Scalar Control of Six-Phase Induction Motor

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***Abstract*—Paper presents MATLAB Simulink model of symmetrical six-phase motor controlled by six-phase frequency converter and analyses its dynamic performance in volts per hertz mode. The new control blocks were elaborated, because Simulink library has no blocks for six-phase motor control. The new reference frame transform blocks were designed for six-phase motor. The experimental stand to validate simulation results was designed and elaborated. Simulation results, compared with experiments indicated good adequacy of designed model.**

Keywords—induction machines; mathematical model; model-driven development; open loop systems; six-phase systems

I. INTRODUCTION

The multiphase motors divide the controlled power on more converter legs and reduce the current of power electronic switches as well as in the larger number of electric motor phase windings. This advantage of multiphase motors leads to solve the main problem of minimization and miniaturization of actuators. The multiphase induction motors have advantages over three phase motors, investigated in [1, 2]: lower torque pulsations at high frequency, higher power per RMS ampere ratio for the same machine volume, reduced the torque ripples in converter fed drives. Beside five phase motors, the six, seven and more phases having motors were designed and investigated. The detailed overview state-of-the art in multiphase electric drives area is presented in the articles [1–4]. The multiphase motors and drives were distinguished for improved reliability: they were able operate under fault conditions in loss one or more converter legs [5–8]. Multiphase machines can start and operate even with some phases open-circuited with not considerable decrease of performance indices. Induction motor performance as a function of phase number is analysed in [9] where measured and calculated phase currents of three phase, four phase, six phase and twelve phase motors having the same stator frame with 48 slots were compared. Data presented in the paper show the current in each stator coil smaller and stator heat loss smaller also with increasing of phase number.

Research in multiphase induction machines in [10] states, that multiphase machine and its control electronics should be considered as a system. Simulation of complex non-linear system even using well-known motor d-q models does not allow using of common simulation packages and needs built in blocks of Matlab/Simulink environment.

Due to mentioned advantages of symmetrical six-phase motors [11– 14] this paper proposes and considers simulation models analysis results symmetrical six-phase motor system with scalar control.

Simulink toolbox "SimPowerSystems" has typical blocks for three phase motors control. It has no blocks for multi-phase motor control. The paper presents designed model of six-phase converter and its control blocks. The experimental stand was elaborated and simulation results were verified experimentally.

II. MATHEMATHICAL MODEL OF SIX-PHASE MOTOR

Multiphase electric motor is described by nonlinear differential equations with time varying mutual inductances. Mathematical description of motor in a stationary three phase reference frame A_s-B_s-C_s due to varying mutual inductances with rotation is seldom used for analysis motor dynamics. Clark proposed convert balanced three phase quantities to orthogonal stationary d^s-q^s (sometimes called α-β) reference frame. Park transformation converts vectors in balanced two-phase reference frame into orthogonal rotating reference frame [15]. Most advanced control systems use both transformations.

Generalized mathematical model of six-phase machine presented in [16] is valid for any displacement angle of stator windings sets and cage rotor. Dynamic equivalent circuit includes mutual stator leakage inductance due to different sets of stator windings occupying the same slot. A d-q mathematical model derived in [17] is applicable for all multi-phase motors and does not include mutual stator leakage inductance. References [16, 17] use the same assumptions: the air gap of the motor is uniform and the distribution of windings is sinusoidal. Magnetic saturation and core losses are neglected.

