DIGITAL SENSORLESS CONTROL OF SURFACE PERMANENT MAGNET SYNCHRONOUS MOTORS FOR A DROWNED OIL PUMP DRIVE

Sergey RYVKIN*, Dmitry IZOSIMOV*, and Mihai CERNAT**
e-mail: *rivkin@ipu.rssi.ru* *e-mail*: *izosim@ipu.rssi.ru* *e-mail*: *cernat@leda.unitbv.ro*
* *Institute of Control Sciences/Laboratory of Adaptive Control for Dynamic Objects, Moscow, Russia*
** *"Transilvania" University of Braşov, Faculty of Electrical Engineering and Computer Science, Romania*

Key words: digital control, sensorless drive, surface permanent magnet synchronous motor, drowned oil pump

ABSTRACT

A novel digitally controlled sensorless drive applied to a drowned oil pump, which provides high operational quality (simplification of the digital control algorithm, reduction of the required controller computing capacity) and high reliability is presented. The results of the drive simulation confirm high dynamic accuracy.

I. INTRODUCTION

Today, there is a need for automated systems for oil pumping such as to reduce labour costs, increase production, and provide higher quality results. The main part of such system is the drowned oil pump (DOP). The DOP is a complicated electromechanical system, which must have very high quality coefficients to ensure reliable operation under heavy conditions. This is why one of the main requirements of such an electromechanical system is reliability, in addition to high functional quality. The reliability requirement is complete and relates to the sets, the energy transformation, and the information. Moreover a very important constraint (limitation) is the volume of the drowned set of the pump. There are two main ways of the solving the foregoing problems. The first way implies using different constructive solutions for the pump, motors, energy source, information, and control devices, etc. This way can be named the hardware one. Another way depends not only on using new control and estimation algorithms, but also on designing a new connection diagram between the different drive sets. It can be named the software one. Of course these two ways offer many possibilities for the solving of the foregoing problems.

The main part of the DOP being the drive system, we will focus on it and show in the following how we apply these two ways to the design of the DOP drive system. The results described in this paper are part of the R&D project of the DOP drive system. The first results of this project related to the control algorithms have been presented in [1, 2]. Hence the structure of the present paper. In the second section the drive architecture is described and analysed. In the third section the new control and estimation algorithms that have been used are briefly presented. In the fourth section the construction of the voltage source inverter and control system that will be used in the experimental set-up is examined. The fifth section describes the results of the drive simulations, the set-up and the experimental research on the dynamic behaviour of the drive system.

II. DRIVE ARCHITECTURE

One of the main requirements of the DOP drowned part is the volume that must be as small as possible. For this reason a high-speed drive has been used. So it is possible to reduce the length of the drowned set of the pump five or six times by a small diameter (approximately 100 mm). A specially designed surface permanent magnet synchronous motor (SPMSM) with Samarium-Cobalt magnets, with stable magnet characteristics up to 250 ^{0}C has been used. As a result there are high requirements to the energy source due to the high frequency (1000 Hz) and to the control system due to the small motor inertia moment.

The energy transfer from the ground converter to the drowned part of the electric drive system is made on direct current. It is used a local-distributed energy source. In this case the complete drowned part of the drive has a voltage inverter source (VIS) feed by the ground rectifier. The dc link voltage value is of 2400 V for a drive power of 200 kW, on purpose the cable losses reducing.

For increasing the reliability two level element-redundancy, especially of the drowned part of the drive (hardware way), is used. The first level is the drive set level; the second one is the set element level. On the first level, the needed drive power of 200 kW is carried out as 4×50 kW units, rigidly connected to one shaft. Each of these four units is a complete drive and has three main sets of SPMSM, VIS and digital control system. VISs are consistently connected on dc link. Such circuit decision allows reducing the high dc voltage to the standard stator one of 400 V, i.e. to raise reliability of motor operation, and improve reliability and life cycle length by shunting the failed VIS and switching it off from the SPMSM.

