INDUSTRIAL IMPLEMENTATION OF A CONTROLLED SENSORLESS SYNCHRONOUS DRIVE WITH HARD START CONDITIONS

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***Abstract*-- The subject of this paper is a synchronous drive of grinding ball mills 4 MW, 150 rpm, 6 kV, 50 Hz on the base of PWM CSI. The system is installed at concentrating plant of Norilsknickel in Russia. Specific of this drive is large stalling torque – up to 125 % of rated torque. And this is a sensorless drive. Other specific feature is a necessity of synchronization with power system and switching to power system.**

Converting-regulating device of this drive isn't designated for hard work conditions. It uses simplified control algorithms. This caused main difficulties of implementation.

Simulation was performed before drive commissioning. It provided reliance in successful results of project and expedient values for most of programmable parameters.

The main result was that it is possible to choose such acceleration of current vector in infra-low speed zone that provides necessary torque with suitable speed oscillations.

Results of simulation were used while drive commissioning. Drive operates successfully with settings of parameters that were defined by simulation. And main features of drive are represented in paper.

***Index Terms*—controlled drive, industrial implementation, PWM CSI, synchronous drive.**

I. INTRODUCTION

The subject is a controlled high-power medium voltage synchronous drive. This is the drive for grinding ball mills of Norilsknickel combine in Russia. Motor ratings are 4 MW, 150 rpm, 6 kV, 50 Hz.

Mills operated before with direct start from power system. But operation was possible only with half of mills full load because of poor power system.

New drive system is designated to solve this problem and provide operation with adjustable speed for perspective. Converting-regulating device (CRD) of this drive is one of PWM CSI type [1]. One CRD is designated to provide sequential frequency start of two mills. After end of frequency start motor is switched to power system. If necessary, continuous operation of one mill with adjustable speed is provided.

CRD of this drive isn't designated initially for hard work conditions. It uses simplified control algorithms. This caused main difficulties of implementation.

Specific of ball mill drive is large stalling torque – up to 125 % of rated torque. Maximal torque is required as 150 % of rated torque. As for large zero-speed torque, it is provided by CRD only with use of rotor position encoder. Without encoder open-loop control is provided for zone of infra-low frequencies. It is known that synchronous motor with open-loop frequency control is an oscillating object in mentioned zone.

Simplified method is used in CRD for regime of switching to power system also: switching with some no-current pause without initial over-speed, switching without advanced equalizing of stator voltage to system voltage.

Simulation was performed before drive commissioning. It provided reliance in successful results of project and expedient values for some programmable parameters.

The main result was that it is possible to choose such acceleration of current vector in infra-low speed zone that provides necessary torque and simultaneously doesn't give time to develop speed oscillations.

Results of simulation were used while drive commissioning. Drive operates successfully with settings for parameters that were defined by simulation.

Experience of drive system design and tuning is represented in this paper.

II. SYSTEM DESCRIPTION

Functional diagram of installation is represented on Fig. 1.

This Figure represent system parts and operation principle. It is possible to add that line converter *VUZL* is an 18-pulse thyristor rectifier-inverter. It converts power system voltage into controlled current in DC link. Machine converter *VUZM* is a current source inverter with PWM based on fully controlled semiconductors, in this case GTO-thyristors are used. Machine converter converts DC link current into three bipolar sets of current pulses in AC output wires. High-frequency components of these sets go into filter capacitor and low-frequency components go into motor stator winding.

Principle of operation is illustrated by Fig. 2.

