic diagram of start-up procedure is shown in Fig. 8. A change in energy flow direction is identified by monitoring the sign of active power value. In turn, a change in the sign of active power value is detected based on waveforms of modulating functions generated in the modulator and measured (or reconstructed) instantaneous values of motor currents. In the induction motor on-switching process, only the active power

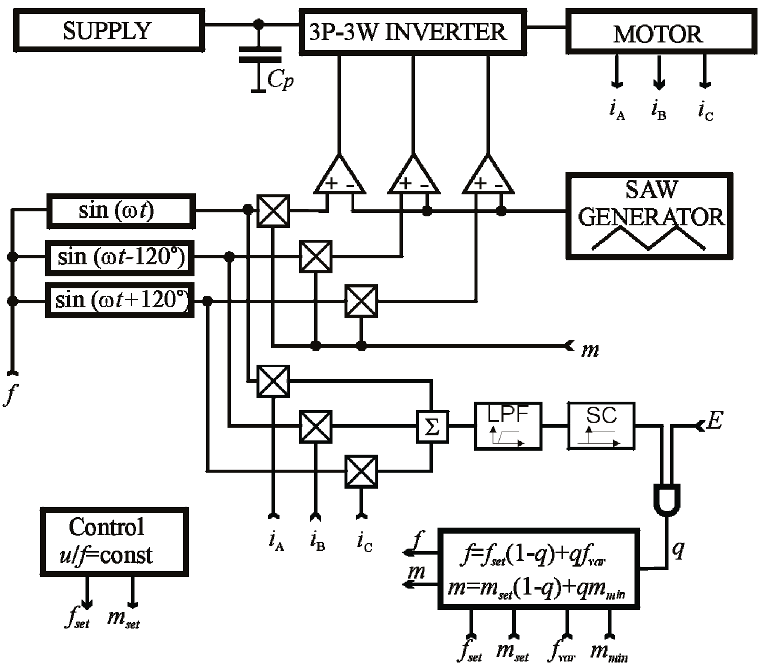

Fig. 8. Modified control system with identification of frequency corresponding to motor speed

sign needs to be identified. Hence it follows that the phase voltage waveforms in equation (6) could be replaced by sinusoidal waveforms of unit amplitude. Such waveform can be supplied from modulator. Then, the sign of the instantaneous power value can be determined using the relationship

$$p_s(t) = u_{\mathrm{ma}} i_{\mathrm{a}} + u_{\mathrm{mb}} i_{\mathrm{b}} + u_{\mathrm{mc}} i_{\mathrm{c}} , \tag{7}$$

where $u_{\mathrm{m}j}$ is the modulating function for the j-th phase.
As a result of determination of the waveform described by equation (7), an approximate result is obtained proportionally to the instantaneous power value.

Further, by application of low-pass filtering, an approximate value is obtained proportional to the power active component. The value changes sign at the moment of levelling the supply voltage frequency with frequency corresponding to the motor's rotor speed. As a result of low pass filtration (LPF), the effect of current measurement imprecision (discretization), noise, or distortion is negligible. As a result of using the filtered signal sign comparator (SC), a binary signal q is obtained. The signal is used to determine the set inverter voltage gain m and the set output waveform frequency f, according to equations

$$m = m_{\mathrm{set}}(1-q) + m_{\mathrm{min}} q , \tag{8}$$

$$f = f_{\mathrm{set}}(1-q) + f_{\mathrm{var}} q , \tag{9}$$

where m_{set} – the set inverter voltage gain, e.g., according to scalar control u/f = const; f_{set} – supply voltage waveforms frequency value set by the control circuit; m_{min} – voltage gain corresponding to minimum voltage value in the course of identification of frequency corresponding to current motor speed, f_{var} – the set value of voltages at the inverter output in the course of identification process.

Values of the binary signal q are assigned the following functions

$q = 0 \rightarrow$ control process, e.g., U/f = const., $q = 1 \rightarrow$ start-up.

Figure 8 represents a block diagram of a three-phase modulator extended by adding a circuit serving identification of the starting moment for the assumed induction motor scalar control algorithm. Motor phase currents are denoted i_{A}, i_{B}, i_{C}. The start-up process is controlled by means of external signal E. Start-up control is exercised in such a way that the value E = 1 corresponds to the state enabling the motor to be switched on. Actual embodiment of the electronic circuit used to switch on and start up the induction motor with rotating rotor depends on actual embodiment of the modulator circuit. This is related to the use of internal waveform of modulating functions to identify the sign of instantaneous power [3]. This can be accomplished in the form of a code in control program run on a processor or realized as a logical structure.

5. CONTROL CIRCUIT SUPPLY

One of the assumptions adopted for drives used in HAs or power tools provides that electronic control circuits will be supplied from the intermediate circuit. This assumption makes it necessary to make procedures guaranteeing safe operation of the drive in uncharacteristic situations and at the moment of connecting it to the power supply source.