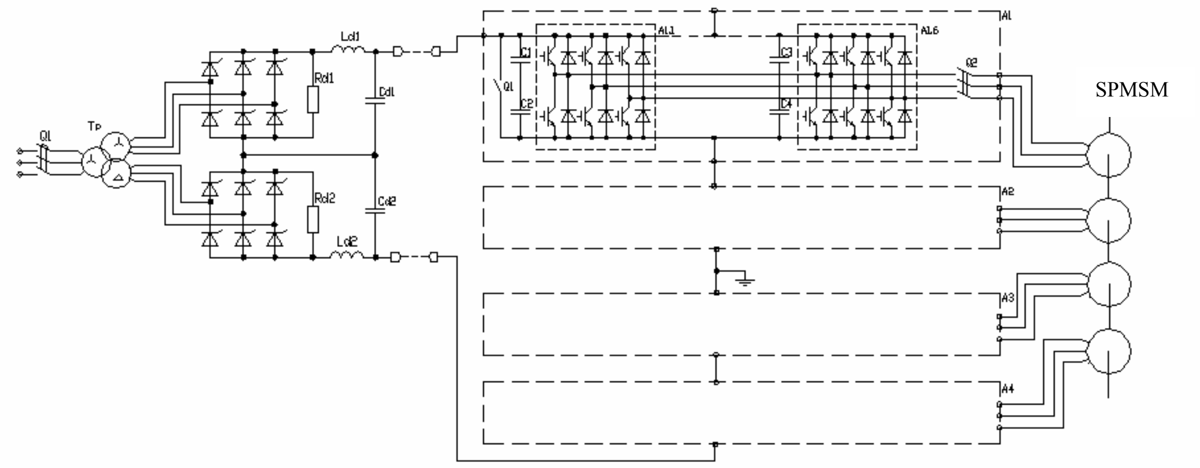

Figure 1. Structure of the power part of drive

In case of drive breakdown, the dc link voltage automatically decreases to 600 V and the remaining drives function normally due to redundancy.
Fig. 1 shows the simplified diagram of the power circuits of the four 50 kW frequency converters.
The upper controller generates the reference value of speed and acceleration, and signals for the VIS switch-on and switch-off. Each drive controller controls and diagnoses the drive. The diagnosis signals are sent to the main upper control station.
As a result such a local-distribution drive has many wire connections of two types: energy and information. The most critical connections are the information ones. There are EMC problems. In this case one of the possible solutions is reducing the number of the information canals between the levels and using a sensorless drive (software way). But from using such a drive follow new high requirements to the drive digital control system. It must solve two important tasks: observation of unmeasured control variables (rotation velocity Ω and position ϑ) and of unmeasured load (load torque T_L) and control of the control variables.

III. CONTROL AND ESTIMATION ALGORITHMS

A. Main approaches to digital control design

The procedure of control design is based on decomposition of an initial task of velocity regulation into two independent tasks of control variable observation and velocity control, by using their estimations and filtering.
The third task is eliminating the influence of the mechanical limitations on the drive dynamics, i.e. generation of "smooth" reference for the control system [3]. In this case, due to the large control error, the system works on the limitation boards. Fig. 2 shows the structure of the control.
As the controller works in discrete time, algorithm design requires a discrete model of the SPMSM. The transition to the digital equations is based on the following assumptions:

