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Computer-assisted Electrodynamic Modeling System for Oil and Gas Industry Electric Drives Study

(Статью представил д-р техн. наук А. Ф. Верлань)

Electrodynamics models of the oil and gas equipment that mainly consist of several controlled electric drives mechanisms and autonomous generators are considered. Applications of the model to drilling and pumping drives are presented.

Рассмотрены электродинамические модели автоматизированного нефтяного и газового оборудования, состоящие преимущественно из управляемых электрических механизмов и автономных генераторов. Приведены примеры использования моделей для буровых и насосных установок.

Key words: electrodynamics models, oil industry electric drives.

The application of the electrodynamic modeling technique is substantiated. The methods of laboratory electrodynamic modeling (EDM) of any complicated mechatronics systems are very effective. A computer guides the model and, at the same time, processes feedback signals and analyzes results data in real time. The thyristor converter is used for the considerable extension of the model's electromechanical characteristics frequency operating range. The modeling process is carried out using industrial 3—5 kW small electrical machines, but it uses the real excitation and control systems of the modeling powerful generators and motors.

Electromechanical systems of the oil and gas industries usually work under harsh technical and climatic conditions which raise several demands and strict requirements for the design of new mechanical, electrical and electronic equipment. The most important here — a special mobile team, using helicopter, ship or all-terrain track-type vehicles etc. can service thousands of pieces equipment in these vast areas (Arctic, tundra, desert, sea jack-up derrick or island, etc.) only once a year, rarely twice. Thus, the equipment which operates in these areas (far away from technical service centers) demands an increase in their durability, reliability and vitality (higher than one year) during new technique designs.

Any unexpected or sudden stop during scientific experiments or technical service of the equipment, even for 10—20 min, whatever the reason (mechanical, electrical, electronic, etc), can bring long-term problems especially during winter: frozen oil-well liquid in the output pipes, drilling mud in the derrick's manifolds or gas condensation in the gas pipeline etc. Such a breakdown will cause the oil well to stop production for several months until the next summer service. In the so-called «reach of sand» wells the stop usually causes the sand to settles down through gravity and blocks turbine or sucker-rod oil pumps' subterranean reverse valves. This makes it difficult or impossible for an automatic self-starting of pumps and results in a forced outage until the next service team visit. The service team then has to make a complicated extra lift of the well exploitation pipe column and clean the sand from it.

Oil and gas wells are extremely hazardous and explosive installations: during emergency cases there may be big leakages of gas or oil (a small emission of gas and oil is always there). Therefore gas and oil field installations must not have any sparking elements which can provoke fire or explosion at near 10 m minimum around the well. All systems should have fire- and explosion- proof motors, switches, control systems etc.

Further, the working conditions of boring and oil (gas) extraction equipment are characterized by abrupt or cycling torque on the shafts. Some 70—80 % of them are sophisticated systems, full of power electronics, several electrical machines, with their control systems and so on. For instance, there are electric drives such as boring winches, or boring-mud and cement piston pumps, rotary tables, electromagnetic brake mechanisms, centrifugal subterranean turbine pumps and sucker-rod oil pumps. These specific working conditions produce an unfavorable pulsation in the voltage supplying networks and lead to the premature wearing out of the electrical and electronic equipment.

There are some sophisticated scientific and technical problems for investigation in order to optimize the technology of the above-mentioned installations (being designed or existing) which have to serve under these severe, quasi-periodical and quasi-shocking conditions of work. Natural field investigations of the mechanisms are important, but, as mentioned above, putting into practice any of these experiments is very complicated and risky work for these equipments and also for the technical personnel. (Often the local oil board authority is contrary to any scientific and technical field tests).

Recent results [1—6] indicate that PC mathematical modeling can help to study the dynamics of such oil electromechanical equipment. Very often it leads to difficult analysis due to a protracted real investigation time (several minutes), the random complex manner of the voltage fluctuations across the motors and yields a very rigorous character of the IM and SM full algebraic-differential non-linear equations. Their solutions often do not give a strict homology between the results obtained and the real processes [7].

Therefore, methods of electrodynamic modeling of the complicated electrical drive systems are still very efficient. They are widely used both in the synthesis, analysis and experimental trial of new multi-machine DC and AC drives, their automatic control systems, and mechanisms such as diesel-generators, pumps, winches, drilling table system etc.

The named analyses were conducted by means of the Special Computer-Assisted Lab Electro-Dynamic Model (CALEDM). Standard industrial small (3 — 5 kW) machines, but real automatic excitations and technological control systems (if any) of the modeling systems are used in the model.

