POTENTIAL OF AC DRIVES WITH SEMI-CLOSED CONTROL

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Abstract. Control systems are considered for synchronous and asynchronous AC drives that combine advantages of open-loop and closed-loop systems. They operate as open-loop systems for quick processes and as closed-loop ones for slow processes. Application field covers mainly high-power MV controlled drives. In this field known methods don't provide desired results because of specifics of high-power frequency converters. These are: low and sometimes unlimitedly low frequency of system closing, resonant stator circuits.

Considered systems are composed on the base of methods of non-linear multi-connected subordinate control systems those are supplemented by principle of semi-closed control. These provide high quick-responsibility and high accuracy of control, type dynamics. As an example the synchronous drive is considered on the base of PWM CSI. Simulation showed that results are suitable for most of high-power controlled drives including most dynamical ones.

I. TASKS OF THE PAPER

Modern controlled AC drives are performed with open-loop control as well as with closed-loop control. Each variant has own advantages. Open-loop control provides high-quick responsibility. Closed-loop control provides high accuracy and suppressing of some external influences, type dynamics.

In the field of high-power medium voltage (MV) AC drives frequency converters are used with relatively low frequency of system closing. They are VSI and CSI with modulation frequency up to 0.6 kHz (VSI with MV IGBT – up to 1 kHz). In some synchronous drives load commutated inverter (LCI) is used with frequency of system closing beginning from zero level.

CSI obligatory includes filter capacitor in parallel to motor stator. This composes resonant circuit. Resonant frequency for this circuit isn't less than 150-200 Hz. Sometimes we need LC filter on VSI output with the same or more resonant frequency. Additional accumulating elements add state variables to control object. And resonant frequency is too close to modulation frequency.

In addition currents and voltages in such drives may include pulsation with high magnitude. Those exist in feedback signals and are amplified by control part of quick-responsible closed-loop system. High magnitude of pulsation in output of control part narrows range of useful output signal and decrease use of a frequency converter.

Most of known structures of closed-loop control systems can operate in such conditions only with low quick-responsibility. In CSI drives and VSI drives with filter resonant processes are left uncontrolled.

Tasks of this paper are as follows:

to propose method of synthesis that provides combination of positive characteristics of open-loop control and closed loop control – high quick-responsibility and high accuracy;

to investigate main features of these semi-closed control systems and to represent results of simulation for processes of drive with such control system.

Solution of mentioned tasks is based on the theory of non-linear multi-connected subordinate control systems [1], [2] and on newly proposed principle of semi-closed control. This provides operation of system as open-loop one for quick processes and as closed-loop one for slow processes.

Investigation is performed for asynchronous and synchronous drives with PWM VSI and PWM CSI. Synchronous drive with LCI is investigated also. An example considered here is synchronous drive on the base of PWM CSI. Short results for LCI drive are represented also.

II. CONTROL OBJECT

Control object is shown on Fig. 1. It includes: synchronous motor *M* with electromagnet brush-type excitation, position sensor *BQ* on shaft of motor, PWM CSI, output filter capacitor *CM*, exciter. Line side of converter is represented as a controlled current source and isn't considered here. Vector $\mathbf{z}_{MUVW} = (z_{MU}, z_{MV}, z_{MW})$ defines state of converter bridge. Each element of this vector has value 0 or +1 or –1. Output inverter current $i_{MU} = i_D$ corresponds to value $z_{MU} = +1$, current $i_{MU} = 0$ corresponds to value $z_{MU} = 0$, current $i_{MU} = -i_D$ corresponds to value $z_{MU} = -1$. Vector $\mathbf{z}_{MUVW}$ is formed by *Modulator* that is controlled by vector $\mathbf{y}_{M\alpha\beta}$ in stationary frame. Exciter is controlled by voltage reference u_{RRf}. Position sensor forms direction vector of *d* axis of the rotor $\mathbf{1}_d = (\cos\gamma, \sin\gamma)$ for control system. Designations for voltages and currents and their conditionally positive directions are evident from diagram.

Structural diagram of this control object is represented on Fig. 2. All the variables and parameters besides of time and time constants are represented as relative values. Base values are accepted as usually for electric machines. Designation for base angle frequency is Ω_b (rad/s).