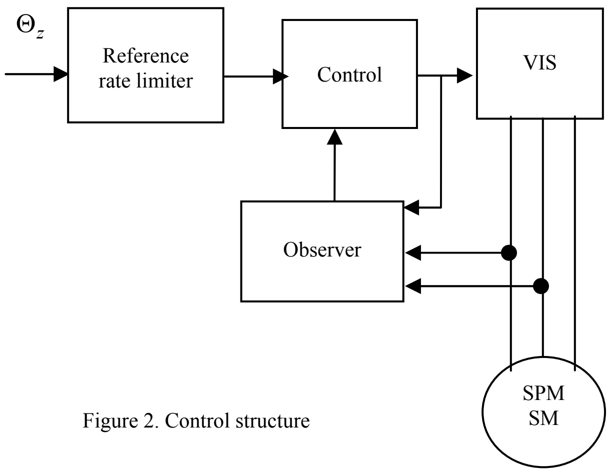

Figure 2. Control structure

- The motor behaviour is analyzed over a sampling period T ;
- The rates of the mechanical switching (typical time constant 10 - 100 ms) and VIS switching (typical time constant 10 - 100 μs) processes in SPMSM are essentially different; PWM frequency is fixed (PWM period is constant);
- The duration of a sampling period Δ is equal to the PWM period;
- The estimation control variables have been calculated once for a sampling period**.**

The measured variables are the currents and voltages in the SPMSM stator windings. PWM components in both current and voltage measurements should be excluded. For avoiding a switching component in current measurements it is necessary to measure the currents not in any, but in certain moments of time during the PWM period. The digital controller holds information about the average voltage value without the PWM component. It is the reference value of the voltage.

The following features caused by the discrete character of calculations in a digital regulator are inherent to deciding the assigned control task. The control task cannot be carried out faster than for two sampling periods. Namely, the first period $[n,\ n+1]$ is used for calculations of the desired value of the VIS voltage by using the initial information about variables, received as a result of the measurements and available in the processor. The second period $[n+1,\ n+2]$ is used for achieving the designed control. The specified delay should be taken into account appropriately in the synthesis of the external closed regulation loop (regulation loop of speed, state etc.).

B. Reference rate limiter

There are such drive limitations as:

- speed Ω limitation

$$|\Omega| < \Omega_{\max} \tag{1}$$

following from voltage limitation of the power supply and mechanical durability;

- acceleration a limitation

$$-\frac{T_{max}+T_L}{J} = a_{min} < a < a_{max} = \frac{T_{max}-T_L}{J} \tag{2}$$

following from current limitations of the power converter and another drive dynamics limitations. Here T_{max} is a maximal value of the motor torque, J is the drive inertia moment.

In view of the above, generation of the reference for the control system must consider the following conditions:

- Achievability of the reference under dynamics limitation in case the reference cannot be realized;
- Absence of a dynamic error by submission to a control of the achieved reference
- Maintaining operation in a stable linear zone in the case of deviations of the control variables.

The reference rate limiter represents a dynamic system with limitations on the variables and on their change rate. The in- and output signals of the limiter have such indices: superscript n is the simplified period number, subscript lim is the output signal that is the reference signal for the control, subscript z is the drive reference signal that is the input signal. The high level regulator (e.g. digital control system) generates a reference value of position ϑ_z^n. The digital equations of the rate limiter motion can be written:

$$(\Delta\,\vartheta)_z^{n+1} = (\Delta\,\vartheta)_z^n + (\Delta\,\Omega)_z^n T + \frac{(\Delta\,a)_z^n T^2}{2} + \frac{v^n T^3}{6} \tag{3}$$

$$(\Delta\,\Omega)_z^{n+1} = (\Delta\,\Omega)_z^n + (\Delta\,a)_z^n T + \frac{v^n T^2}{2} \tag{4}$$

$$(\Delta\,a)_z^{n+1} = (\Delta\,a)_z^n + v^n T \tag{5}$$

where

$(\Delta\vartheta)_z^n = \vartheta_{lim}^n - \vartheta_z^n$,

$(\Delta\Omega)_z^n = \Omega_{lim}^n - \Omega_z^n$,

$(\Delta\,a)_z^n = a_{lim}^n - a_z^n$,

and v is the rate limiter control.