The motor d-q equations in synchronously rotating reference frame are expressed as voltage drops and as well as across two sets of stator windings and single common rotor winding voltages referred to stator as this [16]:

$$\begin{cases} v_{qs1} = r_s i_{qs1} + \dfrac{d\psi_{qs1}}{dt} + \omega\psi_{ds1}; \\ v_{ds1} = r_s i_{ds1} + \dfrac{d\psi_{ds1}}{dt} - \omega\psi_{qs1}; \end{cases} \quad (1)$$

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and:

$$\begin{cases} v_{\mathrm{qs2}} = r_{\mathrm{s}} i_{\mathrm{qs2}} + \dfrac{\mathrm{d}\psi_{\mathrm{qs2}}}{\mathrm{d}t} + \omega\psi_{\mathrm{ds2}}; \\ v_{\mathrm{ds2}} = r_{\mathrm{s}} i_{\mathrm{ds2}} + \dfrac{\mathrm{d}\psi_{\mathrm{ds2}}}{\mathrm{d}t} - \omega\psi_{\mathrm{qs2}}; \\ v'_{\mathrm{qr}} = r'_{\mathrm{r}} i'_{\mathrm{qr}} + \dfrac{\mathrm{d}\psi'_{\mathrm{qr}}}{\mathrm{d}t} + \left(\omega_0 - \omega_{\mathrm{r}}\right)\psi'_{\mathrm{dr}}; \\ v'_{\mathrm{dr}} = r'_{\mathrm{r}} i'_{\mathrm{dr}} + \dfrac{\mathrm{d}\psi'_{\mathrm{dr}}}{\mathrm{d}t} - \left(\omega_0 - \omega_{\mathrm{r}}\right)\psi'_{\mathrm{qr}}; \end{cases} \tag{2}$$

where flux linkages are aligned with the direct and quadrature axes:

$$\begin{aligned} \psi_{qs1} &= \left(L_{ls} + L_{lm} + L_m\right) i_{qs1} + \left(L_{lm} + L_m\right) i_{qs2} + L_m i'_{qr}; \\ \psi_{ds1} &= \left(L_{ls} + L_{lm} + L_m\right) i_{ds1} + \left(L_{lm} + L_m\right) i_{ds2} + L_m i'_{dr}; \\ \psi_{qs2} &= \left(L_{ls} + L_{lm} + L_m\right) i_{qs2} + \left(L_{lm} + L_m\right) i_{qs1} + L_m i'_{qr}; \\ \psi_{ds2} &= \left(L_{ls} + L_{lm} + L_m\right) i_{ds2} + \left(L_{lm} + L_m\right) i_{ds1} + L_m i'_{dr}; \\ \psi'_{qr} &= \left(L'_{lr} + L_m\right) i'_{qr} + L_m \left(i_{qs1} + i_{qs2}\right); \\ \psi'_{dr} &= \left(L'_{lr} + L_m\right) i'_{dr} + L_m \left(i_{ds1} + i_{ds2}\right). \end{aligned} \tag{3}$$

Notations used in the formula sets (1), (2) and (3) are: ψ_{qs1}, ψ_{qs2} are stator q axis flux linkage components; ψ_{ds1}, ψ_{ds2} are stator d axis flux linkage components; ψ'_{qr}, ψ'_{dr} are rotor q and d axis flux linkage components; L_{ls} is stator leakage inductance; L_{lm} is mutual stator leakage inductance; L_{m} is air gap inductance; L'_{lr} is rotor leakage inductance; i_{qs1}, i_{qs2} are stator q axis current components; i_{ds1}, i_{ds2} are stator d axis components; i'_{qr} and i'_{dr} are correspondingly rotor current q and d axis components; ω_{r} is rotational speed of two-pole motor.

The electromagnetic torque calculated according to formula:

$$\begin{aligned} T_{\mathrm{e}} = \frac{3}{2}\left(\frac{P}{2}\right)\left(\frac{L_{\mathrm{m}}}{L'_{\mathrm{lr}}}\right) &\left[\psi'_{\mathrm{dr}}\left(i_{\mathrm{qs1}} + i_{\mathrm{qs2}}\right)\right. \\ &\left. -\psi'_{\mathrm{qr}}\left(i_{\mathrm{ds1}} + i_{\mathrm{ds2}}\right)\right], \end{aligned} \tag{4}$$

where P is number of poles.

