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Development of a Sucker Rod Pumping Unit Simulation Model

D.S. Torgaeva, M.P. Sukhorukov, Y.A. Shinyakov, N.A. Shalyapina

Abstract*: *In this paper a process of development of sucker rod pumping unit (SRPU) simulation model with "oil reservoir-well" and control systems is presented. In this paper is presented process of development of sucker rod pumping unit (SRPU) simulation model with "oil reservoir-well" and control systems. The developed model describes the SRPU blocks for oil production in detail, allows studying the system with various equipment and well parameters and provides the logic of the closed loop system. It becomes possible to develop optimal control algorithms based on obtained dependencies. The results of simulation of operation and sucker rod pump (SRP) faults are given.

Keywords*: *simulation model, sucker rod pump, electromechanical drive, control system, wattmeter card, dynamic liquid level.

I. INTRODUCTION

SRP are widely used in the process of oil production from low production rate wells and wells with various complications such us: high water cut, sand ingress, high viscosity or temperature of well fluid, the aromatic hydrocarbons, salt and paraffin formations. Namely, in cases where the use of centrifugal pumps becomes ineffective. In addition, this production method allows exploiting small production fields with low flowrates that have been decommissioned [1]. Field of application and number of operating SRPU is increasing year to year. This allows making a conclusion that developments aimed at improving the design of installations and systems of control, monitoring and telemetry become relevant.

II. LITERATURE REVIEW

Majority of modern SRP control systems use methods based on indirect measurement of the dynamic liquid level in the oil well annular space to control the flowrate, dynamometer methods for diagnosing faults in SRP and wattmetry methods for diagnosing surface equipment [2]. The disadvantage of this approach is the need to use a large number of sensors of physical quantities. It leads to an increase in the cost of control system and decrease in its reliability.

Nowadays "sensorless" SRPU control systems are gaining popularity [3-4]. These systems realize control algorithms based on measuring and processing signals from electrical quantities sensors (voltage and current of the drive windings, power consumed by the drive (wattmeter card)). Wattmeter card shows the load change over time and wattmetry method allows creating control and diagnostic algorithms for which only electric quantity sensors are needed [5]. However, the complexity of mathematical analysis is a significant drawback of the wattmetry method. Consequently, exiting solutions in the field of creating control and diagnostic algorithms require either the implementation of complex mathematical models of the control object which assumes preliminary measurement and addition of a large number of time variable parameters of this object into the system or a preliminary study of each object in order to identify various diagnostic parameters and coefficients.

The proposed solutions of these problems are the development of control methods and algorithms that allow controlling SRPU based on analysis of the control object reaction to a change in the control action. To study the control object reaction (SRPU and "oil reservoir-well" subsystem) to a change of different equipment and well parameters and to identify changes in the shape of wattmeter card, it is necessary to develop a simulation model of the control object.

A literature review showed that there are a lot of works aimed at creating simulation models of SRPU blocks. However, there are no simulation models which describe SRPU as closed loop system with "oil reservoir-well" subsystem and control system. There is a model [6] which describes system using elementary theory. This model has a low degree of adequacy and does not allow receiving wattmeter cards that show necessary information about state of the control object. A simulation model describing the SRPU using the exact theory is presented in [7]. However, this model does not take into account a lot of factors, for example: the possible equalization of bottomhole and reservoir pressures, a disruption of the flowrate. Also representing the model in the form of equivalent electrical circuit limits the ability to simulate various faults. In this regard, there is a need to create a simulation model of SRPU, describing it as a closed loop system with the ability to simulate various faults.

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* Correspondence Author
D.S. Torgaeva*, Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russia.
M.P. Sukhorukov, Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russia.
Y.A. Shinyakov, Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russia.
N.A. Shalyapina, Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russia.

III. MATERIALS AND METHODS

The SRPU for operation of single-oil reservoir production fields is shown in Fig. 1 [8].

