FIELD ORIENTED CONTROL OF A SYNCHRONOUS DRIVE

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Abstract. **Field oriented control (FOC) may be used for simple high-power synchronous drives, such as pumps and fans, to unify system with asynchronous drives. But distinction is strong influence of torque component of current on flux. Internal feedback in control object is investigated. This feedback becomes positive one in definite regimes.**

A simple addition in control is proposed, based on features of control object: component of reference for excitation current as function of torque reference and flux reference. Special parameters should be used for flux regulator.

Positive results are confirmed by tests at virtual test bench of high-power AC drives.

I. Tasks of the Paper

Field oriented control (FOC) isn't preferable control method for synchronous drive. A method was proposed for synchronous drive already in [1] – the control in rotating coordinates, and they are *d*, *q* coordinates of ***rotor***. And the first publication on rotor oriented control (ROC) took place a month before the first publication on FOC [2]. ROC is developed further, for example in [3], [4]. Nevertheless, FOC may be expedient for synchronous drives, at least for usual drives as pumps, fans, grinding mills etc. This provides unification of control for asynchronous and synchronous drives.

Simplified functional diagram for FOC of asynchronous drive is shown on Fig. 1 (black lines).

External speed control loop isn't shown. Stator of motor is supplied from frequency converter. Different kinds of frequency converter (FC) are used for FOC: cycloconverter, VSI with PWM, CSI with PWM. Current regulation is included conditionally in FC on diagram. All the variables and parameters are considered here as relative values, besides of time and time constants.

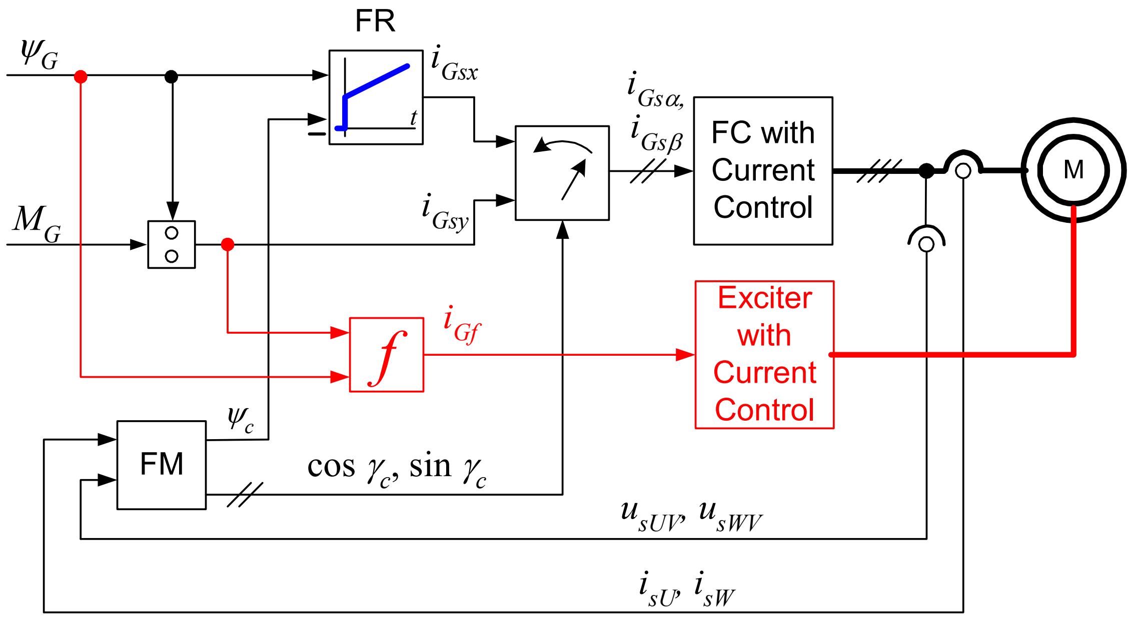

Fig. 1. Simplified functional diagram for FOC of asynchronous drive and a simple addition for synchronous drive (red)