The equation of drive movement is expressed as:

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{1}{J_{\mathrm{r}}}\left(T_{\mathrm{e}} - T_{\mathrm{L}}\right), \tag{5}$$

where ω is motor rotational speed, J_{r} is rotor inertia, T_{e} is electromagnetic torque and T_{L} is load torque.

III. SIMULINK MODEL OF SIX-PHASE INDUCTION MOTOR

Simulink model gives possibility to solve nonlinear differential equations fast and allows comparing parameters at different load or control mode. Matlab/Simulink d-q model of six-phase induction motor in synchronous reference frame is presented in [18, 19]. Inputs of the model is direct current voltages v_{qs1} and v_{qs2}, voltages v_{ds1} and v_{ds2} as well as v'_{qr} and v'_{dr} are assumed equal to zero. Outputs of the model are produced electromagnetic torque and speed. Similar models are ideal models and do not reflect influence of control system power converters and other control system elements usually operating in real electric drive systems.

Simulink library does not contain six-phase converter models and switching blocks necessary to elaborate pulses for converter, producing six-phase output voltages, shifted by 60 electrical degrees. This problem we solved with two three-phase converters, using Clark transform for two sets of three phase voltages with different initial phase angles θ having values of zero and -60 electrical degrees. The Clark transform is used separately for two voltage sets v_{As}, v_{Bs}, v_{Cs} and v_{Ds}, v_{Es}, v_{Fs}. Then for six-phase converter model we can use two conventional three-phase Simulink blocks named “Three phase converter 1” and “Three phase converter 2” controlled by conventional blocks “PWM generator 1” and “PWM generator 2” operating in synchronized mode. The first converter elaborates voltages by 0, –120, –240 electrical degrees with respect to v_{As} reference axis. PWM generator 2 is tuned to produce the other set of voltages v_{Ds}, v_{Es}, v_{Fs} shifted by -120 electrical degrees apart with phase voltage v_{Ds} lagging the voltage v_{As} by 60°.

If stationary d^{s}-q^{s} axes of three phase machine are oriented at angle θ, the voltages $v^{\mathrm{s}}_{\mathrm{ds1}}$ and $v^{\mathrm{s}}_{\mathrm{qs1}}$ can be represented in matrix form as:

$$\begin{bmatrix} v_{\mathrm{As}} \\ v_{\mathrm{Bs}} \\ v_{\mathrm{Cs}} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120^{\circ}) & \sin(\theta - 120^{\circ}) & 1 \\ \cos(\theta + 120^{\circ}) & \sin(\theta + 120^{\circ}) & 1 \end{bmatrix} \begin{bmatrix} v^{\mathrm{s}}_{\mathrm{qs1}} \\ v^{\mathrm{s}}_{\mathrm{ds1}} \\ v^{\mathrm{s}}_{\mathrm{0s1}} \end{bmatrix} \tag{6}$$

where $v^{\mathrm{s}}_{\mathrm{0s}}$ is zero component. In a balanced machine without a neutral wire $v^{\mathrm{s}}_{\mathrm{0s}} = 0$.

Inverse transform of (6) is presented in (7):

$$\begin{bmatrix} v^{\mathrm{s}}_{\mathrm{qs1}} \\ v^{\mathrm{s}}_{\mathrm{ds1}} \\ v^{\mathrm{s}}_{\mathrm{0s1}} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 120^{\circ}) & \cos(\theta + 120^{\circ}) \\ \sin\theta & \sin(\theta - 120^{\circ}) & \sin(\theta + 120^{\circ}) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{\mathrm{As}} \\ v_{\mathrm{Bs}} \\ v_{\mathrm{Cs}} \end{bmatrix}. \tag{7}$$