Deviations between the limiter input and output signals must converge to zero, with the condition that acceleration and rate of limiter output signals do not exceed their minimal and maximal values. In this case there are no additional requirements to the reference signals, in particular, the position reference can change stepwise its characteristic, for example, by positioning. This problem can be solved by the way of a sliding mode organization on the commutation surfaces:

$$S_1^{n+1} = a_{lim}^{n+1} - a_{\,max} = 0 \tag{6}$$

$$S_2^{n+1} = a_{lim}^{n+1} - a_{\,min} = 0 \tag{7}$$

$$S_3^{n+1} = c\ (\Omega_{lim}^{n+1} - \Omega_{\,max}) + a_{lim} = 0 \tag{8}$$

$$S_4^{n+1} = c\ (\Omega_{lim}^{n+1} + \Omega_{max}) + a_{lim} = 0 \tag{9}$$

$$S_5^{n+1} = (\Delta\ a)_z^{n+1} + b_1\ (\Delta\ \Omega)_z^{n+1} + b_2\ (\Delta\ \vartheta)_z^{n+1} = 0 \tag{10}$$

The character of the moving of an error to zero after occurrence of a sliding mode on a commutation surface $S_j = 0,\ (j = 1,\ ...,\ 5)$ is defined by the choice of coefficients b_1, b_2, c.

Additionally the limiter control v^n can be bounded by the minimal and maximal values:

$$-v_{\max}^n < v^n < v_{\max}^n \tag{11}$$

The values of v^n required for performing conditions (6) - (10) on the $(n+1)-$th period have been calculated. Then these values are compared with each other and the least value is used for the calculation of the limiter output signals, i.e. control the reference ones.

C. Control variables estimation

During any sampling period $(n + 1)$ there are measurements of currents that are made at the beginning of this period $i_\alpha^{n+1},\ i_\beta^{n+1}$ and at the end of the previous one $i_\alpha^n,\ i_\beta^n$, the value of the stator windings voltages $u_\alpha^n,\ u_\beta^n$ being known. The first estimation of the angle ϑ_{eq}^n can be calculated:

$$\vartheta_{eq}^n = -\mathrm{atan}\ \frac{i_\alpha^{n+1} - i_\alpha^n - \frac{T}{L}(u_\alpha^n - r\cdot i_\alpha^n)}{i_\beta^{n+1} - i_\beta^n - \frac{T}{L}(u_\beta^n - r\cdot i_\beta^n)}, \tag{12}$$

where L is the stator winding inductance.

If there are any errors generated by sensors and/or information processing systems or there are not enough control variables, for examples the value of the load torque is not known, it is possible to use a state observer [5, 6]. The observer design is based on the mechanical variable equations (the observer variables have superscript *):

$$\vartheta^{(n+1)*} = \vartheta^{n*} + T\,\Omega^{n*} + \frac{T^2}{2J}\,(T_{eq}^n - T_L^{n*}) + l_1(\vartheta^{n*} - \vartheta_{eq}^n)\,, \tag{13}$$

$$\Omega^{(n+1)*} = \Omega^{n*} + \frac{T}{J}(T_{eq}^n - T_L^{n*}) + l_2\,(\vartheta^{n*} - \vartheta_{eq}^n)\,, \tag{14}$$

$$T_L^{(n+1)*} = T_L^{n*} + l_3\,(\vartheta^{n*} - \vartheta_{eq}^n)\,, \tag{15}$$

where l_1, l_2, l_3 are observer coefficients to the differences between the estimated and calculated values of angle position. The calculation of coefficients l_1, l_2, l_3 were carried out depending on the convergence rate of an estimation error to zero, e.g. there are the same three real roots $\lambda_i = \lambda_1 = \lambda_2 = \lambda_3$ of the characteristic equations.

D. Control

The control of SPMSM achieves direct digital vector control of the SPMSM-VIS complex and has two blocks:

- computer of the torque reference value;
- current control.