Inputs of FOC are torque reference M_G and flux reference ψ_G. Outputs of this part of the algorithm are current references $i_{Gs\alpha}$, $i_{Gs\beta}$, in stator frame α, β. FOC is oriented on direction of definite flux vector $\boldsymbol{\psi}_c$. Element *FM* forms feedback signal ψ_c – module of this flux vector and direction vector $\mathbf{d}_c$ = (cos γ_c, sin γ_c) for this flux in stator frame. Controlled flux is defined usually through stator flux and current vectors:

$$\boldsymbol{\psi}_c = \boldsymbol{\psi}_s - L_e\, \mathbf{i}_s. \tag{1}$$

Equivalent inductance L_e is accepted usually for asynchronous drive as $L_e \approx L_\sigma = L_{s\sigma} + L_{r\sigma}$, and they consider controlled flux as rotor flux. Vector diagram is represented on Fig. 2.

Controlled flux is defined by magnetizing component of stator current i_{s1}. Correspondingly flux regulator *FR* forms reference for magnetizing component of stator current i_{Gs1}.

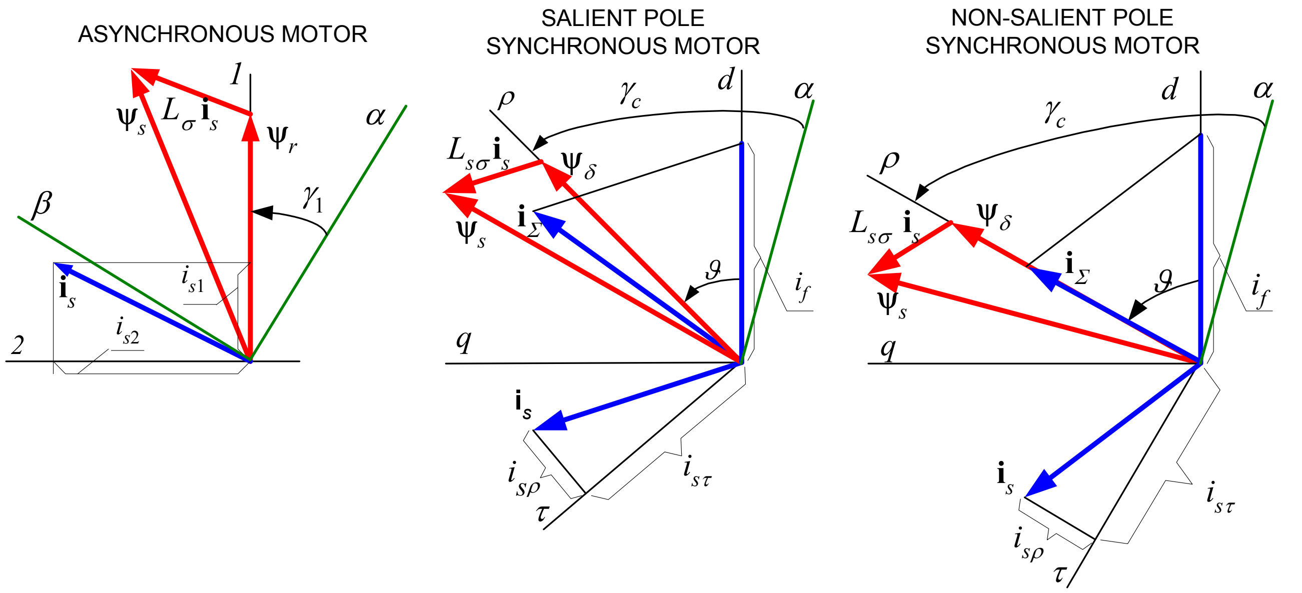

Fig. 2. Vector diagrams for asynchronous and synchronous motors

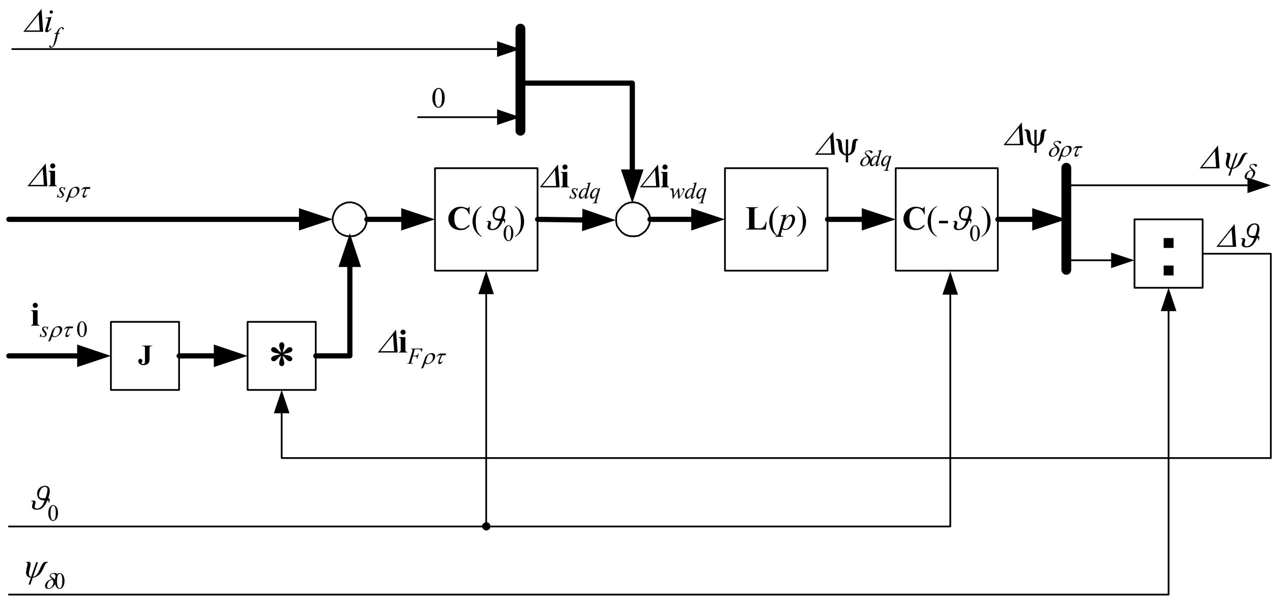

Fig. 3. Structural diagram of control object for synchronous drive with FOC

Torque component of current reference i_{Gs2} is formed from torque reference. Thus current reference is formed in axes *1, 2* oriented on flux vector.

In synchronous motor with electromagnet excitation torque component of stator current influence strongly on flux, and autonomous control of flux in flux frame is impossible one.

Tasks of this work are as follows: investigation of synchronous drive specifics with FOC; finding and tests of simple solution for improvement of FOC for synchronous drive.

II. Specific of a Synchronous Drive with Flux Oriented Control

A. Controlled flux

We are urged to consider module of main flux (air gap flux) vector as control variable of the flux control loop for synchronous drive.

Vector diagrams for steady-state regime of synchronous motors are shown on Fig. 2.

Designations are as follows: d, q – rotor axes; $\mathbf{i}_s$ - stator currents vector; ψ_s - stator flux linkages vector; ψ_δ - vector of main magnet flux (air gap flux); ρ - direction of vector ψ_δ; τ - orthogonal leading direction to vector ψ_δ; ϑ - angle between vector ψ_δ and axis d; $i_{s\rho}$, $i_{s\tau}$, - magnetizing and torque components of stator current, i_f – excitation current, $L_{s\sigma}$ - leakage inductance of stator, R_{cd}, R_{cq} –resistances of damping loops in d, q axes.

Correspondingly in relation (1) $\psi_c = \psi_\delta$ and $L_e = L_{s\sigma}$.