Diagram includes element *Mech-Move* that corresponds to mechanism with its inertia and its internal load torque. Element *SM Electromagnet Loops* isn't opened here, it is represented explicitly in [3]. Besides of that diagram includes link for capacitor *CM.*

One of inputs of control object is vector $\mathbf{z}_{M\alpha\beta}$ that represents 3-dimensional vector $\mathbf{z}_{MUVW}$, mentioned above, in stationary frame:

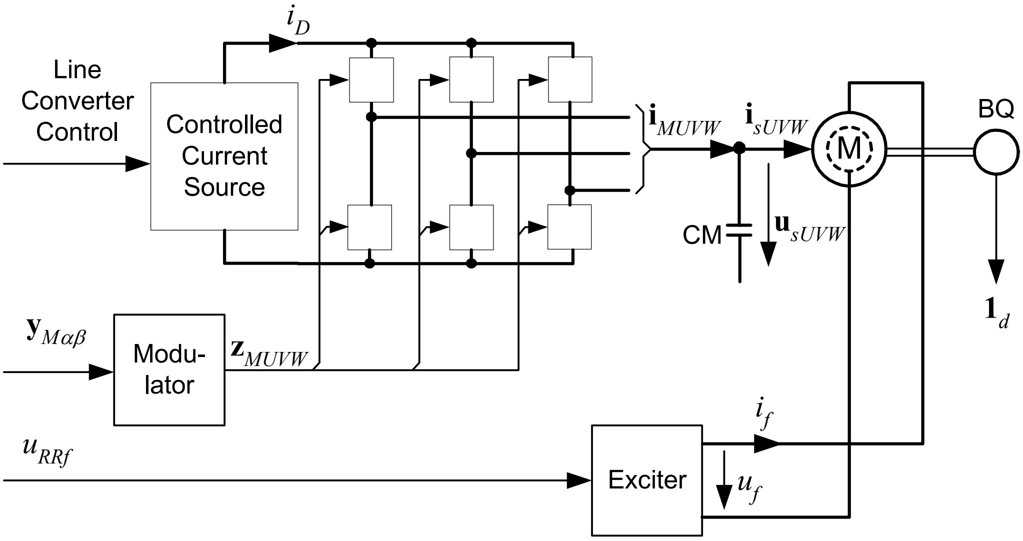

Fig.1. Synchronous drive on the base of PWM CSI

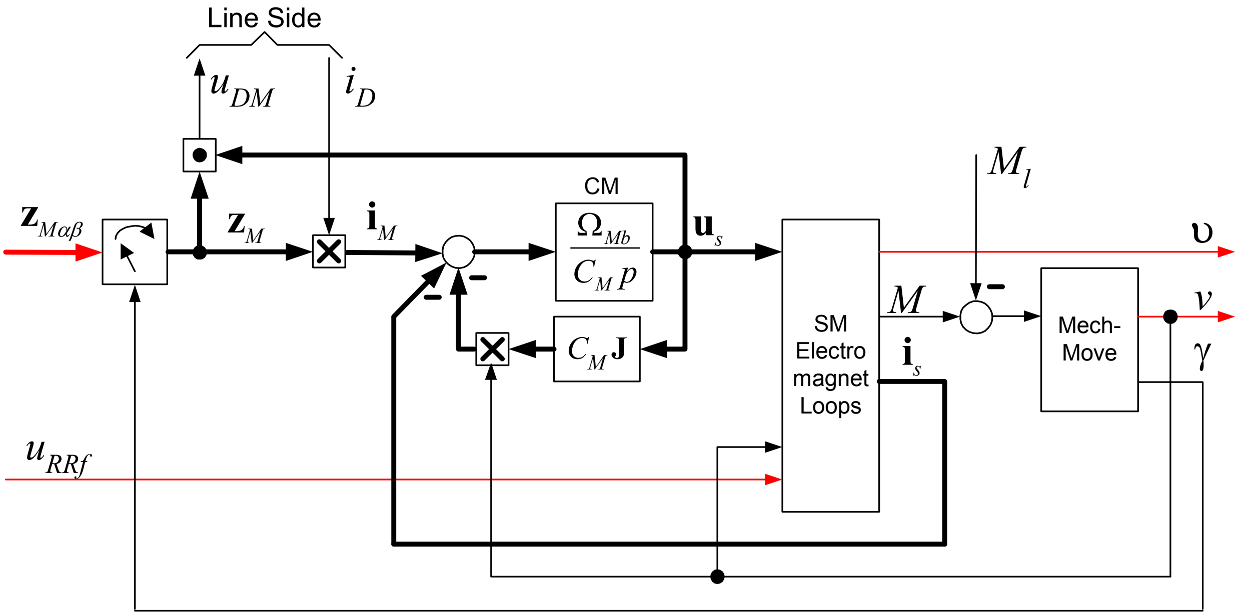

Fig. 2. Structural diagram of the control object

$$\mathbf{z}_{M\alpha\beta} = \mathbf{C}_{23}\mathbf{z}_{MUVW}; \mathbf{C}_{23} = \tfrac{2}{3}\begin{pmatrix} 1 & -\tfrac{1}{2} & -\tfrac{1}{2} \\ 0 & \tfrac{\sqrt{3}}{2} & -\tfrac{\sqrt{3}}{2} \end{pmatrix}.$$

A supposition is accepted that excitation voltage u_f repeats reference u_{RRf}. Because of that this is the second input of the object.