The reference value of the torque is calculated by using the limiter output signals:

$$T_{eq}^n = T_L^{n*} + J\,[a_{\lim}^n + d_0\,(a_{\lim}^n - \frac{T_L^{n*}}{J}) + d_1\,(\Omega_{\lim}^n - \Omega^{n*}) + d_2\,(\vartheta_{\lim}^n - \vartheta^{n*})]\,, \tag{16}$$

where the values of the coefficients d_0, d_1, d_2 are selected from the required values of the roots of the characteristic equation:

$$\begin{vmatrix} 1+\frac{T^2}{2}d_2-\lambda & T+\frac{T^2}{2}d_1 & \frac{T^2}{2}d_0 \\ Td_2 & 1+Td_1-\lambda & Td_0 \\ d_2 & d_1 & d_0-\lambda \end{vmatrix} = 0 \tag{17}$$

The task of the current control block consists in generation of the reference values of the voltages u_d^n, u_q^n, which ensure the solving of the control task. The control aim consists in maintaining the equality of the actual and reference value of the control variable (for example rotation speed). The control law can be written as the following function of the control error of the rotation speed $(\delta\,\Omega)^n$ (or error of rotating angle $(\delta\,\vartheta)^n$):

$$S^n = (\delta\,\Omega)^n + \alpha\,(\delta\,\Omega)^n / T \tag{18}$$

The conditions $\alpha \neq 0$ and $S = 0$ ensure asymptotic convergence of a control error $(\delta\,\Omega)$ with the time constant $\tau = 1/\alpha$. The condition $\alpha = 0$ ensures a finite step procedure of regulation (digital sliding mode) when the equality of the actual value of a rotation velocity with the reference one is provided at time moment $(n+2)$. From this condition

$$(\delta\Omega)^{n+2} = \alpha^2 (\delta\Omega)^n \tag{19}$$

it is possible to calculate the needed average value of the torque T_{eq}^{n+1} and then the needed value of the voltage component u_q^{n+1}:

$$i_d^{n+1} = i_d^n + \frac{T}{L}\,(-r\cdot i_d^n + L\cdot\Omega_{eq}^n\cdot i_q^n + u_d^n)\,, \tag{20}$$

$$i_q^{n+1} = i_q^n + \frac{T}{L}\,(-r\cdot i_q^n - L\cdot\Omega_{eq}^n\cdot i_d^n - \Psi_f\cdot\Omega_{eq}^n + u_q^n)\,, \tag{21}$$

$$u_d^{n+1} = -(L/T)\cdot(i_d^{n+2} - i_d^{n+1}) + r\cdot i_d^{n+1} - L\cdot\Omega_{eq}^n\cdot i_q^{n+1}\,, \tag{22}$$

$$u_q^{n+1} = -(L/T)\cdot(i_q^{n+2} - i_q^{n+1}) + r\cdot i_q^{n+1} + L\cdot\Omega_{eq}^n\cdot i_d^{n+1} + \Psi_f\,, \tag{23}$$

where the current components i_d^{n+2}, i_q^{n+2} on the calculation period $[n+2,\ n+3]$ are:

$$i_d^{n+2} = 0$$

$$i_q^{n+2} = T_{eq}^{n+2} / \Psi_f\,.$$

IV. VIS AND CONTROL CONSTRUCTION

A. VIS Construction

The most significant aspect of the drowned inverter development regards selection and correct application of power transistors. The paper relates to the special approach applied to this problem. In view of the rather high value of the target frequency of the basic harmonic on an VIS output of the inverter (1000 Hz) and power from tens up to hundreds watt applied to the IGBT modules, these could be placed in a pipe of internal diameter of about 107 mm. The second condition was minimizing the influence of the harmful inductances in the switching circuits. In this case it is expedient to apply the modules containing the 3-phase bridge, i.e. it is more favourable to apply parallel and consecutive connection of low-current bridges, than connection of larger modules with one or two keys in the diagram of the 3-phase bridge. Another advantage of low-current modules is that they, as a rule, ensure the better dynamic characteristics and a smaller direct power failure in conducting mode.

The third condition for module selection is the possibility of their effective cooling at cooling watercut temperatures up to 90°C. For deciding it was required, firstly, to choose, despite of the small dimensions of the set, modules with a very large current limits, considering that switching losses are very sharply reduced statically and dynamically, and secondly, to use the Peltier effect for cooling. As a result the compact FS150R12KE IGBT module made by "eupek" was used. This module contains the 3-phase bridge diagram, with a rated current in each bridge shoulder of 150 A at 80°C and a rated voltage of 1200 V. The module footprint is of 120 × 62.5 mm^2. One 50 kW VIS has 6 parallel-connected modules. Consequently the current amplitude in each bridge shoulder at rated load is less than 19 A.