The computer controlled multifunctional electrodynamic model. The computer controlled multifunctional electrodynamic model [2, 8, 9] was designed for the investigation of oil (gas) industry equipment, especially for the controlled multi-machine drives and generators on land and sea derrick platforms. The special EDM for oil and gas industries electromechanical systems (Fig. 1) consists of:

1. Four electrical machines 3—5 kW (M1 — M4) — one AC synchronous (or induction) and three DC — with real excitation and technological control systems (TCS) of the modeling machines.
2. Three thyristor converters 500V and 50—100A (TC1 — TC3) and a TC-controlled reactive power source for 3—5 kVAR.
3. Three two-way function switches and seven simple on (off) switches.
4. PC with A-D and D-A converters.
5. Measuring instruments: power transducers, tachometers (T), voltmeters and ampermeters, oscilloscopes and record systems etc.

DC M4 (sometimes M2) operates as a load generator together with resistances R_L, R_1 and TC3. The other electrical machines, including M2, work as a modeling machines prototype. If necessary, TC1 together with M2 can be used for a diesel system behavior simulation prototype in the model. TC1 and components R_U, L_U, Sw9 and R_{LU} are used to simulate pulsing or abrupt voltage changes of the main supply (just after Sw1). The computer guides the model.

The thyristor rectifier TR3 of the CALEDM load imitation unit (separately shown on Fig. 2) is used for the considerable extension of the model frequency characteristics (compared to the load imitation via the DC generator exciting coil). The method uses TR3 as variable contra-voltage (for both R_G and $R_{TR} << R_{LD}$). When $V_{TR} > V_G$ and is rising DC generator brings down its load — it can