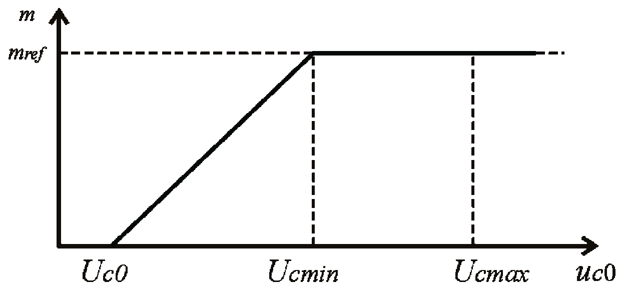

Fig. 9. The set voltage gain vs. the DC-link voltage value at constant controller output value m_{ref}

In such a situation, the best option will consist in adopting a solution based on making the drive operation dependent on the value of voltage on the intermediate circuit capacitor. Such a solution is presented in Fig. 9 in the form of a block diagram. It is assumed that power sources supplying control circuits operate correctly at voltage higher than the value denoted U_{c0}. In the situation when the intermediate circuit voltage average is insufficient to ensure correct operation of supply circuits, the inverter is unable to generate voltages required to be applied to the motor windings. It is assumed that in the course of normal operation of the drive, the intermediate circuit voltage may change in the range from U_{cmin} to U_{cmax}. In a situation where the intermediate circuit voltage falls into range from U_{c0} to U_{cmin}, the controller's output values are re-scaled in proportion to the intermediate circuit voltage value. With dependence of control on the supply voltage value taken into account, the inverter's voltage gain reference value for the capacitor voltage ranging from U_{c0} to U_{cmin} is

$$m = m_{ref}(u_c(t) - U_{c0})/(U_{c\min} - U_{c0})\,. \tag{10}$$

As a result, switching the drive off by mistake or a supply power failure will result in halting the drive by controller. Temporary input voltage fade-out will not necessarily end with motor stoppage as the energy required to sustain correct operation of electronic control circuits is supplied from the intermediate circuit capacitor additionally recharged by motor operating in power generating mode.

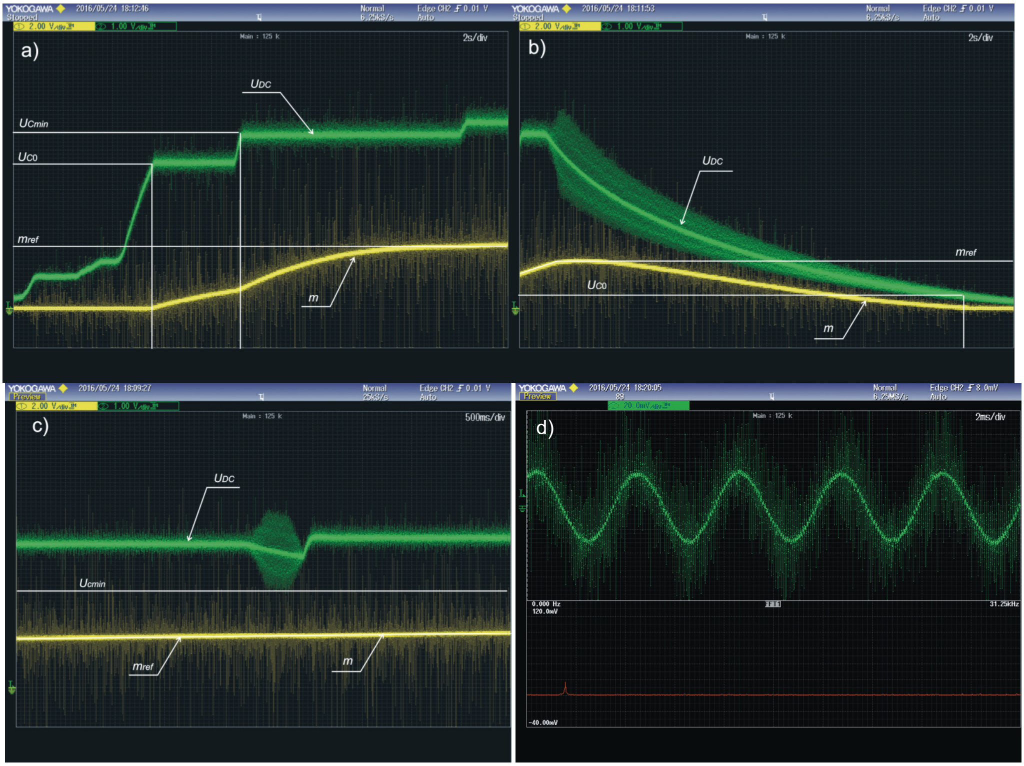

Fig. 10. Measurement results: (a) non-linear increase in DC voltage, (b) switching off DC voltage, (c) temporary DC-link voltage drop, (d) output current in the case of small gain = 0.18 (at 125 Hz)

If the supply voltage appears swift enough at input terminals, the drive will automatically return to normal operation. The interrelation between the DC-link voltage value and the inverter voltage gain imposed by the controller is illustrated in Fig. 9. The measured interactions between the set value of inverter's gain and the DC-link voltage are presented in Fig. 10a–c. If the DC-link voltage is smaller than the U_{C0} value, the set inverter gain m is equal to zero even at non-zero reference value m_{ref}. The inverter gain value m is limited until the DC-link achieves minimal voltage $U_{C\min}$. After this moment a controller controls the voltage to referenced value m_{ref}. The case of rising DC-link voltage from zero after unexpected power off is shown in Fig. 10a. The reaction of controller when the supply power is off is presented in Fig. 10b. In such a situation the inverter gain is falling down to zero at non-zero reference value m_{ref}. If the DC-link voltage is equal to U_{C0}, the inverter's output voltage equals zero and the voltage is sufficient for the controller supply. When the DC-link voltage changes above the $U_{C\min}$ value, then the m_{ref} is not adjusted (Fig. 10c). The output current in the case of small voltage gain has the sinusoidal form. The current wave and Fourier analysis are presented in Fig. 10d.

6. CONCLUSION

High speed motor drive presented in the paper is a good solution in HAs or power tools. The main feature of the solution elaborated is a reduced cost of motor drive resulting from the number of sensors limitation and from reduced motor dimensions arising from the motor operation in a high speed range. The speed control connected with DC-link voltage makes the drive resistant to supply voltage change and when it is off. The proposed drive is automatically stopped when the controller supply voltage is too small for normal operation. In addition, the speed identification allows the motor to be started with a non-zero speed, limiting the possible damage of the switches.

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