B. General equations

Saturation isn't taken into account. Additional designations for non-saturable motor are as follows: L_{md}, L_{mq} – inductance for main flux in d, q axes, L_{cd}, L_{cq} – full inductances of damping loops in d, q axes.

For non-salient pole motor : $L_{md} = L_{mq}$.

Main relations for synchronous drive with FOC are deduced:

$$i_{sd} = i_{s\rho}\cos\vartheta - i_{s\tau}\sin\vartheta; i_{sq} = i_{s\rho}\sin\vartheta + i_{s\tau}\cos\vartheta;$$

$$\psi_{\delta d} = \psi_\delta \cos\vartheta; \psi_{\delta q} = \psi_\delta \sin\vartheta;$$

$$\psi_{\delta d} = L_{md}(i_f + i_{sd}); \psi_{\delta q} = L_m i_{sq};$$

$$\psi_\delta \sin\vartheta = L_{mq}(i_{s\rho}\sin\vartheta + i_{s\tau}\cos\vartheta).$$

In particular, such general result for ϑ angle is useful:

$$\tan\vartheta = \frac{i_{s\tau}}{\psi_\delta / L_{mq} - i_{s\rho}}. \qquad (2)$$

C. Structural diagram of the control object

For small deviations the equations are represented in graphical form as structural diagram on Fig. 3.

Designations are as follows: $\Delta\psi_{\delta dq}$ – deviation of main flux vector in d, q frame, $\Delta\mathbf{i}_{wdq}$ – deviation of vector of the windings sum current in d, q frame (stator and excitation), $\mathbf{L}(p)$ – transient operator that expresses deviation of flux vector through deviation of sum current vector in chosen steady-state regime, Δi_f – deviation of excitation current, $\Delta\mathbf{i}_{s\rho\tau}$ - deviation of stator current vector in ρ, τ frame, $\mathbf{i}_{s\rho\tau0}$ – vector of stator current for chosen steady-state regime, $\psi_{\delta0}$ – main flux for chosen steady-state regime, $\Delta\psi_{\delta\rho\tau0}$ – deviation of main flux vector in initial ρ, τ frame, corresponding chosen steady-state regime; matrices on the diagram are as follows:

$$\mathbf{C}(\vartheta_0) = \begin{pmatrix} \cos\vartheta_0 & -\sin\vartheta_0 \\ \sin\vartheta_0 & \cos\vartheta_0 \end{pmatrix}, \mathbf{J} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}.$$

Inputs of control object are deviation vector of stator current $\Delta\mathbf{i}_{s\rho\tau}$ and deviation of excitation current Δi_f. Outputs are deviation of main flux $\Delta\psi_\delta$ and deviation of angle $\Delta\vartheta$.

D. Features of the object in flux control loop

Features of object in flux control loop are investigated with flux control through magnetizing stator current. Equations, features of frequency response and time response are analyzed.

It follows (2), that in salient pole motor magnetizing stator current has influence on steady-state value of angle ϑ. Thus ***feedback exists, and it is a positive feedback. Unexpected feature of flux amplification is found***. Equivalent value for differential magnetizing inductance and equivalent time constant may be increased with increasing load up to 2-3 times.

Composing features of control object (with control through magnetizing current and constant excitation current) for steady-state regimes and for middle frequency range, we can approximate object by such equation:

$$\Delta\psi_\delta \approx \frac{1}{1/L_{me} + p/(R_{mf}\Omega_b)}\Delta i_{s\rho}. \qquad (3)$$

Equations are found for parameters in this approximation.

$$K_{\rho.st} = \frac{1}{1 - (L_{md} - L_{mq})\cos\vartheta_0 \sin\vartheta_0 i_{s\tau0}/\psi_{\delta0}}.$$

$$L_{me} = K_{\rho.st}\left(L_{md}\cos^2\vartheta_0 + L_{mq}\sin^2\vartheta_0\right) \qquad (3)$$

$$R_{mf} = \frac{R_{cd}L_{md}}{L_{cd}}\cos^2\vartheta_0 + \frac{R_{cq}L_{mq}}{L_{cq}}\sin^2\vartheta_0. \qquad (4)$$