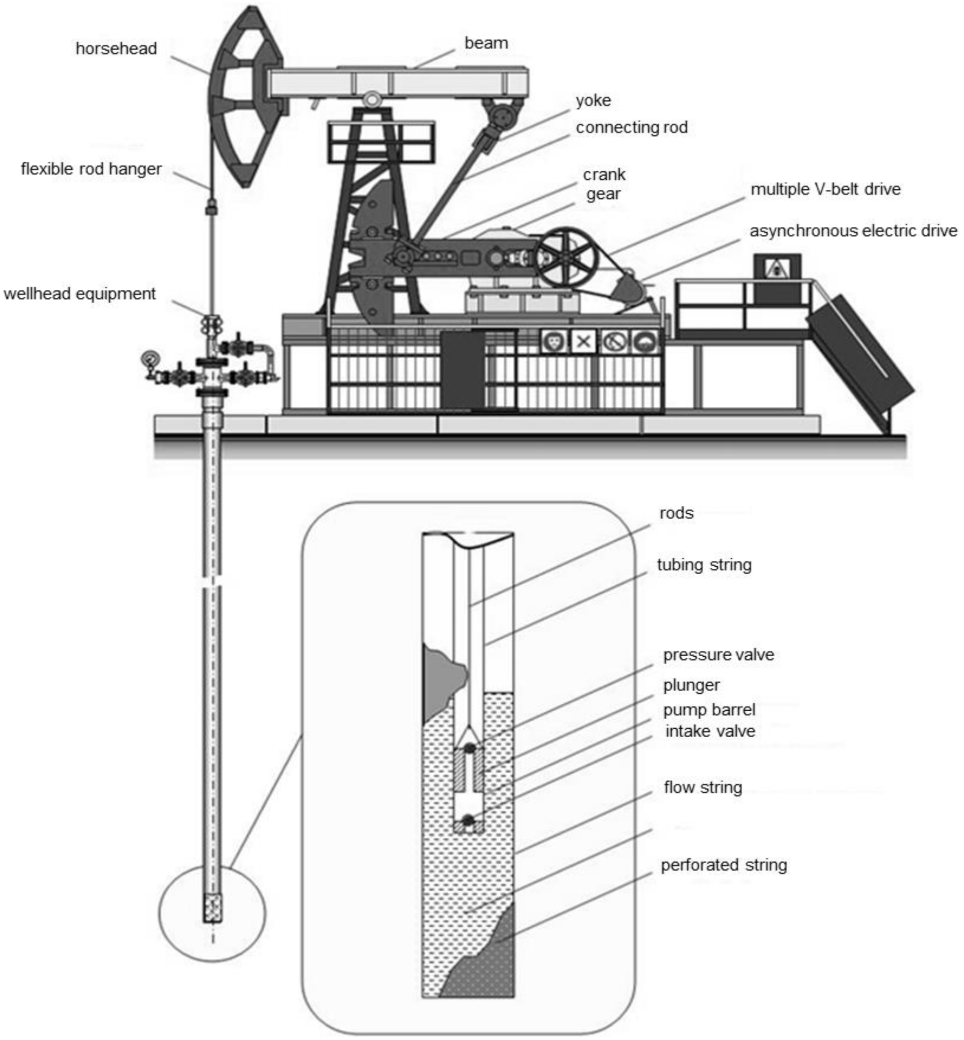

Fig. 1. SRPU

The control action for SRPU is the frequency change of the phase voltage on the asynchronous electric drive windings. Based on this, a simulation model has been developed that shows a change in the dynamic liquid level and power consumed by the drive in response to phase voltage frequency change. The control object presents a complicated system “oil reservoir – well – SRP - electromechanical drive”. Parameters and states of this system are interconnected (fig. 2). To simplify the mathematical description of the object, each block is considered as individual subsystem (individual control object). Input signals (control and disturbing action) for this object are connections with other elements of SRPU. The reaction of an object to input action is an input signal for other elements of the system.