Outputs of object are velocity v and 2-dimensional vector of motor energy variables υ. There is definite freedom in choice of energy variables. For example in [4] vector is accepted as $\upsilon = (\psi_s, \psi_\delta)$; ψ_s is stator flux linkage, ψ_δ is main flux (they are modules of representing vectors).

All the voltages and currents are depictured by representing vectors in *d, q* frame; this is the frame of rotor axes. Input vector $\mathbf{z}_{M\alpha\beta}$ is converted into this frame by conversion of rotation:

$$\mathbf{z}_M = \mathbf{C}(-\gamma)\mathbf{z}_{M\alpha\beta}, \mathbf{C}(-\gamma) = \begin{pmatrix} \cos\gamma & \sin\gamma \\ -\sin\gamma & \cos\gamma \end{pmatrix}.$$

Designations for voltages and currents correspond to diagram of main circuit on Fig. 1.

Mentioned vector υ, torque M and stator current vector $\mathbf{i}_s$ are considered here as outputs of *SM Electromagnet Loops.*

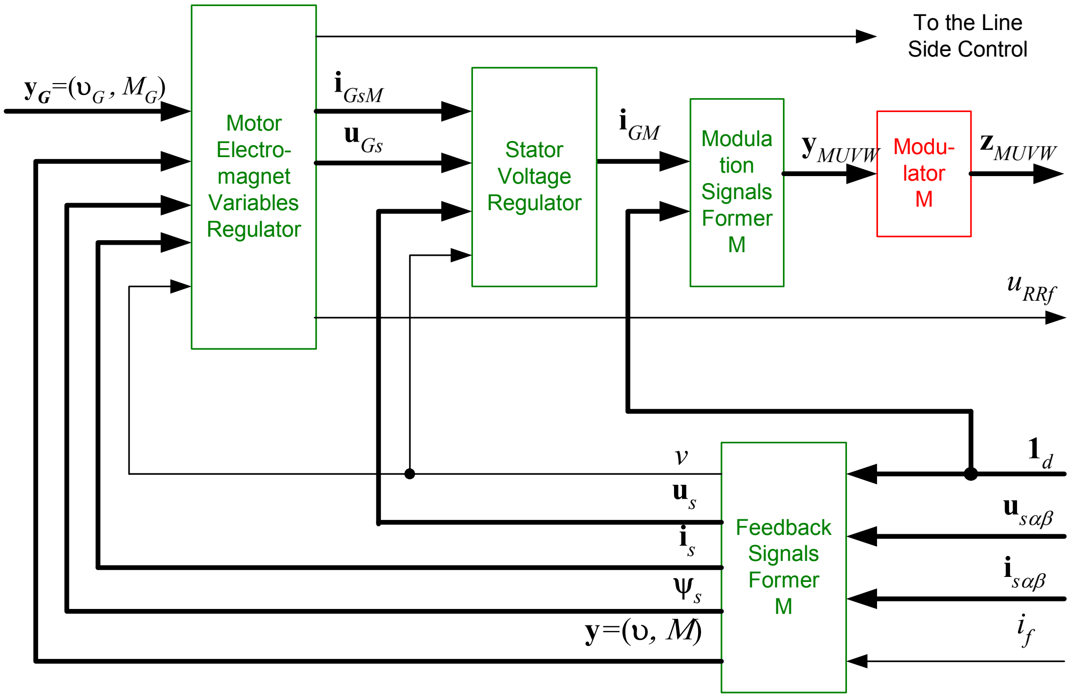

Fig. 3. Structure of the control part

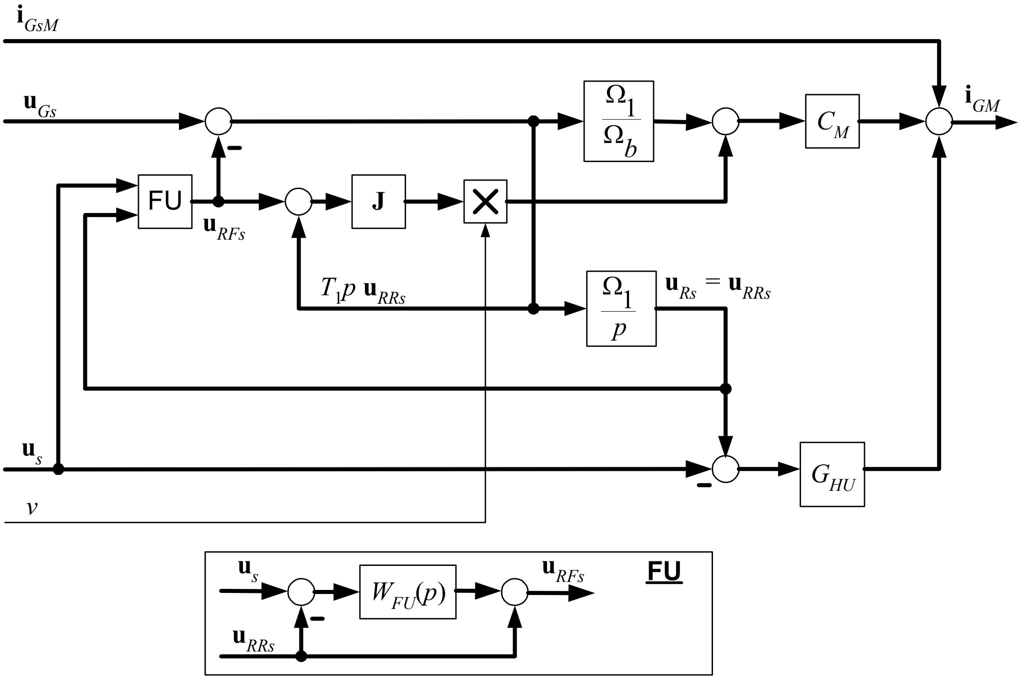

Fig. 4. Inverter current regulator

Output to line side exists also – voltage u_{DM}; base voltage for DC link is accepted here as $U_{Db} = (3/2)\, U_b$.

Specific of the object is a feedback coming over two links. This is one for vector $\mathbf{i}_s$. It causes resonant features. Cross feedbacks between components of vectors exist in link *CM*. This feedback is $C_M\, v\, \mathbf{J}\, \mathbf{u}_s$,

$$\mathbf{J} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}.$$

DC source current i_D and external load torque are considered here as external influences.

III. STRUCTURE OF A SEMI-CLOSED SYSTEM

A. General Structure

Structure of control part is shown on Fig. 3. It is considered jointly with object structure on Fig. 2. Output vector of control part $\mathbf{z}_{MUVW}$ is formed by *Modulator M.* Modulator is considered that implements the vertical control, for example by triangular modulation with carrier magnitude $Y_{mod.m}$= 1 and frequency f_{mod}. Modulator is controlled by vector $\mathbf{y}_{MUVW}$.

The vector is formed by *Modulation Signals Former M.* Input of this element is vector $\mathbf{i}_{GM\alpha\beta}$ - reference for inverter output current. Control vector $\mathbf{y}_{M\alpha\beta}$ shown as input of the object is formed according relation:

$\mathbf{y}_{M\alpha\beta} = \mathbf{i}_{GM\alpha\beta}/(\, z_{iD}\, i_{GM\alpha\beta})$.

Variable $z_{iD} > 1$ participates in control of the line side providing DC link current that corresponds to module $i_{GM\alpha\beta}$ of vector $\mathbf{i}_{GM\alpha\beta}$:

