ENEGRY REGIMES OF HIGH-POWER HIGH-DYNAMIC ADJUSTABLE SPEED SYNCHRONOUS DRIVE

Alexander M. Weinger, Prof., D. Sc., Rockwell Automation/ Allen Bradley, Moscow

The purpose of the report

Synchronous machine with electromagnet excitation as control object has 3-dimensional input and provides the possibility to control two output variables besides of torque. These variables characterize the energy conditions. Expedient and optimized energy regimes were proposed and investigated long time ago, [1]. We understand here energy regimes as dependence of 2-dimensional vector $\boldsymbol{\upsilon}$ from torque and velocity. There is some freedom in the choice of this vector components. For example it was accepted in [1]

$$\boldsymbol{\upsilon} = (\psi_\delta , i_{s\rho}), \tag{1}$$

where ψ_δ is module of representing vector of main flux (flux in the air gap) and $i_{s\rho}$ is magnetizing component of stator current. The choice of function

$$\boldsymbol{\upsilon} = \boldsymbol{\upsilon}\,(M, v) \tag{2}$$

defines for each torque M and velocity v necessary currents and voltages.

A modern control system of a synchronous drive includes in definite form a regulator of motor electromagnet variables and a former of energy regimes as shown on fig. 1.

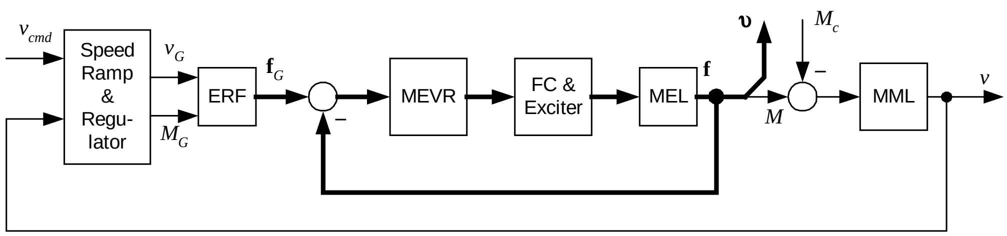


Fig. 1. Structural diagram of a synchronous drive control system: ERF – energy regimes former, MEVR – motor electromagnet variables regulator, MEL – motor electromagnet loops, MML – mechanical move link; $\mathbf{f}$ – output vector of motor electromagnet loops, $\mathbf{f} = (\boldsymbol{\upsilon}, M)$; references are designated with G subscript

Energy regimes former in such system forms reference for energy regimes $\boldsymbol{\upsilon}_G = \mathbf{g}_{ER}\ (M_G, v_G)$ from torque and velocity references and provides reference vector for regulator $\mathbf{f}_G = (\boldsymbol{\upsilon}_G, M_G)$.

Choice of vector function $\mathbf{g}_{ER}$ influents essentially from one side on energy features of controlled drive and from other side on maximal voltages and currents of frequency converter and exciter.

A feature of high-dynamic drives is enough high torque rate in transients. Because of that optimal regimes with essential change of main flux in function of torque are unsuitable for such drives. The change of main flux is the change of large energy of the magnet field in air gap. Quick change of this energy requires too large power and large extra voltages of a frequency converter and an exciter.

Known expedient regimes for high-dynamic drives take into account this feature. Those regimes are shown on fig.2, a, b. Regime fig. 2, a is recommended in [1] for lower speed zone of two-zone speed control. Regime fig. 2, b with current vector orthogonal to stator flux vector that had been known before was recommended in [1] for upper zone (zone of field weakening). Stator flux is supported on the reference level that decreases with speed:

$$\psi_G = \psi_{G0}\min(1, v_0 / v_G). \tag{3}$$

But mentioned known regime for upper zone requires essential increase of main flux with torque. Therefore it requires too large maximal voltage of exciter.

The task of this paper is to consider new power regimes for upper zone that are more suitable for high-dynamic drives. An additional task is to note the role of rotor transversal damping cage in decreasing of maximal voltages for stator and rotor. And last task is to prove that proposed regimes are achievable in closed control system (fig. 1) and this coincides with necessary dynamics for torque and velocity.