Taking $\theta = 0$, the q^{s} axis is aligned with the v_{As} axis. Without zero component, transformation is presented in (8):

$$\begin{aligned} v_{\mathrm{As}} &= v_{\mathrm{qs1}}^{\mathrm{s}}; \\ v_{\mathrm{Bs}} &= -\frac{1}{2}v_{\mathrm{qs1}}^{\mathrm{s}} - \frac{\sqrt{3}}{2}v_{\mathrm{ds1}}^{\mathrm{s}}; \\ v_{\mathrm{Cs}} &= -\frac{1}{2}v_{\mathrm{qs1}}^{\mathrm{s}} + \frac{\sqrt{3}}{2}v_{\mathrm{ds1}}^{\mathrm{s}}, \end{aligned} \tag{8}$$

and the inverse transform becomes:

$$\begin{aligned} v_{\mathrm{qs1}}^{\mathrm{s}} &= \frac{2}{3}v_{\mathrm{As}} - \frac{2}{3}v_{\mathrm{Bs}} - \frac{2}{3}v_{\mathrm{Cs}} = v_{\mathrm{As}}; \\ v_{\mathrm{ds1}}^{\mathrm{s}} &= \frac{1}{\sqrt{3}}v_{\mathrm{Bs}} + \frac{1}{\sqrt{3}}v_{\mathrm{Cs}}. \end{aligned} \tag{9}$$

The synchronously rotating d^e-q^e axes rotate with speed ω_e with respect to d^s-q^s axes and form the angle $\theta_e = \omega_e t$. Subscript e often is omitted in synchronously rotating parameters [20]. The voltages on d^s-q^s axes can be transformed into rotating d-q axes by this way:

$$\begin{aligned} v_{\mathrm{qs1}} &= v_{\mathrm{qs1}}^{\mathrm{s}}\cos\theta_{\mathrm{e}} - v_{\mathrm{ds1}}^{\mathrm{s}}\sin\theta_{\mathrm{e}}; \\ v_{\mathrm{ds1}} &= v_{\mathrm{qs1}}^{\mathrm{s}}\sin\theta_{\mathrm{e}} + v_{\mathrm{ds1}}^{\mathrm{s}}\cos\theta_{\mathrm{e}}. \end{aligned} \tag{10}$$

Transformation of rotating reference frame into stationary is related by formulas:

$$\begin{aligned} v_{\mathrm{qs1}}^{\mathrm{s}} &= v_{\mathrm{qs1}}\cos\theta_{\mathrm{e}} + v_{\mathrm{ds1}}\sin\theta_{\mathrm{e}}; \\ v_{\mathrm{ds1}}^{\mathrm{s}} &= -v_{\mathrm{qs1}}\sin\theta_{\mathrm{e}} + v_{\mathrm{ds1}}\cos\theta_{\mathrm{e}}. \end{aligned} \tag{11}$$

Thus sinusoidal variables in synchronously rotating reference frame appear as dc quantities.

v_{Ds}, v_{Es} and v_{Fs} are transformed to stationary reference frame in the same way as three phase voltages that are shifted by 120^0 apart and with phase voltage v_{Ds} lagging behind the voltage v_{As} by 60 electrical degrees:

$$\begin{aligned} &\begin{bmatrix} v_{\mathrm{Ds}} \\ v_{\mathrm{Es}} \\ v_{\mathrm{Fs}} \end{bmatrix} = \\ &\begin{bmatrix} \cos(\theta-60°) & \sin(\theta-60°) & 1 \\ \cos(\theta-180°) & \sin(\theta-180°) & 1 \\ \cos(\theta-300°) & \sin(\theta-300°) & 1 \end{bmatrix} \begin{bmatrix} v_{\mathrm{qs2}}^{\mathrm{s}} \\ v_{\mathrm{ds2}}^{\mathrm{s}} \\ v_{\mathrm{0s2}}^{\mathrm{s}} \end{bmatrix} \end{aligned} \tag{12}$$

and inversely:

$$\begin{aligned} &\begin{bmatrix} v_{\mathrm{qs2}}^{\mathrm{s}} \\ v_{\mathrm{ds2}}^{\mathrm{s}} \\ v_{\mathrm{0s2}}^{\mathrm{s}} \end{bmatrix} = \\ &= \frac{2}{3}\begin{bmatrix} \cos(\theta-60^0) & \cos(\theta-180^0) & \cos(\theta-300^0) \\ \sin\theta & \sin(\theta-180^0) & \sin(\theta-300^0) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{\mathrm{Ds}} \\ v_{\mathrm{Es}} \\ v_{\mathrm{Fs}} \end{bmatrix}. \end{aligned} \tag{13}$$