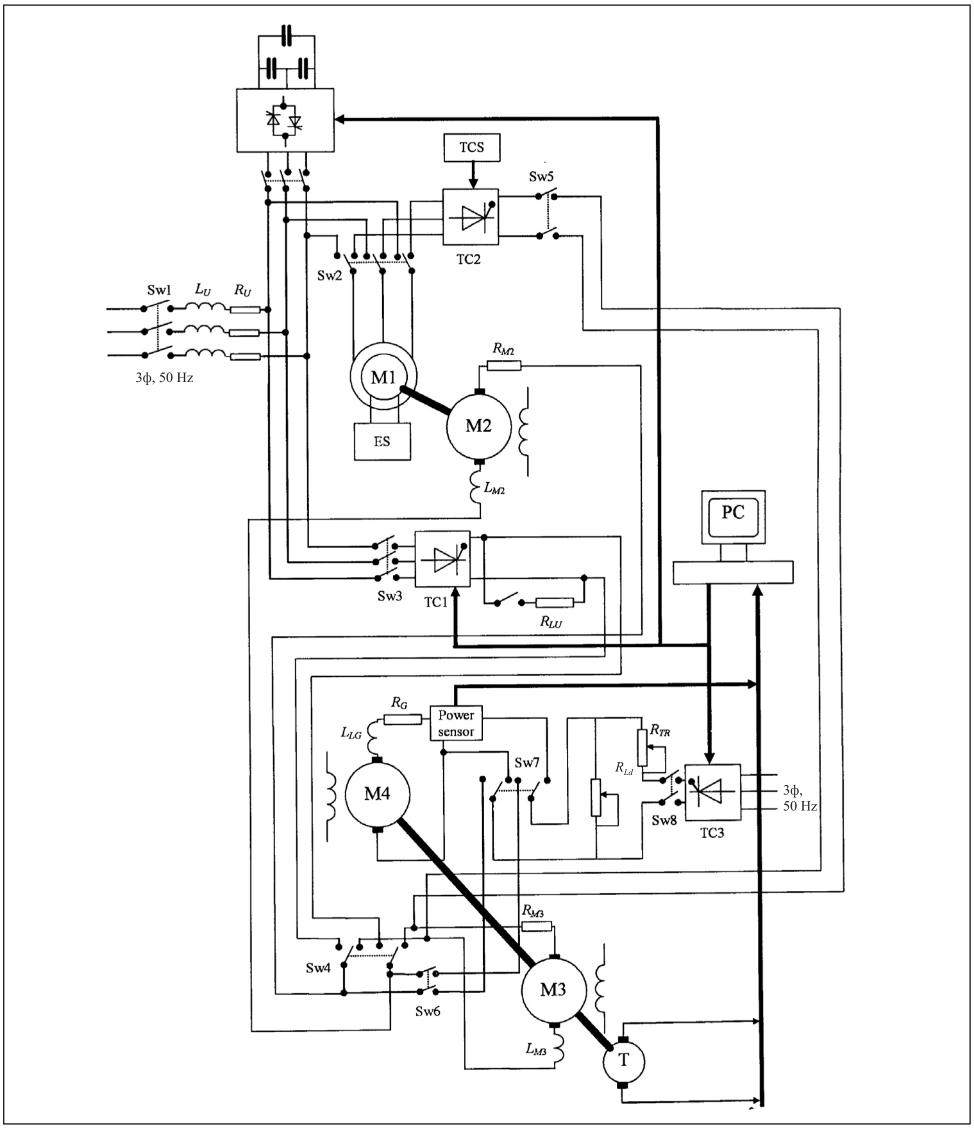

Fig. 1. The computer assisted electrodynamic model basic electrical diagram: TCS — Technological Control System; ES — Exciting System; TC — Thyristor Converter

be even shifted into motor regime (the investigating drive — into generator regime). When $V_{TR} < V_G$ and is decreasing there is an increasing motor regime of the investigating drive.

It should be stressed here that CALEDM facilitates the study of higher and lower inertial electrical machines rather than the model ones (using a negative or

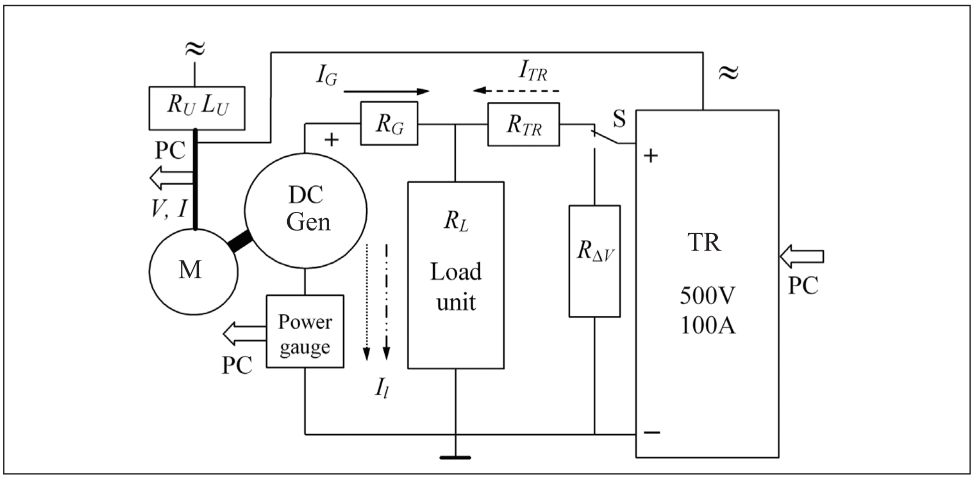

Fig. 2. Basic electrical diagram of the EDM load and voltage pulsation imitation unit: —► — max load regime current ($I_{TR} = 0$, $I_G = \max$); ····► — min generate regime current ($I_{TR} = \max$, $I_G < 0$)

slightly positive sliding feedback), and analyzes the influence of the long rod transient processes on its eclectic drive. A special program can simulate the functional characteristics of the long rod and then different working regimes can be modeled. All these create similarity of the models processes and the real objects, extend their functional opportunities and permit some parametric variations.

All the above mentioned features provide the model with universality and allow the combining of the model elements for the simulation of the various industrial equipment mechatronic systems.

Practical applications. ***Synchronous or induction motor (SM or IM) simulations under leap dynamic load and voltage cycle or abrupt fluctuation.*** This study dealt with the problem of oil extraction field sucker-rod pumps (SRP) and their specific conditions of work. It will be presented in detail step by step. The other practical applications will be presented in brief — equipment connections and results.

The following chain of the model elements was connected: 3 phase main, switches S1 (on) and S2 (left position), M1— prototype drive model and M2 — mechanical load simulating machines, S4 (in the middle position), S6 (on), Sw7 (left position), Sw8 (on), thyristor converter TC3 for the rapid-load simulation, 3 phases main. The load imitation control as well as the main experimental data interpretation was made using a PC (see result on Fig. 3 — a real oscillogram). For easy presentation a simplified (for this case) version of Figure1 diagram is shown on Fig. 2.