Dependence of equivalent parameters from load (from torque component of stator current $i_{s\tau}$) is shown for an example of salient-pole motor 5 MW, 1500 rpm on Fig.4. This is real motor of blower drives. Motor parameters are as follows: L_{md} = 2.7; L_{mq} = 1.2; $L_{s\sigma}$ = 0.1; $L_{cd\sigma}$= 0.15; $L_{cq\sigma}$=0.16; R_s = 0.0065; R_f= 0.0014; R_{cd} = 0.019; R_{cq} = 0.027. Electromechanical time constant of the drive is T_j = 30 s.

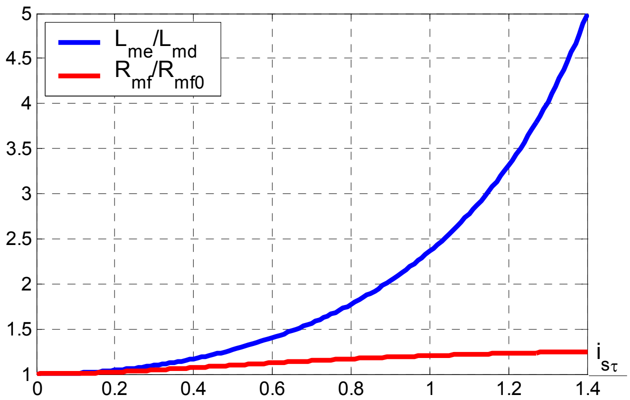

Fig. 4. Equivalent parameters of a salient-pole synchronous motor

Characteristics correspond to steady-state regime with $\psi_{\delta0}$ = 1 and magnetizing component of stator current as function of flux:

$$i_{s\rho} = \frac{R_f}{R_s + R_f} \frac{\psi_\delta}{L_{md}}. \quad (5)$$

This is close to optimal value of magnetizing stator current, [3].

For this example equivalent differential inductance L_{me} exceeds inductance L_{md} approximately 2-times in rated regime. Parameter R_{mf} hasn't essential change.

This analysis may be used for choice of drive programmable parameters.

III. PROPOSED SOLUTION

A simple addition to FOC of asynchronous drive is shown on Fig. 1 by red lines. This is element *f*, forming reference for excitation current i_{Gf}. Function is proposed as accurate one for non-salient pole motor and gives good approximation for salient pole motor.

$$i_{Gf} = \sqrt{(\psi_G / L_{md})^2 + i_{Gs\tau}^2}. \quad (6)$$

Characteristics of excitation current are shown on Fig.5 for previous example.

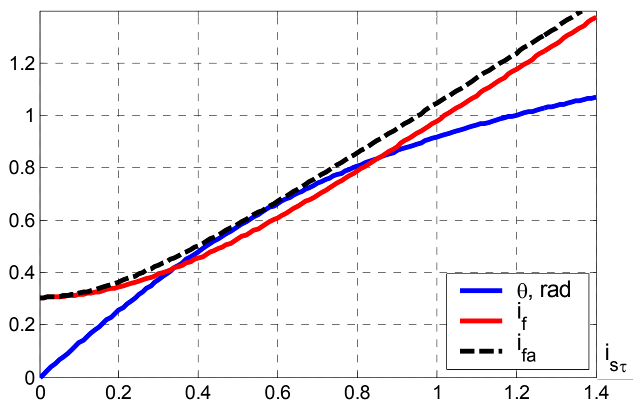

Fig. 5. Excitation current of the synchronous motor

Characteristics correspond to regimes with flux $\psi_\delta = 1$ and magnetizing stator current according to (5). Excitation current i_f is calculated using accurate equations, and current i_{fa} corresponds to approximation (6). We see enough suitable approximation.