The approach used

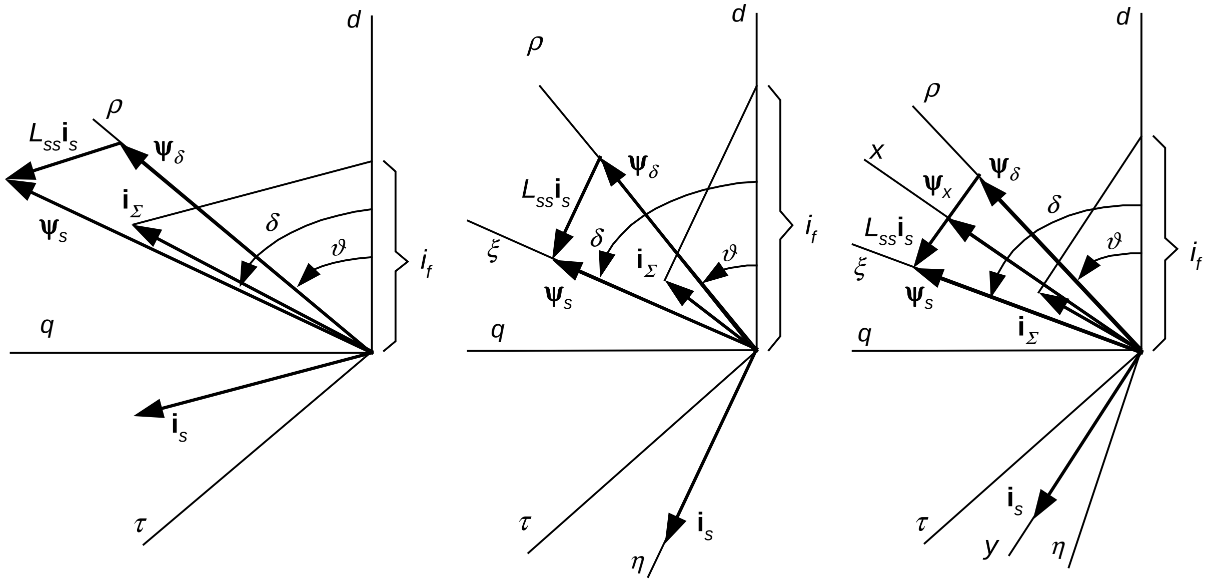
New energy regimes for upper speed zone are proposed. Vector diagram is shown on fig. 2, c. Vector $\boldsymbol{\psi}_x$ is supported on reference level (3); this vector moves from main flux to stator flux with speed. Stator currents vector is orthogonal to vector $\boldsymbol{\psi}_x$ with maximal speed.

Formulas for complete speed range are:

$$\boldsymbol{\psi}_x = [1 - a\, f(v_G)]\, \boldsymbol{\psi}_\delta + af(v_G)\, \boldsymbol{\psi}_s;\ \psi_{xG} = \psi_G \tag{4}$$

$$f(v_G) = \max[0, (v_G - v_0)/(v_{\max} - v_0)]; \tag{5}$$

$$i_{sxG} = i_{s\rho.opt}\,[1 - f(v_G)]; \tag{6}$$



a. $\psi_\delta = \psi_G$, $i_{s\rho} = i_{s\rho.opt}$ b. $\psi_s = \psi_G$, $i_{s\xi} = 0$ c. $\psi_x = \psi_G$, $i_{sx} = 0$

Fig. 2. Expedient and optimized regimes of synchronous motor: $\mathbf{i}_s$ – representing vector of stator currents, $\boldsymbol{\psi}_\delta$ – representing vector of main flux, $\boldsymbol{\psi}_s$ – representing vector of stator flux linkages, ψ_G – flux reference; *d, q* – axes of rotor, ρ, τ - axes connected with vector of main flux, ξ,, η – axes connected with vector of stator flux

Vector $\boldsymbol{\upsilon}$ in this case is accepted in such form:

$$\boldsymbol{\upsilon} = (\psi_x , i_{sx}). \qquad (8)$$

In partial case $a = ½$ main flux and stator flux are equal with maximal speed as shown on fig. 2.