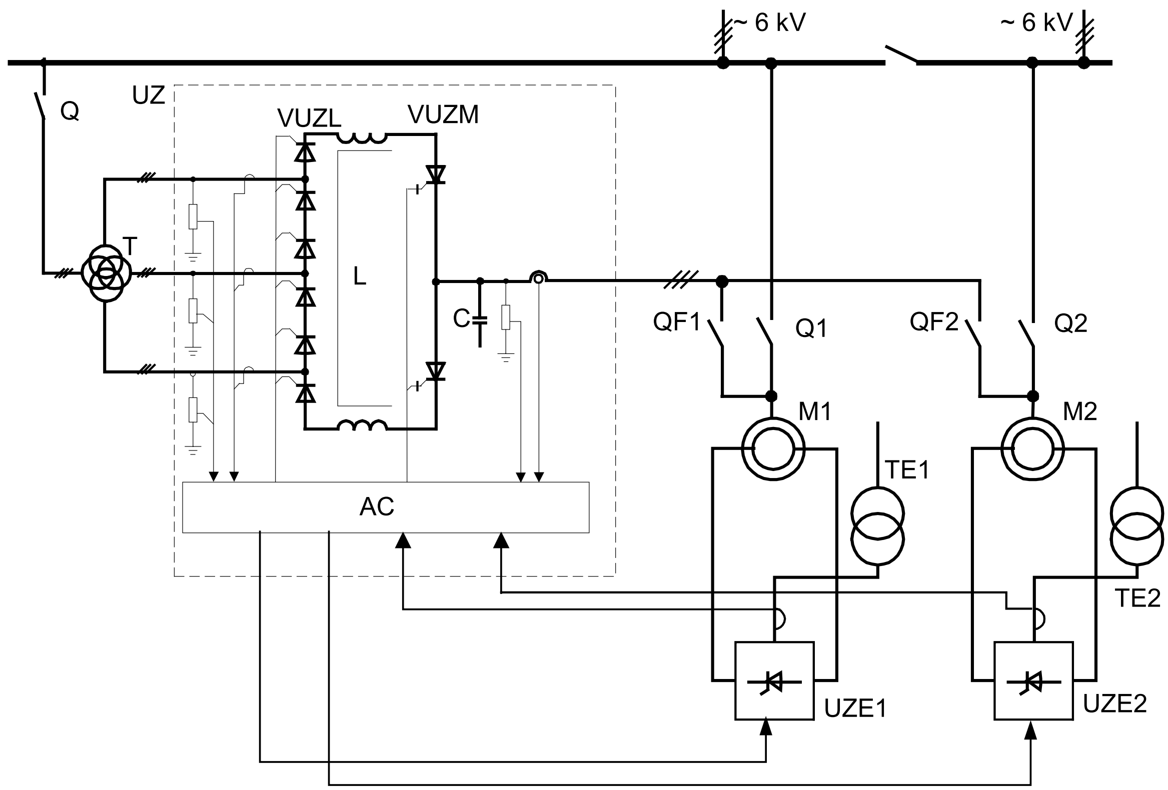


Fig.1. Functional diagram of the drive system: *M1, M2* – motors, *UZ* – CRD, *T* – transformer, *UZE1, UZE2* – exciters, *TE1, TE2* – transformers of exciters, *Q*, *Q1*, *Q2*, *QF1*, *QF2* – contactors, *VUZL* - line converter, *VUZM* – machine converter, *C* – filter capacitor, *L* – DC link reactor, *AC* – automatic control device

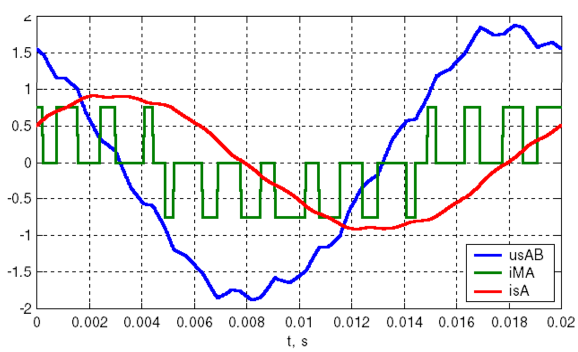


Fig. 2. Operation principle of a PWM CSI: iMA - output current of converter, usAB - stator line-to-line voltage, isA - stator current (relative values)

Control system of this drive is a direct vector control one. Control algorithm provides three closed loops: DC link current control loop, flux control and speed control loops (last two – outside of infra-low speed zone).