Voltage fluctuation influence on electric drives with cycling load. Voltage fluctuations usually have a big influence on the dynamic stability of every elec-

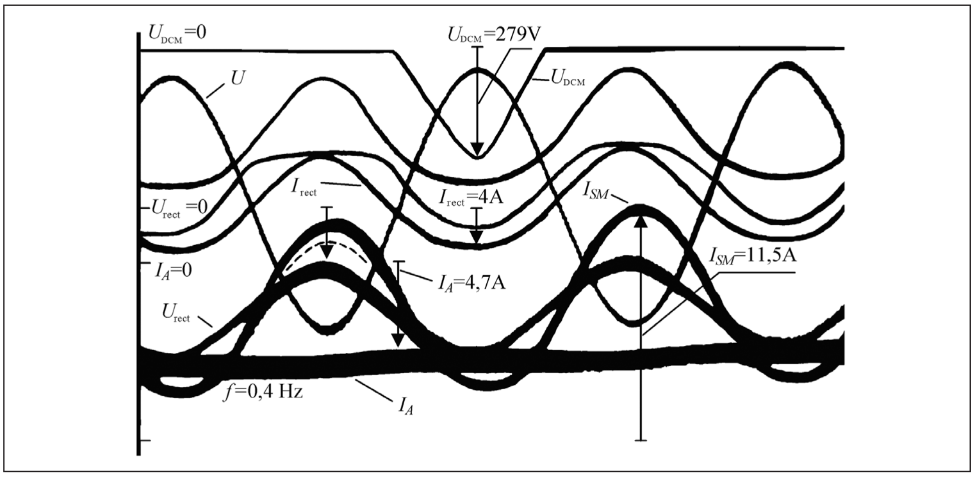

Fig. 3. The sucker rod pump SM electric drive; results of simulation experiments

tric drive and there are some opinions that a synchronous motor SM is more like a «pendulum» than an induction motor IM: the dynamic stability of special brushless synchronous motor (SBSM) under such voltage fluctuations might be worse than IM dynamic stability. Therefore voltage fluctuation influences on IM and SBSM stability were carefully studied and compared.

As mentioned, it is very difficult to use a digital computer for these studies due to a protracted real investigation time (several minutes), the complex manner of the voltage fluctuations across the machine terminals and mainly due to the very stiff character of the IM and SBSM full model equations. Their solutions often do not give a strict match between the results obtained and the real processes.

Simplified computer-assisted lab electro-dynamic model (CALEDM). Actual field investigations of these electrical drives are possible and important. However, due to the extremely hazardous character of oil fields, getting permission from any oil field administration is often extremely difficult. On the other hand, the practicality of conducting these experiments in an oil field over wide scales is very complicated and dangerous work for this expensive, sometimes unique, equipment and a risky job for technical personnel. Thus, the methods of electrodynamic modeling of an electromechanical system are still very efficient.

The simplified CALEDM (see Fig. 2) of SRP IM and SBSM drives study under voltage fluctuations consist of: M — AC synchronous or induction motor; DC GEN — DC generator of mechanical load imitation system; TR — thyristor rectifier 500V / 100A; S — two ways functional switch; PC with A-D and D-A converters; measuring instruments: power transducers, tachometer, voltmeters and ampermeters, oscilloscopes, record systems and so on. There are two types of studies due to S-switch position:

1. Switch S in up position. The DC generator and the thyristor rectifier TR work together as a mechanical load imitation system. The thyristor rectifier TR is used for the considerable extension (up to 10 Hz) frequency characteristics of the mechanical load imitation system. The computer guides the model. Resistance $R_L >> R_G$ and R_T. Here TR uses its variable voltage V_{TR} to counter the generator voltage V_G (E_G). When $V_{TR} > V_G$ and increasing, the DC generator brings down its braking torque and can even enter in the motor regime, whereas the investigating drive M does vice versa — it goes from motor to generator regime. When $V_{TR} < V_G$ and decreasing, the DC generator increases its mechanical braking torque and drive M goes deeper and deeper into the motor regime.

2. Switch S in down position. Thyristor rectifier works on powerful resistances $R_{\Delta V}$. Resistance R_L and inductance L_L help to simulate the voltage pulsation or abrupt voltage changes only on the terminals of the investigating motor. A variable powerful DC current through $\mathrm{R}_{\Delta V}$ provides a variable powerful AC current I_{TR} through TR and line elements R_L and L_L leaving on them additional variable voltage drop ΔV and simulates a voltage pulsation controlled by a computer.

Studies were made following instruction [4, 8] and the appropriate criteria of similarity [1] were taken into account:

$$M^* = \frac{M(\Omega/\Omega_N)^\gamma}{M_N},$$

where M^* — relative moment of the load; Ω — angular velocity of the load; M — real moment of the load; Ω_N — nominal angular velocity of the load; M_N — real nominal moment of the load; γ — coefficient of dependency M from Ω.