Processes are considered in control system according fig. 1 that is synthesized on the base of theory of non-linear multi-linked subordinate control system [2]. The first industrial implementation of such system is considered in [1], the last implementation is frequency starting device for synchronous motors 20 MW [3] that is in operation since 1997. As it was proven by theory and by practice such system provides typical dynamic features of velocity control loop that may be reflected with equations (for partial case with proportional-integral velocity regulator):

$$\begin{aligned} &M(t) = (1+8Tp)B_4(Tp)M_{AL}(t);\\ &B_4(z) = 1/\{1+8z[4z(1+2z(1+z))]\}; T = 1/(4\Omega_v); \qquad (9)\\ &M_{AL}(t) = M_L(t) + T_j p v_G(t). \end{aligned}$$

Here Ω_v is velocity loop bandwidth. Operator $p = d/dt$ is the derivation operator.

For currents and fluxes of motor without damping cage a feature was proven in [1] that they are close in transients to values of torque and speed according characteristic of energy regimes former. This feature is used here to proceed with approximate formulas for maximal voltages in new energy regimes. For motor with damping cage approximate values for maximal voltages are accepted by change of parameter L_{mq} (transverse inductance for main field) with parameter

$$L'_{mq} = 1/(1/ L_{mq} + 1/ L_{cq\sigma}) \qquad (10)$$

where $L_{cq\sigma}$ is leakage inductance of the transversal damping loop.

Other way for investigation used here is simulation of processes in mentioned closed control system. Model for smooth component was used for estimation of maximal voltages. This is one irrelative to type of frequency converter. Results are checked in model of synchronous drive on the base of PWM CSI with 18-pulse thyristor line converter. Simulation was performed for parameters of two synchronous motors: 1) 4 MW, 40/80 rpm, 2) 7 MW, 300/600 rpm.

Estimation of maximal voltages

Formulas for maximal currents and voltages based on mentioned approach are:

$$I_{s.\max} \approx (v_{\max}/v_0)\, M_{1.\max}/ \Psi_{G0}; \qquad (11)$$

$$\mathrm{tg}\ \chi_{\max} \approx L_{exq}\, I_{s.\max}\, v_{\max}/(\, v_0\ \Psi_{G0}) = z;$$

$$\begin{aligned} I_{f.\max} \approx\ & (1/(1 + z^2))^{1/2}\, [v_0 \Psi_{G0}/(\, v_{\max} L_{emd}) +\\ & + (1 + L_x/L'_{md})\, z\, I_{s.\max}]; \qquad (12) \end{aligned}$$

$$\begin{aligned} U_{s.\max} \approx\ & \{[R_s I_{s.\max} + v_0 \Psi_{G0} + L_{esq}\, I_{s.\max}/(7T\Omega_b)]^2 +\\ & + [L_{sx} v_{\max} I_{s.\max}(1 + (L_{exq}/(\, v_0 \Psi_{G0}))I_{s.\max}/(7T\Omega_b))]^2\}^{1/2}; \qquad (13) \end{aligned}$$

$$U_{f.\max} \approx R_f\, I_{f.\max} + L_{f\sigma}\, I_{f.\max}/(7T\Omega_b). \qquad (14)$$

$$L_{esq} = L_{s\sigma} + L'_{mq};\ L_{exq} = a\, L_{s\sigma} + L'_{mq};$$
$$L_{sx} = (1 - a)\, L_{s\sigma};\ L_x = aL_{s\sigma}.$$

$M_{1.max}$ here is maximal torque with maximal speed.

Simulation results

Simulation results are represented for low speed drive. Parameters of plate rolling mill main drive 4MW, 40/80 rpm, 6/12 Hz are used. Speed loop bandwidth in this control system is Ω_v = 25 rad/ s.

Maximal torque and acceleration in upper zone are assigned here decreasing with speed.

Processes are shown on fig. 3. These are: acceleration – load step-up – load step-down – deceleration.