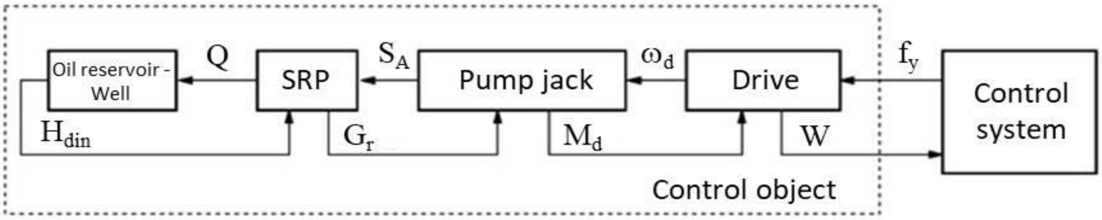

Fig. 2. The control object structural-functional diagram

Q – SRP flowrate, SA –polished rod motion law, ωd – rotating speed of the drive shaft, fy – control signal, Md – moment of resistance on drive shaft, Gr – polished rod load, Hdin – dynamic liquid level in annular space, W – average power consumed during the period

A. Simulation model "oil reservoir - well"

This model describes the subsystem "oil reservoir – well - SRP". The control action for this subsystem is the change in the pumped fluid amount (SRP fluid flow). A description of this interaction has been given in the works devoted to the development of SRPU control systems [2, 9]. But the developed models take into account only the influence on the parameters characterizing the SRPU productivity (the strokes per minute, the stroke length of the polished rod, the diameter of the plunger and the pump coefficient of fullness), and the theoretical flowrate on the position of the dynamic level. However, a change in the dynamic liquid level has a significant effect on the bottomhole pressure. This affects the rate of formation fluid inflow and the well flowrate.

Based on the fluid flow equation and Dupuis formula the following equation for the dynamic liquid level in annular space is obtained [10]:

$$H_{din}(t)=\frac{1}{\pi(r_w-r_{ts})^2}\left(\int_0^t\left(\frac{2\pi kh(P_0-P_b(t))}{\mu\ln\frac{R_k}{r_w}}-v_{pl}S_{pl}\beta\right)dt+H_{din}(0)\right) \qquad (1)$$

where: h – oil reservoir thickness (m), P_0 – oil reservoir pressure (Pa), P_{bot} – bottomhole pressure (Pa), R_k – oil reservoir radius (m), r_w – well radius (m), S_{pl} – plunger sectional area (m^2), n - strokes per minute, v_{pl} - plunger speed (m/s), β – pump coefficient of fullness ($\beta \in [0,1]$) [11], H_{din} – dynamic liquid level position (m), r_{ts} – tubing string outer radius (m), $H_{din}(0)$ – dynamic liquid level initial value, (m).

The resulting equation takes into account the logic of the control object. This allows creating a simulation model for the study of control systems.

B. SRP simulation model

The SRP simulation model is a mathematical model of the subsystem "well – rod string – plunger liquid column – flow string – pump jack". The control action is the motion law change of the polished rod (rod suspension point (RSP)). The disturbing action is a change of the dynamic liquid level in the annular space. The response of the system to a control action is a change in the stroke length and plunger speed. Such response causes a change in fluid flow (1) and force in the RSP. The SRP simulation model is based on SRP mathematical model described in papers [12, 13].

C. The pump jack simulation model

The pump jack (PJ) simulation model describes interaction of subsystems "polished rod – walking beam – four-bar mechanism – counterbalancing system – crank – drive shaft". This system shows interrelation between force applied to the polished rod and moment of resistance on the drive shaft. In this case, the control action is a change in the rotating speed of the drive shaft; the disturbing action is the force change in the RSP; the reaction of the system to the control action is the change in the law of RSP motion and the moment of resistance on the drive shaft. The model is divided into two blocks: a block for setting the RSP motion law and block for calculating the moment of resistance on the drive shaft.

Often when building a SRP simulation model the harmonic motion law of the rod suspension point is used. However, in practice, the motion law of the rod suspension point is more complex and depends on the parameters and kinematic schemes used by pump jack. To overcome this assumption, it is necessary to introduce the RSP motion law for a given crank motion law and to give a solution to the direct problem of kinematics [14].