Specific of design for this application is that both converters are chosen for continuos operation with maximal torque of drive and all the passive power elements are chosen for motor rated regime.

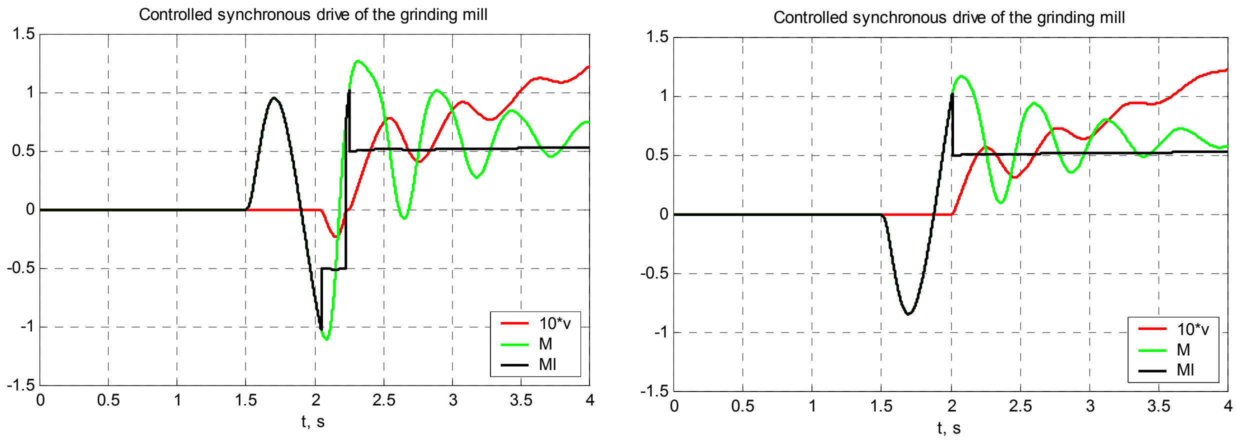
III. Problem of Zero Speed Torque

It was mentioned that CRD of this drive uses simplified control algorithm. The algorithm provides necessary zero speed torque for this drive (up to 125 % of rated one) only with use of rotor position encoder. But it is very difficult to use position encoder for 40-pole motor of this drive. Geometry angle errors in coupling between motor and encoder will cause 20-times more errors in electrical angle.

Of course it is preferable to provide operation without encoder. But in this case control algorithm provides open-loop operation for infra-low speed zone (below 5 Hz). Vector of stator currents is rotating with programmable angle acceleration and programmable module. Specialists know that synchronous motor with open-loop frequency control is an oscillating object, and such regime isn't suitable generally.

Our idea was to use open-loop control only for short-time transients and to choose drive parameters which provide satisfactory processes. Available parameters which play role for infra-low speed zone are: module of stator currents vector, acceleration for this vector, time constant for closed excitation current loop.

Processes of drive were simulated before drive commissioning. Advanced model of synchronous machine was used in simulation [2]. Load was simulated as sum of two components: component increased with speed and large dry friction component.



$\zeta_0 = 0$ $\zeta_0 = \pi$

Fig. 3. Processes of drive model for two values of initial angle ζ_0 between currents vector and d axis of motor: v – velocity, M – motor electromagnet torque, M_l – load torque (relative values)

Results of simulation with chosen parameters are shown on Fig. 3. Such processes may be considered as suitable for ball mill. Torque oscillations don't exceed permitted limits.

IV. Parameters for Flux Control Loop

Control system of drive includes flux control loop with simple PI regulator. Feedback signal of this regulator is a definite equivalent flux of motor. Output of the regulator is command for excitation current. In this simple structure flux regulator doesn't influent stator current.Regulator implements equations:

$\psi_F = \psi_s - L_e \mathbf{i}_s$, $i_{Gf} = (\Omega_F / L_m)\,(T_{FR} + 1/p)\,(\psi_G - |\,\psi_F|)$.