A special or personal computer (PC with A/D and D/A converters) governs the load or voltage-pulsation simulation systems (see Fig. 2). Previously the CALEDM was governed by a hybrid analog-digital computer and later by a PC. The typical for SRP character drive load was produced by a special program using the mathematical equations of a mechanical load on the shaft (or power, or current and so on). Similarly, study is done for voltage pulsation simulation on the electrical machine terminals. Sometimes the mechanical load, current or voltage of IM or SBSM are recorded on a tape during a visit to the oil field and used in the CALEDM. The computer compares these signals with the appropriate feedback signals from the electrodynamics model sensors (torque, voltage, power, current or speed gauges). Built-in control software forces the model to interpret the recorded signals and reconstruct them in the model elements. All these factors provide an acceptable simulation of the actual dynamic processes in a drive.

IM and SBSM Stability Analyses. The main reason for taking the coming down approach of modeling the IM and SBSM stability problem is the following: it is accepted as an evident assumption that the main influence on stability of IM and SBSM (with constant exciting current) ought to exert:

1. The low frequency voltage harmonics equal or very close to the frequencies of the shaft torque oscillations (0,05—0,5 Hz), especially the counter phase to oscillations (β_V = 180°);

2. The relatively high frequency harmonics (2—20 Hz), equal or closely matching to the electro-mechanical resonance frequencies of IM or SBSM SRP drive shaft systems.

Suppose the voltage oscillates between $V_{\max}$ and $V_{\min}$ with an angular velocity Ω_V and epoch angle β_V according to:

$$V = V_{\min} + 0{,}5(V_{\max} - V_{\min})[1 + \cos(\Omega_V t + \beta_V).$$

For the first (low frequency) case the voltage fluctuation Ω_V was taken as equal to Ω_M (the frequency of the shaft torque oscillation) and $\beta_V = 180°$ (for four fixed voltage drop deviations $\Delta V = V_{\max} - V_{\min} = 0$; 5; 15 and 20 %). The moment on the motor shaft was presented as:

$$M = M_{\min} + 0{,}5(M_{\max} - M_{\min})(1 - \cos\Omega_M t).$$

The motor was gradually loaded further up to the stability limit by increasing only $M_{\max}$ ($M_{\min}$ = const ≈ 0,15 ÷ 0,2). The last stable state value of $M_{\max}$ was taken as the sought limit result for the comparison of IM or SBSM stability factor.

First results. Based on various investigations [10, 11] it was found that on average every 1 % of this low frequency counter phase voltage pulsation reduces IM dynamic stability by about 1,75 — 2,5 % and SBSM by about 2 — 3 %. The results show an almost equal dynamic stability for both IM and SBSM under this low frequency voltage pulsation.

In the second (high frequency resonance) case the electromechanical resonance frequencies of the IM and SBSM electric drives were approximated by the model. Due to the relatively high value of these frequencies of voltage pulsation (2 — 20 Hz, for IM even higher) it was evidently clear that the stability of the IM and SBSM might be easily broken down during any maximum torque on their shafts.

From this point of view for every fixed value of $M_{\max}$ = 1,2; 1,4; 1,6 and 1,8 the value of $\Delta V = V_{\max} - V_{\min}$ ($V_{\max} = V_{\text{nom}} = 380$V) was slowly increasing from 0 to the limit of the motor stability, or $V_{\min}$ was being reduced slowly from $V_{\min} = V_{\max}$ down to the drive stability limit, and the last value of $V_{\min}$ (or ΔV) was taken for comparison as the sought border result of IM and SBSM resonance dynamic stability.

Second results. Similarly, based on various investigations it was found that, on average every 1 % of this high (resonance) frequency voltage pulsation reduces the IM dynamic stability by approximately 1,5—2 % and for the SBSM by 2,1—2,4 %. Again, it is seen that the figures are almost the same and from a dynamic stability point of view both IM and SBSM are almost equal under this high (resonance) frequency voltage pulsation. But the Fourier analysis of the several waves of the real voltage fluctuation (see Fig. 2) has shown that the maximum amplitudes of these high frequency harmonics (higher than 2 Hz) are less than 0,5 % of ΔU. Hence the total stability losses will be negligibly small for both motors (less than 1 %).

The results obtained were used for the technical and economical substantiation and application of a SBSM that has shown considerable reduction of energy losses in power supply network, the rise of group dynamic stability, reliability of the pumps motors, and even oil field ecological improvement [3].