Flux regulator in proposed solution is the same as for asynchronous drive. Only parameters should be calculated specifically according Part II.

Such solution provides automatic control only for torque and main flux. But synchronous motor as control object has 3-dimensional input. Opportunity exists for automatic control of magnetizing stator current in addition. With considered solution accuracy for magnetizing current depends on accuracy of approximation (6). With known ROC systems for synchronous drives (for example, [1], [3]) 3-dimensional control is provided. Such control is proposed by evident addition to proposed solution in frames of FOC also, but this isn't considered here.

IV. INVESTIGATION OF PROCESSES AT VIRTUAL TEST BENCH

A. Test bench

Tests are performed at virtual test bench of MV controlled drives. The bench includes real control cabinet of the serial MV controlled drive PowerFlex 7000 and computer model of drive power part, operating in real time. Diagram of the test bench is shown on Fig. 6.

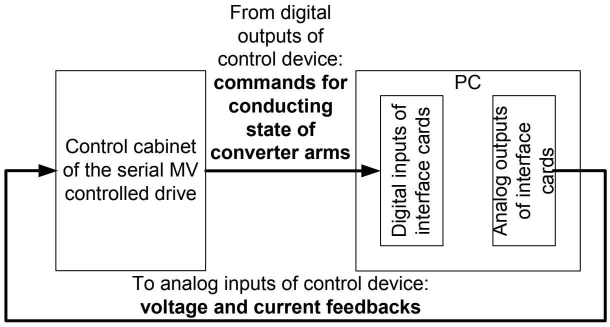

Fig. 6. Virtual test bench of MV drives

Model of the power part includes mechanism, motor, frequency converter, power supply. Practical coincidence of processes of the bench and real operating MV drives was confirmed many times previously.

B. Investigated drive and results of tests

The blower synchronous drive is tested with salient-pole motor 5 MW, 1500 rpm, 50 Hz and frequency converter on the base of PWM CSI. Simplified diagram of the drive is shown on Fig. 7. Motor parameters were represented in Part II. Frequency converter includes 18-pulse thyristor converter on line side and PWM current inverter on motor side. Intermediate DC link includes reactor with inductance L_D = 0.96. Capacitor battery with capacitance C_M = 0.38 is connected to inverter output. Maximal used modulation frequency is 300 Hz.

Structure of system corresponds to Fig. 1; parameters of flux regulator are calculated on the base of Part II of this paper. Bandwidths of control loops are as follows: for current control loop Ω_i = 200 rad/s; for flux control loop Ω_ψ = 2.5 rad/s; for speed control loop Ω_v = 1 rad/s.

Example of processes with load step-up – step-down is shown on Fig. 8. Processes are suitable ones.