$i_D \approx z_{iD}\, i_{GM\alpha\beta}$.

Vector $\mathbf{y}_{M\alpha\beta}$ is transformed into 3-phase vector with known zero sequence signal to provide full use of the DC current.

Feedback signals are provided by *Feedback Signals Former.* Its functions are evident ones from diagram. Additional designations for feedback vectors are: $\boldsymbol{\psi}_s = (\psi_{sd}, \psi_{sq})$ – vector of stator flux linkage, $\mathbf{i}_w = (i_{sd}, i_{sq}, i_f)$ – 3-dimensional vector of winding currents.

Properly regulating part is a cascade chain of regulators traditional for subordinate control systems. It begins with speed regulator that isn't shown on diagram. Speed and flux ramps aren't shown also. Output of speed regulator is torque reference M_G. Besides of that reference υ_G is formed as function of torque and speed references, [4]. Shown part includes *SM Electromagnet Variables Regulator*and *Stator Voltage Regulator.* Additional regulator for additional state variables of object represents the first specific feature of the structure. Other feature is in all the shown regulators; namely these regulators implement proposed method. And an additional feed-forward connection differentiates the diagram from cascade chain. This is an additional reference $\mathbf{i}_{GsM}$ that goes from *SM Electromagnet Variables Regulator* to *Modulation Signals Former* over *Voltage us Regulator.*

Control part is considered here as continuous one. Of course it is designated for microprocessor implementation. But modern DSP provides such computation rate that processes of discrete time system are close to ones for continuous system. And simulation of processes that is represented in this paper is performed in discrete-time system.

B. Stator Voltage Regulator

This is shown on Fig. 4. The base is PI regulator in *d, q* frame that was proposed yet in [5]. The main input is reference vector $\mathbf{u}_{Gs}$ from *SM Electromagnet Variables Regulator*. The output is vector $\mathbf{i}_{GM}$ that represent reference for smooth components of inverter output current.

Most of designations are evident from diagram. A designation Ω_1 (rad/s) is used for bandwidth of this control loop.

Specifics are:

- additional hard negative feedback with coefficient G_{HU}; this provides more efficient integral part of regulator; method was proposed in [1];
- feedback element *FU* that implements proposed method of the semi-closed control.