Similar to resulted earlier, all other simulations systems of the oil field and jack-up electric drives were conducted.

Controlled thyristor rectifier and direct current motor (TC-DCM) type of variable speed drive simulation. The following chain of the model elements was connected: three 3 phase main, S1 (on), S3 (on), TC1 — prototype model of industrial one, S4 (right position), M3 — prototype DC machine model and M4 — mechanical load simulating machines, S7 (right position), TC3 — rapid-load simulator, three phase main. This study dealt with a variable speed drive widely used in oil industry for the design of land and sea (jack-up or sub) derrick platforms. Similar to resulted earlier, the land or jack-up derrick winch block-hook-tackle variable speed drive systems simulations were conducted.

The moment on the winch block-hook-tackle variable speed drive shaft was presented as:

$$M_w = M_s - M_a \exp(-t^2/\tau)\cos(\Omega_w t),$$

where M_w — moment on the winch; M_s — winch steady state moment; M_a — oscillation amplitude of winch system (longitudinal oscillation of the boring column); Ω_w — its angular velocity; τ — damping time constant.

The motor was also gradually loaded further up to the stability limit by increasing only M_a. The last stable state value of $M_{\max}$ was taken as the sought limit result for the stability factor comparison of different types winch electric drives.

The PSpice and CALDEM simulations results for the jack-up platform boring winch block-hook-tackle system drive TC+DCM after its rope slack cutback is presented on Fig. 4 [4, 10].

The synchron motor + DC generator + DC motor (SM + DCG + DCM) drive simulation (land derrick mud pump variable speed drive). The following chain of the model elements was connected [10]: three phase main, S1 (on), S2 (left position), M1 — prototype model of industrial SM, M2 — prototype DCG

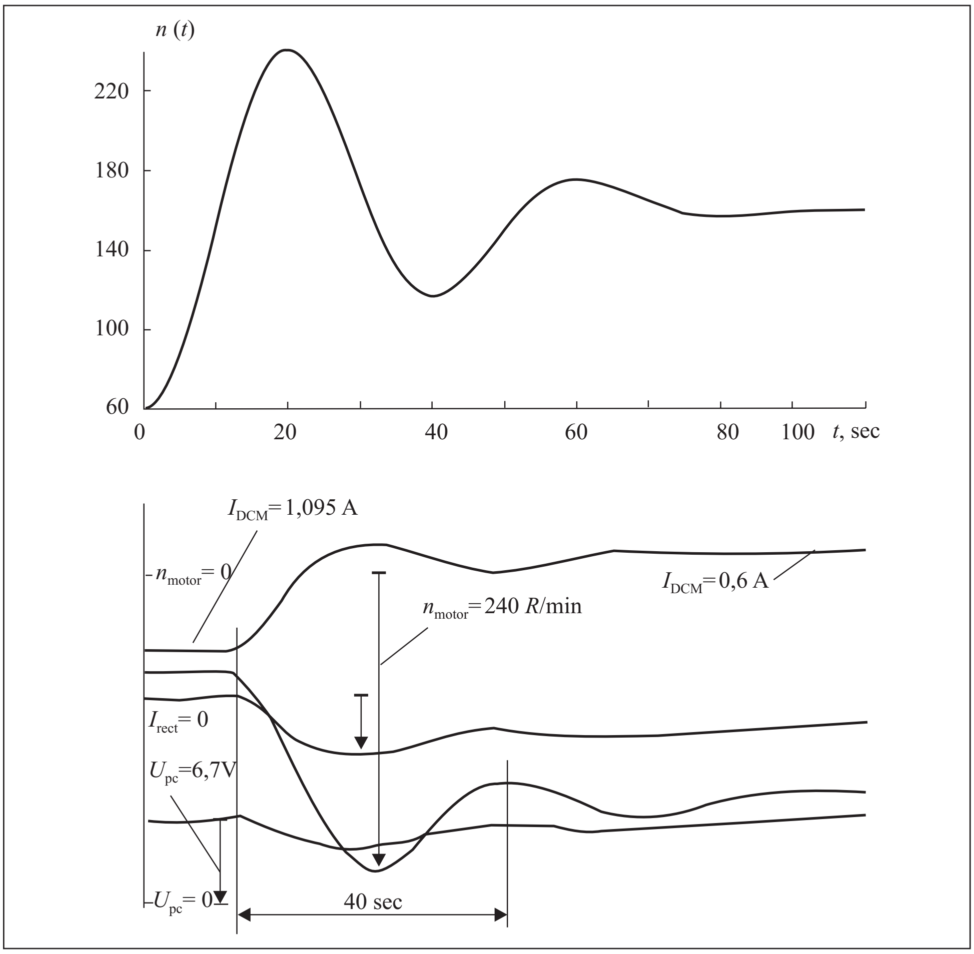

Fig. 4. The PSpice and CALEDM simulations results for the boring winch (after its rope slack cutback) TC+DCM system electric drive

machine model, S4 (right position), M3 — prototype DCM machine model, M4 — mechanical load simulating machines, S7 (left position), S8 (on), TC3 — rapid-load simulator.