Voltages $v_{\mathrm{qs2}}^{\mathrm{s}}$ and $v_{\mathrm{ds2}}^{\mathrm{s}}$ can be transformed to synchronously rotating reference frame:

$$\begin{aligned} v_{\mathrm{qs2}} &= v_{\mathrm{qs2}}^{\mathrm{s}}\cos\theta_{\mathrm{e}} - v_{\mathrm{ds2}}^{\mathrm{s}}\sin\theta_{\mathrm{e}}; \\ v_{\mathrm{ds2}} &= v_{\mathrm{qs2}}^{\mathrm{s}}\sin\theta_{\mathrm{e}} + v_{\mathrm{ds2}}^{\mathrm{s}}\cos\theta_{\mathrm{e}}, \end{aligned} \tag{14}$$

where $\theta_{\mathrm{e}} = \omega_{\mathrm{e}}\mathrm{t}$ remains the same.

Inverse transform looks like this:

$$\begin{aligned} v_{\mathrm{qs2}}^{\mathrm{s}} &= v_{\mathrm{qs2}}\cos\theta_{\mathrm{e}} + v_{\mathrm{ds2}}\sin\theta_{\mathrm{e}}; \\ v_{\mathrm{ds2}}^{\mathrm{s}} &= -v_{\mathrm{qs2}}\sin\theta_{\mathrm{e}} + v_{\mathrm{ds2}}\cos\theta_{\mathrm{e}}. \end{aligned} \tag{15}$$

Thus we can apply equations for transform of two three phase voltage sets having with 120° degrees apart and displaced one from other by –60 electrical degrees.

Motor model is elaborated according equations has two quadrature axis inputs v_{qs1} and v_{qs2} supplied by constant voltage equal to peak value of sine wave phase voltage. Direct axes voltages v_{ds1} and v_{ds2} are assumed equal to zero.

Outputs of Simulink model are delivered torque, speed and currents i_{qs1}, i_{ds1} and i_{dr}', i_{qr}' in d-q reference frame. They can be transformed to stationary reference frame d^s-q^s according to equations similar as (11) and then to three phase reference frame according to equation (8). Currents i_{qs2} and i_{ds2} are transformed to stationary reference frame according to equation similar to (15) and to three phase system according to (12).

The model shown in Fig. 1 consists of two conventional three-phase Simulink blocks named “Converter 1” and “Converter 2” controlled by blocks “PWM generator 1” and “PWM generator 2”. Switching pulses at the output of the block “Converter 1” produce voltage set with shift in phase 0, -120, -240 electrical degrees with respect to reference axis, corresponding v_{As} direction of conventional three phase system. Block “PWM generator 2” generates pulses for block “Converter 2” to produce the set of three phase voltages v_{Ds}, v_{Es} and v_{Fs}, where initial phase voltage v_{Ds} is shifted by 60 electrical degrees with respect to the voltage v_{As} generated by the block "Converter 1", so it produces three phase voltage set, shifted by -60, -180 and -300 electrical degrees.

This control method of both two three-phase converters allows getting six phase voltage system with each phase voltage shifted by 60 electrical degrees.

Motor model is designed in synchronously rotating reference frame according to equations (1–5). It has two quadrature axis inputs v_{qs1} and v_{qs2} supplied by constant voltage equal to peak value of converter output voltage. Direct axes voltages v_{ds1} and v_{ds2} are assumed equal to zero. Output of each converter produces system of three phase voltages, which are converted to stationary two-phase system correspondingly by equations (9) and (13). Other two blocks fulfil transform from stationary reference frame to synchronously rotating frame by equations (10) and (14). Output of these blocks is direct current voltage. These signals are transferred to motor model. Transform formulas similar to (11, 8) and (15, 12), where voltage variable is replaced by current variable, are used to calculate six phase currents of the motor. The electromagnetic torque, developed by six-phase motor at no load is shown in Fig. 2.