Even after serial failure of 2 modules the current load on the module will not exceed 16 % of the rated face value and the loss in the rest of the working modules will be of about 84 W.

Up to 8 Peltier elements (30 × 30 mm^2) are placed under the module footprint. Each Peltier element can conduct thermal power of approximately 16 W by a temperature difference about 30°C between the module and the watercut pipe, having a temperature up to +90°C. This means, that for a rated drive load, module temperature at 16 % current load does not exceed 70°C, that "it is quite comfortable" for the module. In case of a module failure, this is separated from the VIS.

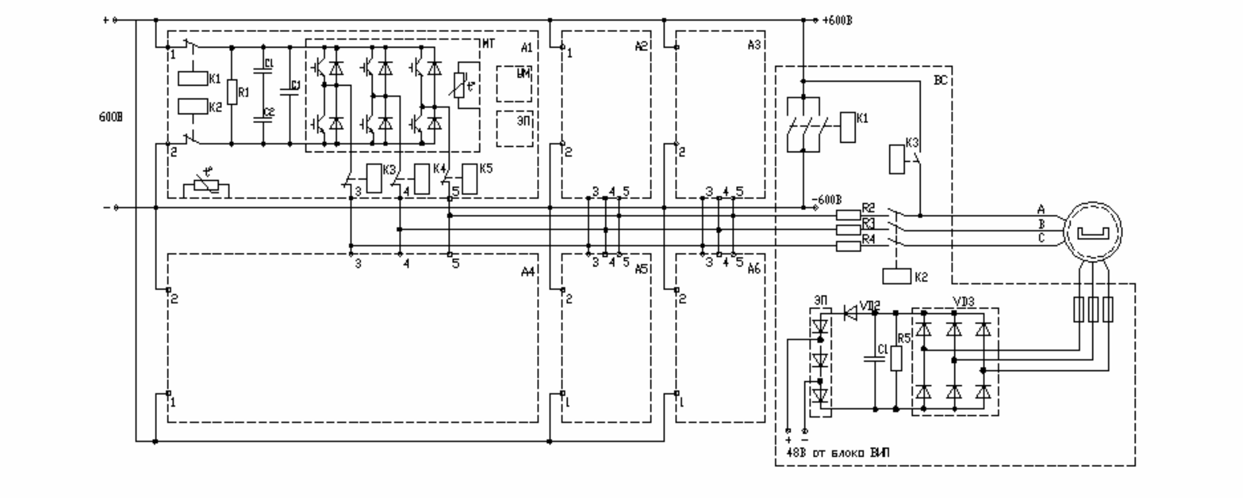

Figure 3. Structure of the drive system.

by small-sized relays, shown on the drive diagram of Fig. 3. By this specific approach to module selection, the designed VIS achieves very high efficiency - more than 98%.

B. Control

As marked above, the digital control system has a hierarchic local-distributed structure. The upper level is a ground control. The lower level is a local-distributed control system, which has four drive controls. This drive control is designed on the basis of the TMS320F2810 microprocessor. The upper controller generates the reference value of speed and acceleration, and the VIS switch-on and -off signals. At the same time, as the VIS contains a significant number of parallel connected modules with a certain redundancy, and each upgrade of equipment is expensive enough, maintaining the diagnosis of the drowned equipment and its connection with certain logical operations is rather important. For the purposes of diagnosis and failure analysis it is necessary to transfer the information from the gauges of the drowned part to the main upper control station.

In the design of the drowned part control certain features of the drive construction were taken into consideration: small pipe diameter: approximately 100 mm and a great pipe length (1.5 m/section). In these conditions it is important to provide noise stability and protection of control circuits. One of the possible solutions is reducing as far as possible the quantity of low-current circuits and their length. For this, the peripheral low productivity controller placed directly near each module collects numerous signals from sensors of electric and non-electric variables. The information exchange with higher level controllers is made through the CAN-interface channel that needs only 2 wires, i.e. many times less than in case of one general controller for the whole inverter.