Similar to resulted earlier, the land derrick mud pump variable speed drive systems simulations were conducted.

The moment on the double piston mud pump motor shaft was presented as:

$$M_B = 0{,}5 M_{\max}(\sin(x) + \mathrm{abs}(\sin(x)) + \cos(x) + \mathrm{abs}(\cos(x)));$$

$$M_S = 0{,}45 M_{\max}(\mathrm{abs}(\sin(x)) - \sin(x) - \cos(x) + \mathrm{abs}(\cos(x)));$$

$$M_P = M_B + M_S,$$

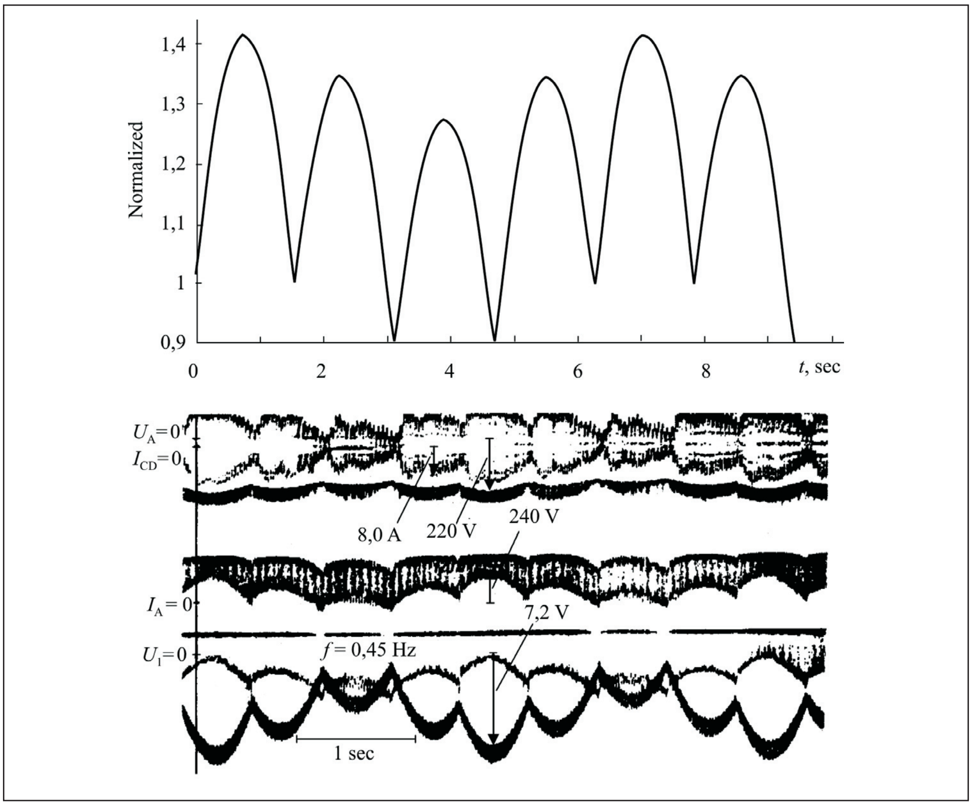

Fig. 5. The PSpice and CALEDM simulation results for the boring mud piston pump SM + DCG + + DCM drive

where x — the rotating angle; M_P, M_B and M_S are the total pump, big and small piston push moments.

The motor was also gradually loaded further up to the stability limit by increasing only $M_{\max}$. The last stable state value of $M_{\max}$ was taken as the sought limit result for the stability factor comparison of different types electric drives. The MATLAB and CALEDM simulations results for the boring land derrick mud pump controlled speed SM + DCG + DCM drive simulation is presented on Fig. 5.