Velocity at starting is shown in Fig. 3. Transform formulas similar to (11, 8) and (15, 12) are used to calculate currents of six-phase motor. Fig. 4 presents all six starting currents of motor at no load.

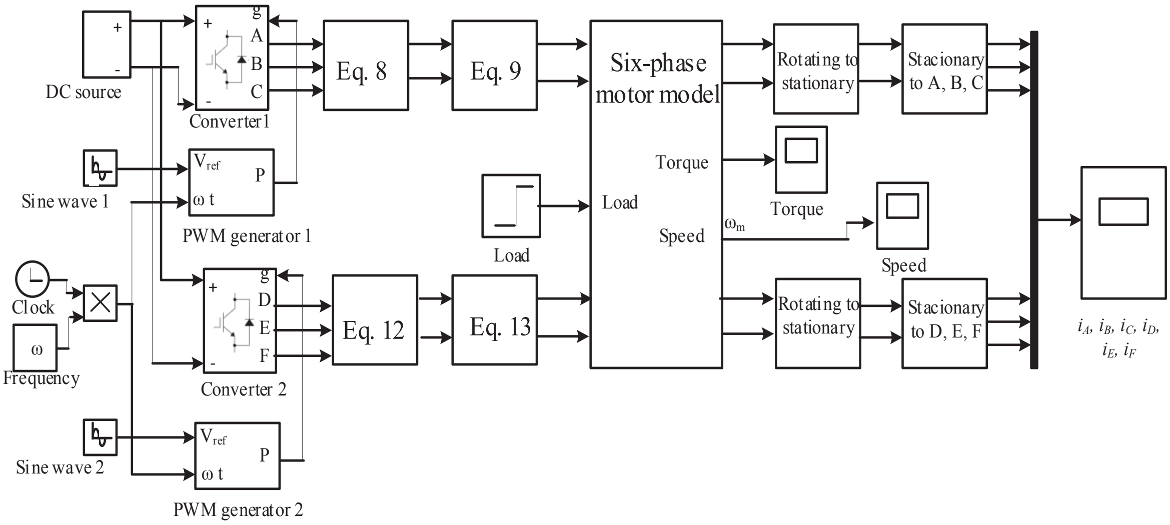

Fig. 1. Model of frequency controlled six phase motor.

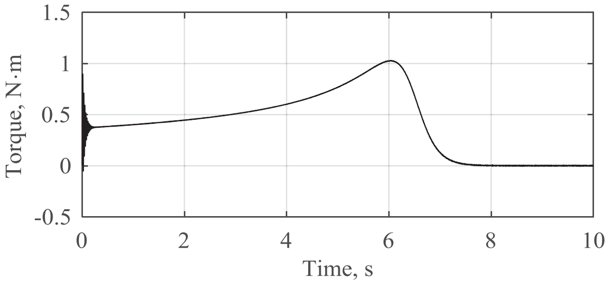

Fig. 2. Starting torque of motor at no load.

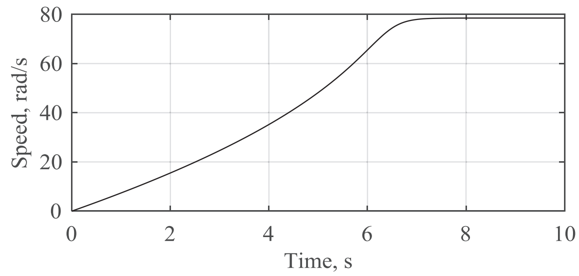

Fig. 3. Starting speed at no-load.