Designations are as follows: ψ_F – feedback flux vector, $\mathbf{i}_s$ – stator currents vector, L_e – equivalent inductance, i_{Gf} - reference for excitation current, Ω_F – flux loop bandwidth, L_m – magnetizing inductance, T_{FR} – equivalent time constant, ψ_G – reference for flux.

Such algorithm corresponds well enough to features of asynchronous motor. But synchronous machine has unsymmetrical rotor because of excitation winding on d axis at least. And problem is to choose suitable parameters for regulator to provide enough resource of stability in different regimes and enough smooth flux feedback signal at least.

A simple analysis helps to choose parameters.

Assumptions are as follows:

- no-load regime;
- FC operates as ideal current source;
- stator current is controlled independently from flux control;
- bandwidth for control loop of excitation current is much wider than this for flux control loop;
- only one damping loop for each of d, q axes;
- feedback variable for flux control loop is module of flux vector for damping loops;
- small deviations of variables are considered.

With such assumptions it is possible to express feedback variable ψ_{cd} through excitation current command $i_{f.cmd}$:

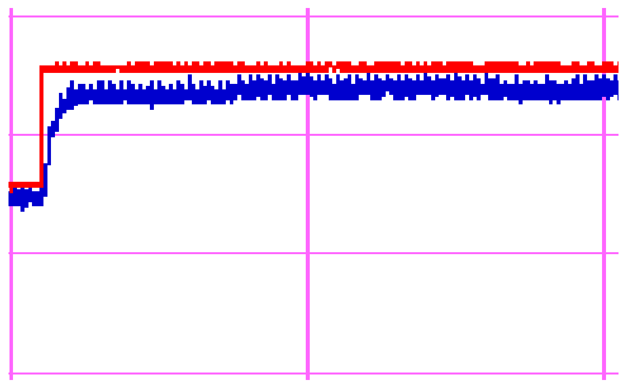


Fig. 4. Ball mill drive. Response of current control loop. Reference step for DC link current: $I_{DG}(0) = 0.4$, $\Delta i_{DG} = 0.2$ (relative values). Time grid division – 0.1 s

$$\psi_{cd} = L_{md} \frac{1}{1 + T'_{c0} p} i_{f.cmd}.$$

Here L_{md} is inductance from main field for d axis and T'_{c0} is time constant of longitudinal damping loop with open stator and excitation windings.

With such object it is possible to use flux regulator corresponding equation:

$$i_{Gf} = \frac{\Omega_\psi}{L_{md}} \left(T'_{c0} + \frac{1}{p} \right) (\psi_G - \psi_F).$$

Designations are as follows: Ω_ψ – bandwidth of flux control loop, ψ_G – flux reference, ψ_F – feedback variable of control loop.

Accepted assumptions are rough enough but experiment whereas drive start-up proved their relevance.

On the base of this analysis it was proposed to use such values for parameters:

$L_e = L'_{sq}$, $L_m = L_{md}$, $T_{FR} = T'_{c0}$.

Additional designation here is: L'_{sq} – transient inductance of stator for q axis.