Feedback element operates with two inputs: vector $\mathbf{u}_s$ of the stator voltage and output vector $\mathbf{u}_{RRs}$ of the regulator integral part. Element includes low-pass filter with transient operator $W_{FU}(p)\ \mathbf{1}_2$ where $\mathbf{1}_2$ is the unity matrix of the 2nd order. Vector $\mathbf{u}_{RRRs}$ goes directly to output of the element. Vector of stator voltage goes to output through the filter. And vector $-\mathbf{u}_{RRs}$ is added to the filter input. Thus feedback for quick processes is implemented by internal vector $\mathbf{u}_{RRs}$ and this for slow processes is done by controlled vector $\mathbf{u}_s$ of the object.

Feedback element output $\mathbf{u}_{RFs}$ is used not only for regulator feedback but also for compensation of internal cross feedback of object: vector $C_M v \mathbf{J}\mathbf{u}_{RFs}$ is a part of current reference.

A simple case for feedback filter is the 1st order filter with bandwidth Ω_{FU} (rad/s). In this case feedback vector is expressed simply through inputs of feedback element:

$$\mathbf{u}_{RFs} = \frac{T_{FU}p}{1+T_{FU}p}\mathbf{u}_{RRs} + \frac{1}{1+T_{FU}p}\mathbf{u}_s, T_{FU} = \frac{1}{\Omega_{FU}}. \quad (1)$$

It is supposed for analysis that velocity v is changed slowly and may be considered as parameter. Inverter with accepted modulator is considered as linear non-inertial element. This is a usual supposition for definite limited quick-responsibility of control. Pulsations in output current of the inverter are considered as an independent external disturbance $\mathbf{i}_{Mn}(t)$. Thus output current of the inverter is expressed as

$$\mathbf{i}_M(t) = \mathbf{i}_{GM}(t) + \mathbf{i}_{Mn}(t). \quad (2)$$

Let's consider the transient operator of the closed loop for voltage reference $\mathbf{u}_{Gs}$ in absence of disturbance: $\mathbf{i}_{Mn}(t) = \mathbf{0}$.

It is easy to show that such relations exist:

$$\mathbf{u}_s(t) = \mathbf{u}_{Rs}(t) = \mathbf{u}_{RFs}(t) = \frac{1}{1+T_1 p}\mathbf{u}_{Gs}(t); T_1 = \frac{1}{\Omega_1}. (3$$

This means that both internal vectors of the regulator coincide with voltages vector. All three vectors are expressed through reference as output of a 2-dimensional 1st order filter with bandwidth Ω_1. Such transient operator was initially accepted as desired one for this loop.

To show advantage provided by semi-closed control let's consider transient operator expressing current reference through disturbance signal.

And this will be the most evident thing with $v = 0$, $\mathbf{u}_{Gs} = \mathbf{0}$ and in absence of hard feedback $G_{HU} = 0$. With this supposition current reference is expressed as

$$\mathbf{i}_{GMn}(t) = -\frac{1}{1+T_1 p}\frac{1}{1+T_{FU} p}\mathbf{i}_{Mn}(t). \qquad (4)$$

It means that pulsation on output of the control part in semi-closed system is filtered by additional filter with bandwidth Ω_{FU} in series with filter with bandwidth Ω_1. This allows necessary filtering.

C. SM Electromagnet Variables Regulator

This regulator is constructed on the same base as previous one. But it is more complicate: this isn't internal one and control object in this loop is much more complicate. Format of this paper doesn't allow to show structural diagram, and the regulator is represented by equations.

Bandwidths for SM electromagnet variables control loop is accepted with usual relation for subordinate control systems:

$$\Omega_2 = \Omega_1 /2. \qquad (5)$$

Inputs of the regulator are 3-dimensional vectors: reference $\mathbf{y}_G$ and feedback $\mathbf{y}$. Additional feedbacks are: 3-dimensional vector of winding currents $\mathbf{i}$ and vector of stator flux linkages $\boldsymbol{\psi}_s$. Outputs are 2-dimensional vectors: reference for the *Stator Voltage Regulator* $\mathbf{u}_{Gs}$, feed-forward connection for inverter current $\mathbf{i}_{GsM}$, - and excitation voltage reference u_{RRf}.

Internal state vectors and variables of the regulator are:

$$\begin{aligned}
&\mathbf{y}_R = \frac{\Omega_2}{p}(\mathbf{y}_G - \mathbf{y}_{RF}); \boldsymbol{\psi}_R = \mathsf{F}_\psi \mathbf{y}_R; \mathbf{i}_R = \mathsf{F}_i \mathbf{y}_R;\\
&\mathbf{y}_{RR} = \frac{1}{1+T_1 p}\mathbf{y}_R;\\
&\boldsymbol{\psi}_R = (\boldsymbol{\psi}_{Rs}, \psi_{Rf}); \boldsymbol{\psi}_{RRs} = \frac{1}{1+T_1 p}\boldsymbol{\psi}_{Rs};\\
&\mathbf{i}_{RR} = \frac{1}{1+T_1 p}\mathbf{i}_R; \mathbf{i}_{RR} = (\mathbf{i}_{RRs}, i_{RRf}).
\end{aligned} \qquad (6)$$

Here F_ψ and F_i are non-linear differential operators of SM magnet circuit (including damping loops of rotor).