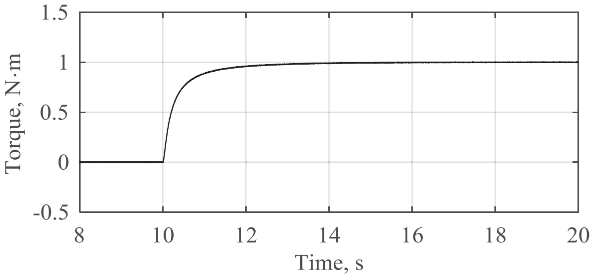

Fig. 4. Dynamic torque at motor loading by 1 Nm load.

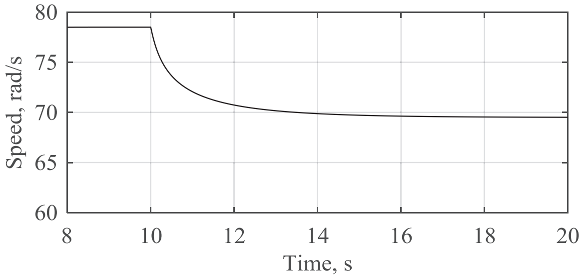

Fig. 5. Six-phase motor speed at loading by 1 N·m load.

The maximum starting current value at starting reaches 0.72 A. With speed it reduces up to 0.4 A.

Figures 5, 6 and 7 present six-phase motor torque, speed and currents at loading by 1 N·m.

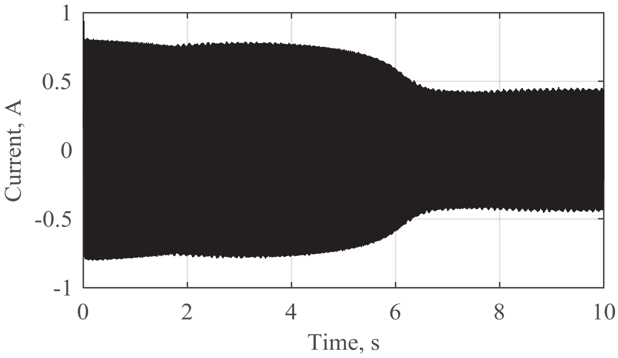

Fig. 6. Motor current at no-load starting.

At loading motor speed from synchronous speed 78.5 rad/s reduces up to 69 rad/s, i.e. motor operates with slip equal to 12%.

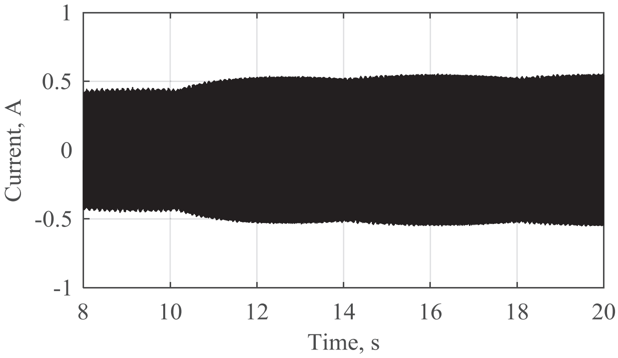

Fig. 7. Motor current at loading.

Motor current at loading by 1 N·m load increases from 0.4 A up to 0.5 A.

IV. Experimental Experimental Investigation of Frequency Controlled Six-Phase

Drive experimental rig shown in Fig. 5 consists of six-phase motor, supplied by six-phase frequency converter, producing six phase voltages, shifted by 60 electrical degrees. Computer serves as controlling device for converter. Axes of direct current motor and experimental motor are fitted via couplings with torque and speed measuring device. Both devices are supplied by direct current voltage. Motor torque, speed and currents were recorded with oscilloscope. Picture of real experimental stand is shown in Fig. 5.

The six-phase motor parameters were measured experimentally performing locked rotor and no load tests. Leakage mutual inductance L_{lm} was defined experimentally also. Motor parameters are presented in Table I.