V. SIMULATION RESULTS

All above-mentioned algorithms were simulated by means of MatLab 6.5.0 and Simulink 5.0 [1, 2]. The model mainframes were written in C++ programming language. The drive simulation system includes:

- SPMSM model;
- VIS model, reflecting PWM algorithm;
- Model of the observer;
- Model of a digital regulator;
- Model of a reference rate limiter;
- Means of generation of the given rotation speed;
- Means of process indication;
- Means of input of SPMSM parameters.

The digital blocks such as rate limiter, observer, VIS and control are considered discretely, with 1 ms periods. The simulation was carried out with real physical variables by using primary SI units (V, A, N·m, s).

The acceleration a is bounded by the maximal values, $a_{max} = a_{min} = 630601$ s^{-2} the output velocity is bounded by $\Omega_{min} = 220\cdot\pi$ s^{-1}, $\Omega_{max} = 2200\cdot\pi$ s^{-1} the variable v or limiter control is bounded by $v_{max} = 101760$ s^{-3}. The sampling period is $T = 66.666$ ms.. The limiter coefficients are: $b_1 = 25\ s^{-1}$, $b_2 = 0$, $c = 1$ s^{-1}.

The data of the used SPMSM and its two-phase model are presented in Table 1.

Table 1
The data of the used SPMSM and its two-phase α-β model

	SPMSM	Two-phase model
P (kW)	50	50
U_{ph} (V)	220	270
R (Ω)	0.0385	0.0385
L (mH)	0.24	0.24
p	2	1
J (kg·m^2)	0.01	0.025
Ω (rad/s)	1000·π	1000·2π
Ψ_f (N·m/A)	0.05	0.0606
T_L (N·m)	15.9	7.95
i_{qmax} (A)	215	263

The modes of the observer are identical and equal to 0.9. The modes of the control are identical too, and equal 0.98. The control coefficients are the values $a_0 = 0.9412$, $a_1 = -17.73$, $a_2 = -1782$.

Process analysis was carried out considering transitive characteristics using the reference signals for the speed

and the load, presented in Fig. 4, which allow the analysis of the drive behaviour in different modes. In the figures below the horizontal scale is time one (s), the vertical scale is the reference value after the limiter, or the control variable or the estimated one.
The analysis of processes was carried out under the transitive characteristics with using of the special reference signals of the rotation speed and the load, which are presented in Figs. 4 - 5. Such inputs signals allow analyzing drive behaviour in the different modes. On given below figures horizontal scale is time one (s), vertical scale is the reference value after limiter, or the control variable or estimated one.

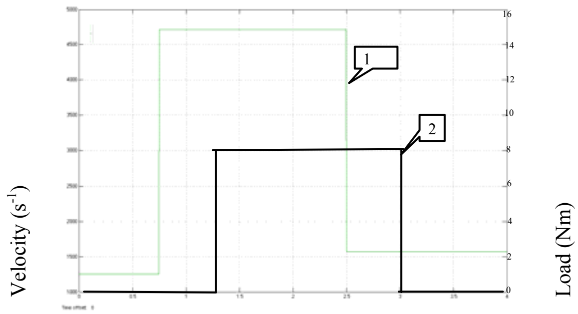

Figure 4. Reference signal of velocity (1) and load (2)

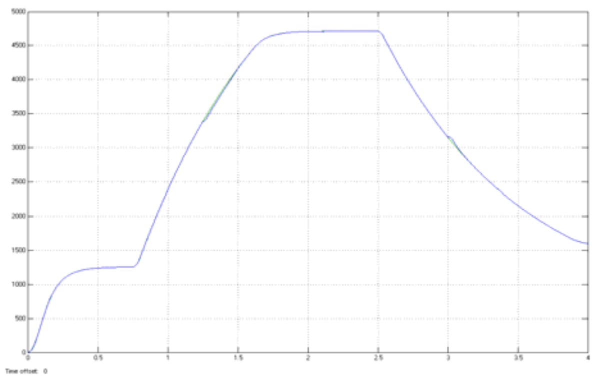

Figure 5. Reference signal of the velocity (limiter output), actual velocity and its estimation