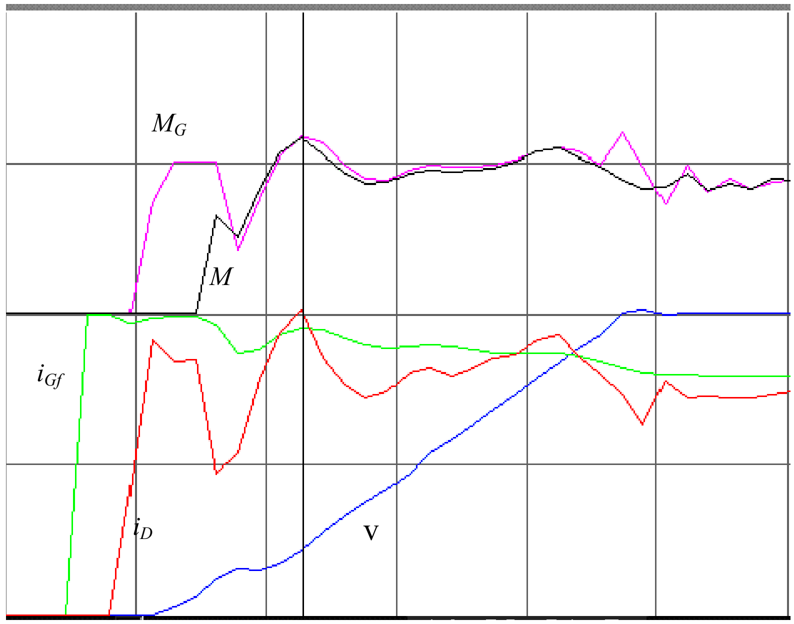


Fig. 5. Time grid division – 5 s.
M_G - Torque Reference, M - Torque, v - Velocity Feedback, i_D - DC Link Current, i_{Gf} - Command for Excitation current.
Variable relative values for time marked with black cursor: M_G = 1.173, M =1.160, v = 10.7 Hz, i_D = 1.019, i_{Gf} = 0.956

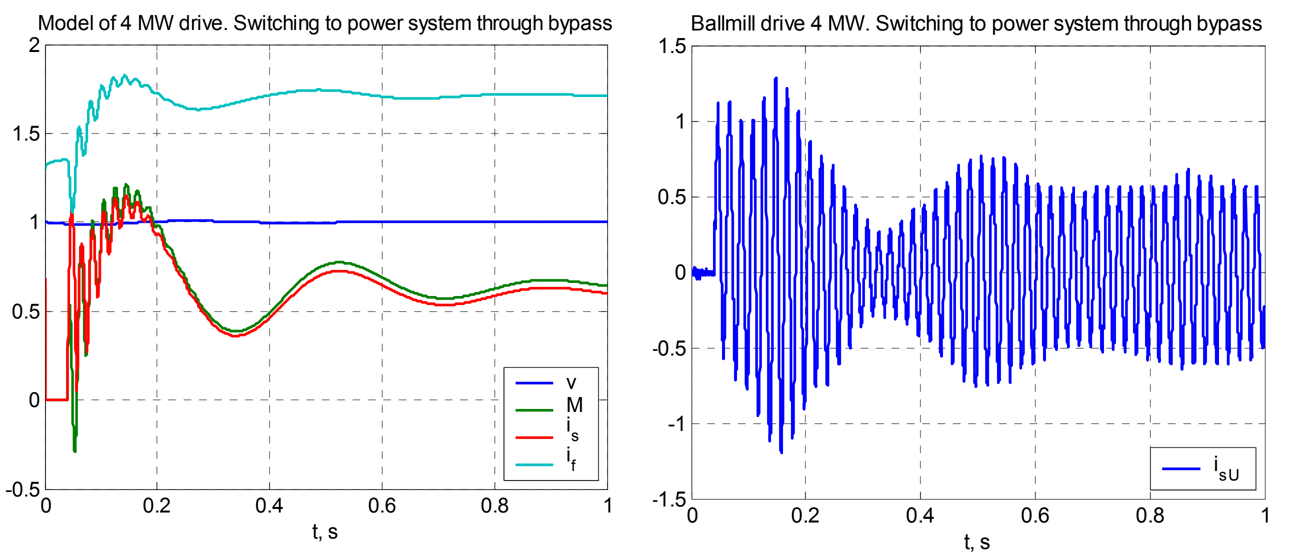


Fig. 6. Processes of drive model and real drive while switching to power system:
Model: v – velocity, M – electromagnet torque, i_s – stator current (module of representing vector), i_f - excitation current.
Real drive: i_{sU} – instantaneous phase current (relative values)

V. Problem of Switching to Power System

Simplified method is used in control algorithm for switching to power system also: switching with some no-current pause without initial over-speed, switching without advanced equalizing of stator voltage to system voltage. Absolutely smooth switching is impossible with such algorithm. But in this installation contactors are used with enough stable time for turn-on and turn-off. This provides enough small no-current pause: T_P = (40 $\pm$ 10) ms. Simulation showed that stator current shocks after switching from drive to power system are suitable with definite angle lead before switching considering zones for pause time and voltage module.