With ideal regulation internal vectors $\boldsymbol{\psi}_{RR}$, $\mathbf{i}_{RR}$ should coincide with vectors $\boldsymbol{\psi}$, $\mathbf{i}$ of the machine.

Semi-closed control is provided by feedback filters. Their outputs are:

$$\begin{aligned}
&\mathbf{y}_{RF} = \mathbf{y}_{RR} + W_{FY}(p)(\mathbf{y} - \mathbf{y}_{RR});\\
&\boldsymbol{\psi}_{RFs} = \boldsymbol{\psi}_{RRs} + W_{FF}(p)(\boldsymbol{\psi}_s - \boldsymbol{\psi}_{RRs}).
\end{aligned} \qquad (7)$$

Here $W_{FY}(p)$, $W_{FF}(p)$ are filtering transient operators.

Regulator outputs correspond to equations:

$$\begin{aligned}
&\mathbf{u}_G = (p/\Omega_b)\boldsymbol{\psi}_R + \mathbf{u}_{Gv} + \mathbf{R}_w \mathbf{i}_R + R_{HI}(\mathbf{i}_{RR} - \mathbf{i});\\
&\mathbf{u}_G = (\mathbf{u}_{Gs}, u_{Gf}); u_{RRf} = \frac{1}{1+T_1 p}u_{Gf}; \mathbf{i}_{GsM} = \mathbf{i}_{RRs}.
\end{aligned} \qquad (8)$$

Dynamical component $(p/\Omega_b)\boldsymbol{\psi}_R$ in real control system is implemented through differences. Matrix $\mathbf{R}_w$=diag(R_s,R_s,R_f) corresponds to winding resistances. Component of voltage reference corresponding to rotation EMF of the machine is:

$$\mathbf{u}_{Gv} = v\mathbf{J}(\boldsymbol{\psi}_{Rvs}, 0); \boldsymbol{\psi}_{Rvs} = \boldsymbol{\psi}_{RFs} + \boldsymbol{\psi}_{Rs} - \boldsymbol{\psi}_{RRs}. \qquad (9)$$

Parameter R_{HI} is coefficient for current hard feedback (like voltage hard feedback in the *Stator Voltage Regulator*).

Features for filtering of pulsation are like those of the previous regulator.

IV. RESULTS OF SIMULATION

Simulation was performed for an example of synchronous drive on the base of PWM CSI. Parameters of a drive are used with motor 7 MW, 300/600 rpm, 30/60 Hz.

Resonant frequency of stator circuit is $f_{res} \approx 150$ Hz. Modulation frequency of the CSI is $f_{mod} = 450$ Hz. Bandwidth of internal control loop is $\Omega_1 = 800$ rad/s. Speed loop is accepted with bandwidth $\Omega_v = 50$ rad/s. Matching filter is added after speed regulator with bandwidth $\Omega_{va} = 200$ rad/s. Variant with P speed regulator is represented here.

Simulation is performed for discrete-time model. Sampling time for object model is $T_{s0} = 10$ µs, sampling times for blocks of the algorithm are: for *Modulator* – the same time T_{s0}, for *Modulation Signals Former*, *Current iM Regulator*, *Voltage us Regulator, Feedback Signals Former* and for *SM Electromagnet Variables Regulator* – $T_{s1} = 100$ µs, for the speed regulator – $T_{s2} = 500$ µs. These times provide suitable operation of the algorithm.

Type check processes of a controlled drive are represented on Fig. 5: start without load torque, load step-up, load step-down, deceleration to full stop. Speed command $v_{cmd} = 2$ is accepted to demonstrate drive operation in the upper speed zone with field weakening. Dynamical torque for acceleration-deceleration is accepted $M_{dst} = 2$; load step is accepted $M_{lst} = 1$ that corresponds approximately to twofold stator current with weakened field..

Designations for variables are as follows: v_G – speed reference, M_l –load torque, ψ_s – stator flux linkage (module of vector), ψ_δ – main flux (module of vector), M – electromagnet torque, v – speed, i_s – stator current (module of vector), i_f – excitation current, u_s – stator voltage (module of vector), u_f – excitation voltage.

Fig. 6 represents begin of the same process in expanded time. Processes are shown additionally for original stator voltages u_{sd}, u_{sq} and corresponding outputs of feedback element u_{RFsd}, i_{RFsq}.