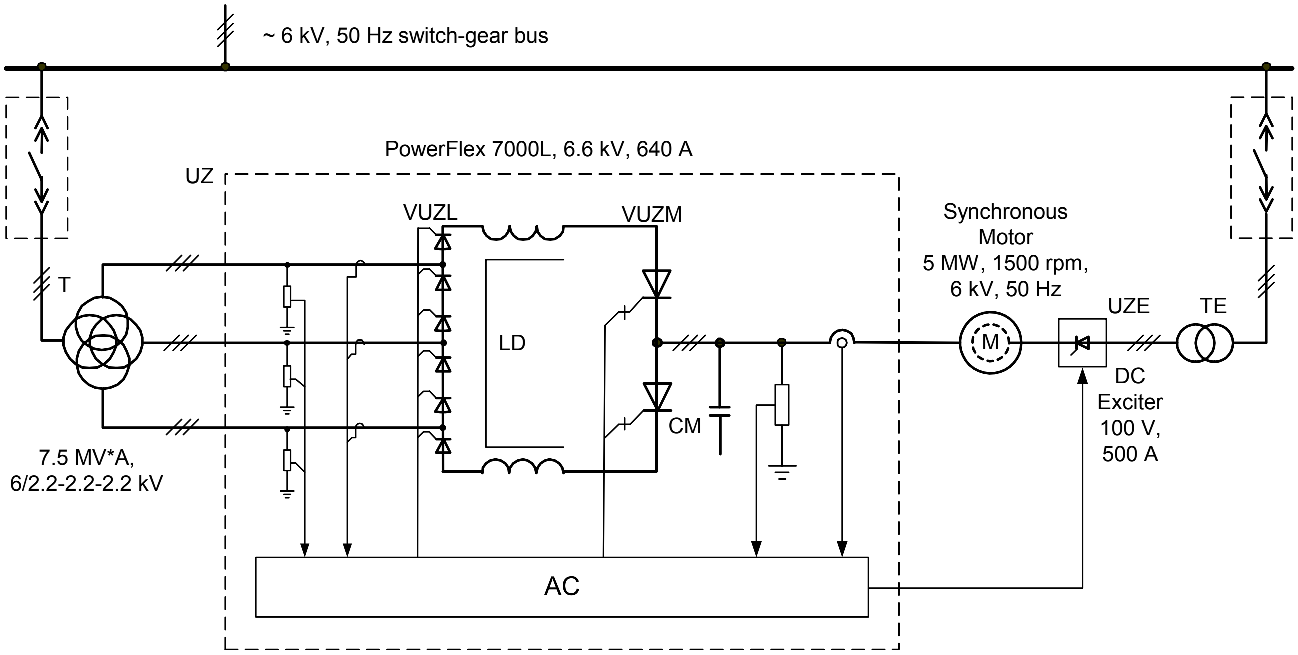

Fig. 7. Simplified diagram of the investigated drive

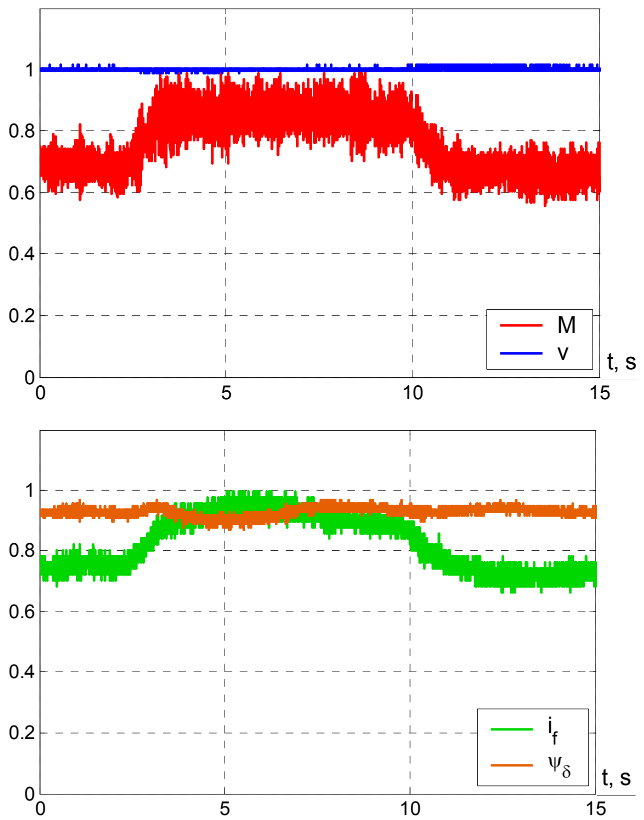

Fig. 8. Drive processes with load step-up and step-down

Results of tests at virtual bench confirm results of theoretical analysis. They confirm that suitable features are achievable even with the simplest excitation control in function of reference of the torque component of stator current. But these are suitable for drives without special requirements to control quality.

V. Conclusion

Field oriented control (FOC), used commonly in asynchronous drives, looses its advantages in synchronous drive. But FOC may be used for simple high-power synchronous drives with proposed addition in control and proposed special choice of parameters, based on features of control object.

Positive results are confirmed by tests at virtual test bench of high-power AC drives.

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