VI. Results of Drive Tuning

While drive commissioning values for programmable parameters were used those found by simulation and by analysis of regimes. And checking of control loops and drive as a complete confirmed that mentioned values provide enough good results.

Steady-state regimes of motor are close to optimized ones. The main feature of such regimes in comparison with regimes while supply from power system is decreased excitation current. In this case excitation current in regime with full load and rated speed is I_f = 135 A whereas rated excitation current is I_{fN} = 220 A. This decreases essentially energy losses in drive.

With maximal modulation frequency of CSI harmonic contents of stator current is suitable one: RMS of all the higher harmonics is less as 8 % of rated current. The same is valid for currents from power system with 18-pulse line converter.

Programmed bandwidth for current control loop is Ω_i = 200 rad/s, for flux control loop is Ω_f = 10 rad/s and for speed control loop is Ω_v = 1.8 rad/s. Responses of control loops are suitable ones. As an example response of current control loop is represented on Fig. 4. It corresponds to programmed bandwidth.

But flux control loop is less quick-responsible than it is defined by programmed bandwidth whereas operation with full load. Simplified flux regulator provides programmed bandwidth for no-load regime. Angle between *d* axis and vector of equivalent flux is increased and because of that quick-responsibility is decreased with full load. Another feature of flux control loop of synchronous machine is that it is possible to check response only for small step of reference. It is caused by limited maximal voltage of exciter.

Enough low bandwidth of speed control loop doesn't characterize low quality of speed control. Really quality is characterized by parameter $K_{Rv} = \Omega_v T_j$, where T_j is electromechanical time constant. In this drive T_j = 4.5 s, and parameter K_{Rv} = 8.1. It is close to level K_{Rv} = 10, that is considered as very good for drives without direct velocity sensor.

Fig. 5 shows processes of drive start with fully loaded ball mill. It is possible to note that process of speed is smooth enough. Drive passes infra-low speed zone without visible oscillations. Then drive goes in closed loop speed control and continues acceleration with programmed rate. In this case drive was started for synchronization with power system, and final part of processes shows operation of position control loop.

Fig. 6 shows processes while motor switching to power system. Processes of drive model are shown for comparison. It is possible to compare phase current of real drive with module of current vector of model. Good correspondence between real drive and model is seen. Process of switching is suitable one. Maximal current exceeds rated value non-essentially. There aren't cases with trip of over-current protection.

Drive system has been in successful operation since February of 2001. Mills operate with full load. Productivity of concentrating plant is increased up to 7 %.

VII. Conclusion

For some applications it is possible to provide successful operation of a synchronous drive on the base of PWM CSI with hard conditions even without position encoder and even with simplified control algorithm. But this requires serious additional design and pre-commissioning work using calculations based on synchronous machine theory and simulation. Of course this doesn't eliminate using of improved algorithms.

References

[1] P. M. Espelage and J. M. Nowak. "Symmetrical GTO current source inverter for wide speed range control of 2300 to 4160 V, 350 to 7000 hp, induction motors", in *Proc. IEEE IAS Annu. Meeting,* 1988, pp. 302-307.

[2] D. Beliaev and A. Weinger. "Advanced models for simulation and control of electric drives", *Applied Simulation and Modelling, Proceedings of the IASTED International Conference*, September 4-7, 2001, Marbella, Spain, pp. 218-223.