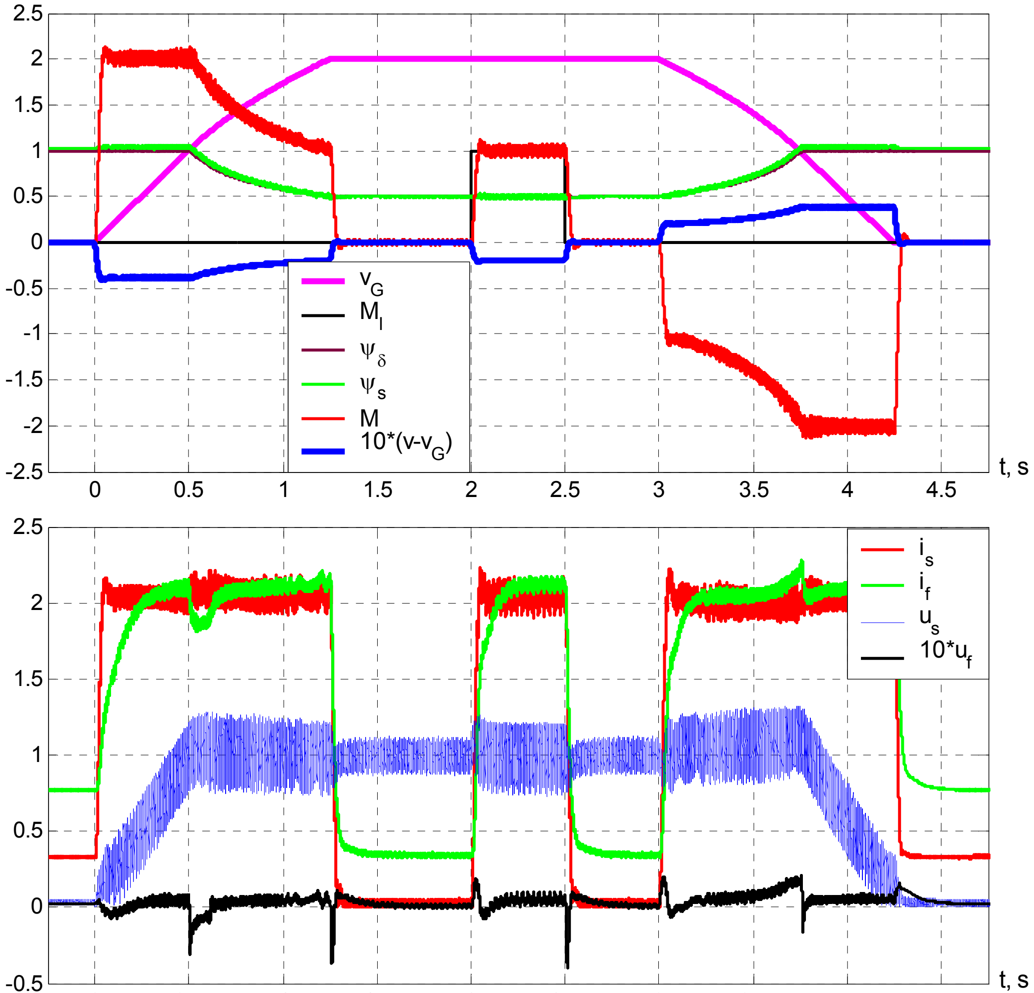

Fig. 5. Processes of a synchronous drive

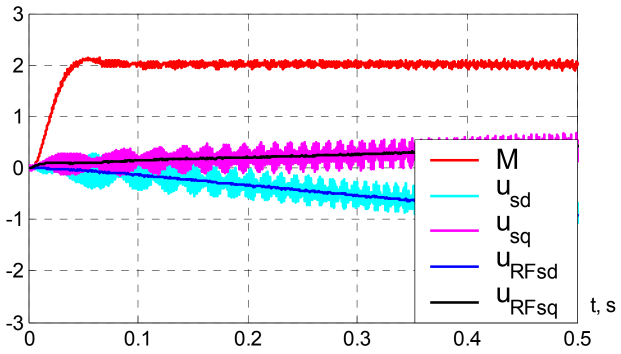

Fig. 6. Initial and formed feedbacks

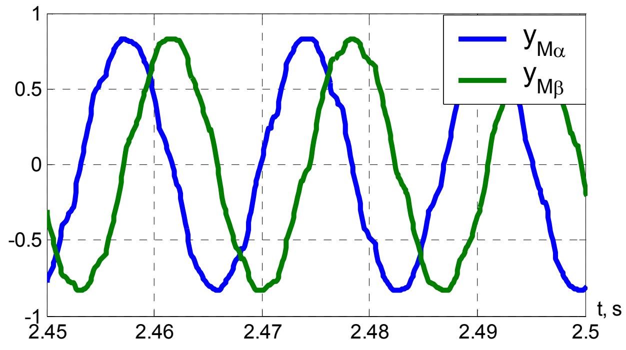

Fig. 7. Control signals for the modulator

Fig. 7 represents components $y_{M\alpha}$, $y_{M\beta}$ for the control vector of the modulator.