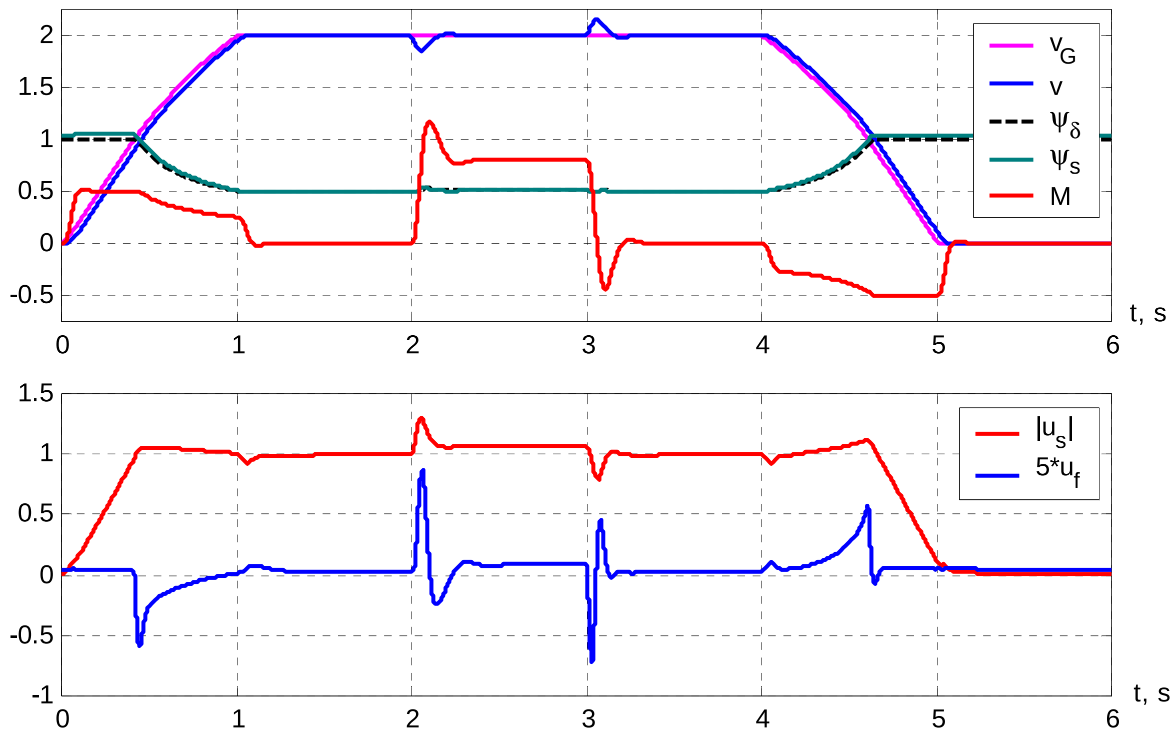


Fig. 3. Processes of drive model

We see here type processes for torque and speed. In upper speed-zone stator flux and main flux are brought together and coincide with maximal speed. Maximal voltages enough good correspond to values from formulas:

	Estimation	Simulation	Simulation for known regimes without transverse cage
$U_{s.max}$	1.33	1.29	1.39
$U_{f.max}$	0.19	0.17	0.34

For this case new power regimes and transverse damping cage decrease two-times necessary maximal voltage of exciter and for 18 % sum dimensional power of frequency converter and exciter.

Conclusion

Proposed power regimes provide decreased value and therefore more expedient parameters of drive power part. Transverse damping loop plays positive role decreasing necessary voltages. Simulation results are close to calculated values. New power regimes are realizable in control system with necessary quality for speed and torque.

References

1. A. M. Weinger. The controlled synchronous drive.- Moscow, Russia: Energoatomizdat, 1985-. 224 ps. (Russian).
2. A. M. Weinger. The generalization of the principle of subordinate regulation with series correction // USSR Academy of Sciences Transactions. Technical Cybernetics.- 1977, # 1.- pp 185-192. (Russian).
3. A. N. Novakovsky, P. A. Tikotsky, Yu .D. Vinitsky, A. M. Weinger. Improvements in automatic control of synchronous machine with machine commutated current inverter.- International Conference on Electrical Machines, September 2-4, 1998, Istanbul, Turkey.- V. 1/3, pp. 78-82.