Inertia of rotor is 0.029 kg·m^2 and number of poles is 8.

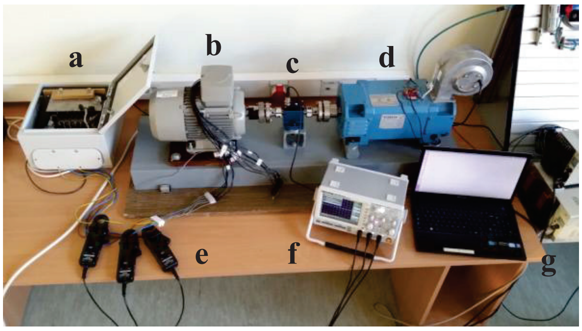

Fig. 8. Experimental rig: a) six–phase voltage source inverter, b) six–phase induction motor, c) torque sensor, d) dc generator as load, e)current clamps, f) osciloscope, g) personal computer.

TABLE I. SIX-PHASE MOTOR PARAMETERS

Parameter	r_s	$r`_r$	L_m	L_{ls}	$L`_{lr}$	L_{lm}
Value	68	4.5	0,295	0.07	0.115	0.07
Units	Ω	Ω	H	H	H	H

Experimental results shown in Fig. 9 starts at time instant $t = 1$. Figure 9 indicates motor current, speed and torque at no-load starting. Torque rises up to maximum value 0.6 N·m and with rising of speed, shown in Fig. 9, b), reduces to load torque due mechanical and ventilation loss.

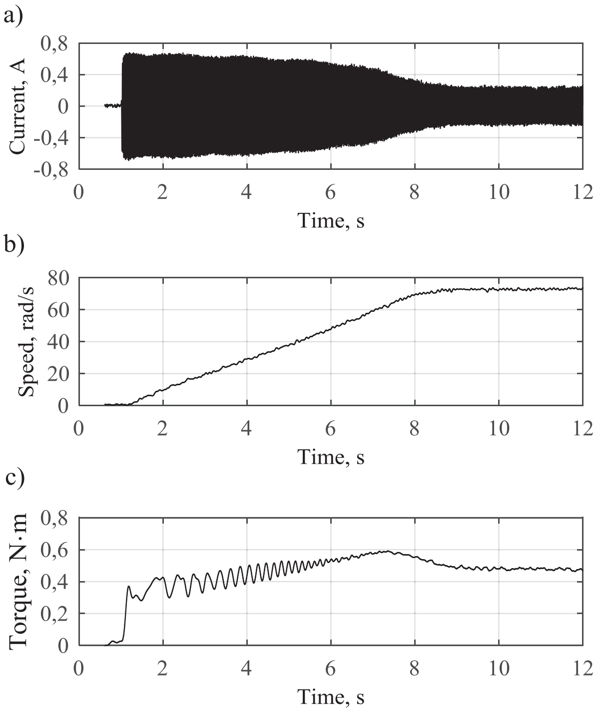

Fig. 9. Transient processes of six-phase frequency drive, when the frequency of supply voltage is 50 Hz: a) stator current, b) rotor speed, c) torque.

Speed reaches steady state value about 78 rad/s. Settling time is about 7 s.

Comparison of simulated and experimental currents (Fig. 4 and Fig. 9, a)) and speed transients (Fig. 3 and Fig. 9, b)) show good adequacy between simulated and measured values. The greater difference is in torque transients due to impossibility to fix initial oscillations experimentally.

V. CONCLUSIONS

Elaborated Simulink model of frequency controlled six-phase motor gives possibility to form two sets of voltages shifted by 60 electrical degrees using two typical three phase converters with application of two PWM generators controlled by specially tuned two Sine wave blocks, establishing the sets of generated three phase voltages. Possibility to keep ratio of output voltage RMS value and frequency constant is solved.

Experimental results compared with simulated indicate good adequacy of speed and current transients. We indicated that simulation of torque transients requires identifying motor parameters more exactly. This will be solved in the nearest future.

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