The autonomous power marine derrick (jack-up or sub) platforms system: diesel D + SG + TC + DCM and load (rotary table, mud piston pump, winch system drives) simulation. The following chain of the model elements was connected [10]: 3 phase main, S1 (on), S2 (left position), TC1 (controlled by PC), S4 (left position), M2 — diesel prototype model, M1 — prototype SGen machine model, S2 (right position), TC2 — industrial TC prototype model, S5 (on), M3 —

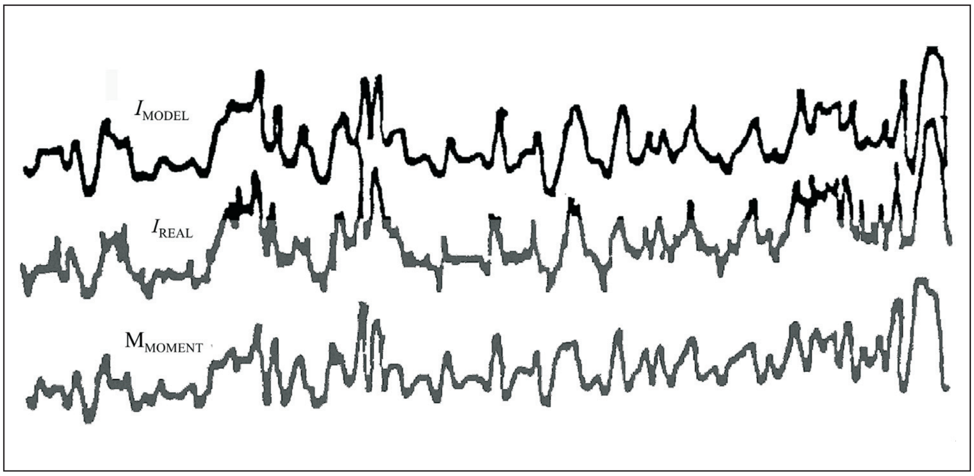

Fig. 6. The simulation results for the autonomy marine derrick SG + TC + DCM rotating table electric drive

DCM machine prototype model, M4 — mechanical load simulating machines, S7 (right position), S8 (on), TC3 — rapid-load simulator, three phase main (rotary table electric drive oscillograms are on Fig. 5).

Here it should be stressed that this computer-assisted electrodynamics model provides the opportunity to study higher and lower inertial electrical drives and also such equipment which are is under development or not available among the model elements, for example, different types of electromagnetic clutches [9], the modern electromagnetic brakes and so on. In such a case it is possible to use a DCG + DCM system to model them. The so-called functional characteristics of a clutch can be simulated by the help of synthesis in a computer (using a special program) and then different working regimes can be modeled and tested. All these create similarity of the processes in the models and the real objects, extend their functional opportunities, and permit the wide variations of their parameters.

The special or personal computer through A/D and D/A converters governs the load and voltage-pulsation reproduction systems (see Fig. 2). The PC produces the driver loads typical for oil industry: in every case a special program was used in accordance with the mathematical equations of the mechanical load on the shaft (or power, or current and so on). Similarly, it is done for voltage pulsation simulation on terminals of the electrical machine (variable current of the controlled TC1 provides the required voltage drop on R_U and L_U). Sometimes the mechanical load or current and voltage magnetogrammes were recorded in the oil field and used in this EDM (Fig. 6). The computer compares these signals with the appropriate feedback signals from the electrodynamic model sensors (moment, voltage, power, current, speed gauges etc.). The built-in computer special control system software forces the model to follow up the given signals (moment, power, current or voltage) and repeat them. All these permit an acceptable imitation of the natural processes in any derrick electric drive.

Conclusions. Using electrical machines 3—5 kW, the model has carried out simulations and investigations of complicated electromechanical systems (like derrick electrical drives) with a power up to 600 kW and shaft cycle moment pulsation frequency from 0 to 10 Hz and for the network voltage deviation up to 30%. The proposed computer-assisted electrodynamic model of controlled electric drives has made it possible to reduce the number of necessary investigations under the oil field harsh conditions of the first electric drives prototypes and obtain generalized results of their static and dynamic stability in the following projects:

1. The substantiation of the partial replacement of IM by claw-pole brushless SM for the subterranean sucker-rod pump and synthesis of its specific excitation control system [1, 6, 8].
2. The comparison of different variable speed electric drives with cycle shaft load on the power consumption smoothing effect for the oil field mechanism [1, 3, 6].
3. The control systems design, probation and first start-up investigations of the unique powerful controlled electric drives of the super-deep boring system (BU-15,000) for 15 km, Saatli, Azerbaijan, and other projects [3, 7].

Розглянуто електродинамічні моделі автоматизованого нафтового і газового обладнання, які складаються переважно з керованих електричних механізмів і автономних генераторів. Наведено приклади використання моделей для бурових та насосних установок.

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