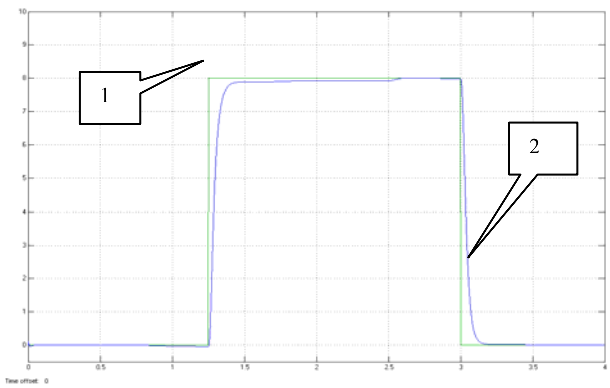

Figure 6. Actual load (1) and its estimation (2)

In Figs. 5 - 6 the drive behaviours are depicted. The reference value of velocity, its actual value and its estimation are practically equal.
The influences of the 20% error of the reference value of the induction and moment of inertia and of ADC on drive behaviour were investigated too.

VI. CONCLUSIONS

A hierarchic local-distribution structure of the digitally controlled sensorless drive for the drowned oil pump is presented. The developed drive system provides high operational quality and high reliability. The drive architecture from the reliability viewpoint is described and analyzed. Two-level redundancy is used for the power part of the drive. The first level is the drive set level. The second one is the set element redundancy. On the first level the needed 200 kW power drive is achieved by four 50 kW ones, connected rigidly on one shaft. Each of these four drives is a complete drive and has three main sets, including high speed SPMSM, VIS and digital control system. The control system has two levels. The upper one is a ground control. The lower level is a local-distribution control system, which has four drive controls. The new control, estimation and limitation algorithms have been specially designed. The results of the drive simulation have confirmed high dynamic accuracy and in addition simplification of the digital control algorithm, reduction of the required controller computing capacity. The drive dynamic behaviour will be examined using the described special set-up and experimental tests.

REFERENCES

1. S. Ryvkin, D. Izosimov, D. Aksarin, and M. Cernat, Digital Sensorless Control of an Exterior Permanent Magnet Synchronous Motor, Proc. 11th International Power Electronics & Motion Control Conf. EPE - PEMC 2004, Riga, Latvia, 2004, CD-ROM.
2. S. Ryvkin, D. Izosimov, A. Sarychev, L. Raskin, and D. Aksarin, Remote Control for the Oil Drowned Pump, Proc. International Symposium on Remote Engineering and Virtual Instrumentation, REV, Villach, Austria, 2004, CD-ROM.
3. S. Ryvkin, D. Izosimov, and S.Baida, Digital Reference Rate Limiter Design, Proc. 9th International Conf. on Optimization of Electrical and Electronic Equipment, OPTIM ’04, vol.3, pp.103-108, Brasov, Romania, 2004.
4. M. Cernat, V. Comnac, Fl. Moldoveanu, Sensorless Speed and Direct Torque Control of Interior Permanent Magnet Synchronous Machines Based on Extended Kalman Filter, Proc. Second International Conference on Electrical and Electronics Engineering, ELECO’2001, 7-11 November 2001, Bursa-Turkey, ISBN 975359-479-4, Vol. Electric Control, p. 311-316.
5. J. Vittek, S. J. Dodds, Forced dynamics control of electric drives, EDIS – Publishing Center of Zilina University, Slovakia, 2003, ISBN 80-8070-087-7.
6. H. Kvakernaak and R. Sivan Linear optimal control systems. John Wiley & Son Inc., NY, 1972.