Processes of speed and torque are close to known type processes of a controlled drive with subordinate control, difference is in limit of 5 %. The same is valid for fluxes. Pulsations in represented signals of feedback element are suppressed 20-times for this example. Control signals for the modulator are enough smooth. Represented quick-responsibility overlaps requirements of the most dynamical high-power drives. And possibilities of PWM CSI are confirmed for all the high-power drives.

V. OTHER EXAMPLES

Close results are achieved for other kinds of asynchronous and synchronous drives.

Short results are represented for synchronous drive on the base of LCI. Specific is that frequency of system closing begins from zero. SM electromagnet variables regulator in simulated system is close to considered above one. Controlled vector of this regulator is here $\mathbf{y} = (\psi_s, i_{sx}, i_{sy})$; i_{sx}, i_{sy} –components of stator current on direction of vector ψ_s and on orthogonal leading direction. Bandwidth of feedback element FY is proportional to speed and begins from zero level. System is considered with indirect measuring of rotor speed and angle. Fig. 8 demonstrates processes for a model of this drive.

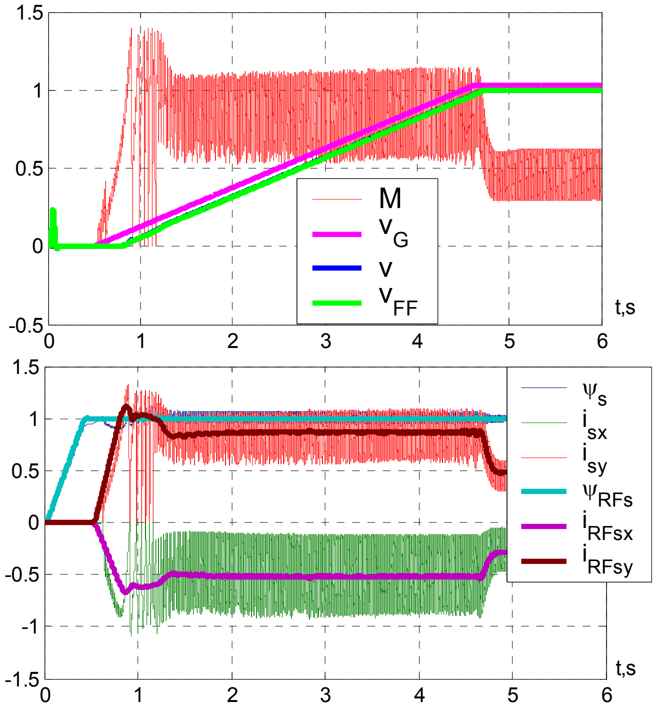

Fig.8. Processes of the drive on the base of LCI

Parameters of model correspond to operating drive that is used as frequency starter for synchronous motors 20 MW,[6]. Only electromechanical time constant and acceleration are changed. Bandwidth for electromagnet variables control loop is $\Omega_e = 50$ rad/s and this for speed control loop is $\Omega_v = 10$ rad/s. Processes are represented with P speed regulator. Processes are shown for drive start with stalling torque $M_{stall} = 0.6$ and constant load torque $M_{l0} = 0.5$.

New designations for variables are: v_{FF} – indirectly measured speed feedback, ψ_{RFs}, i_{RFsx}, i_{RFsy} – components of feedback vector for electromagnet variables regulator.

Consequent intervals of processes are seen here:

1. Turning on of excitation; feedback signals former moves its internal axes d_{FF}, q_{FF} for coincidence with real position of d, q axes.
2. Rise of electromagnet torque with stalled rotor.
3. Begin of move and acceleration in infra-low speed zone; commutation of inverter is provided by suppression of DC link current.
4. Further acceleration and transition to steady-state regime with natural commutation of the inverter.

Process of speed is close to desired one. Measured speed in this scale of time almost coincides with real speed. Feedback signals for electromagnet variables are good filtered and simultaneously don't lag from useful smooth components of real signals. As a result semi-closed control provides more accurate regulation of electromagnet variables.

VI. CONCLUSION

1. Semi-closed control provides high quick-responsibility of the speed loop for a controlled AC drives simultaneously with filtering of pulsation in feedback signals. This is possible including difficult cases with relatively low modulation frequency and resonant stator circuit.

2. Good filtering of pulsation allows to decrease reserve in voltages of a frequency converter and exciter. This is important for high-power drives.

3. Example with drive on the base of PWM CSI confirms that such kind of drive is suitable, on level with VSI drives, in all the range of high-power drives including most dynamical ones.

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