The kinematic diagram of the pump jack with a single-working beam is shown in Fig. 3 [15].

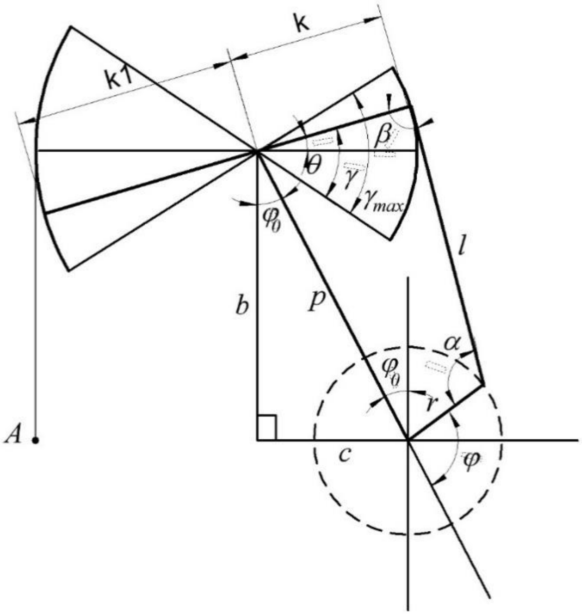

Fig. 3. The kinematic diagram of PJ with double-working beam, where: k1 – length of the walking beam front arm, k – length of the walking beam back arm, l – length of the connecting rod, p – the shortest distance between the centre of the walking beam oscillation center and crank center of rotation, r – crank radius, φ – crank turn angle, φ_0 – angle between vertical line and direction p, c – projection of p on horizontal, b – projection of p on vertical, γ – back arm angle of rotation with respect to p, α – angle between crank and walking beam, β – angle between back arm of walking beam and crank, θ – angle of deviation of walking beam from horizontal position

The rod suspension point motion law (point A) is described by the following simultaneous equations:

$$\left\{\begin{array}{l}
s_A(t)=k_1\left(\arccos\frac{k^2+p^2-(l+r)^2}{2kp}-\gamma(t)\right);\\
\varphi_0=\mathrm{arctg}\frac{c}{b};\\
\varphi=\pi-\arccos\left(\frac{p^2-k^2+(l+r)^2}{2p(l+r)}\right)-\omega_{cr}t;\\
\gamma(t)=\mathrm{arctg}\frac{\sin\varphi(t)}{\frac{p}{r}+\cos\varphi(t)}+\mathrm{arctg}\frac{\sin\beta(t)}{\frac{k}{l}-\cos\beta(t)};\\
\beta(t)=\arccos\left(\frac{(l^2-p^2)+(k^2-r^2)}{2lk}-\frac{pr}{lk}\cos\varphi(t)\right);
\end{array}\right. \qquad (2)$$

To calculate the moment of resistance on the drive shaft, it is necessary to perform a dynamic analysis of the pump jack to determine the rotational moment on the crank.

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The theory of the dynamic analysis of the balanced pump jack can be divided into elementary, improved and exact. The method of calculating the pump jack dynamics using an elementary theory is given in [16]. This method is the simplest and is valid with these following assumptions and is valid with these following assumptions:

- the cutpoint of the connecting rod and the tail half of walking beam move in a straight line;
- the deflection angle of the connecting rod from vertical is taken equal to 0.

These assumptions are valid only for axial kinematic schemes of the pump jack with a walking beam length much shorter than the radius of the crank. This kind of kinematic schemes is a special case. Therefore, to build a universal model of the control object, it is necessary to use an improved theory. The widely used method of calculating the dynamics described in [17]. Significant disadvantages of this method are the need to calculate the projections of all the forces applied to the PJ on a vertical and horizontal plane followed by an iterative calculation of balancing moments.

Zhukovsky's method is applied to solve this problem [7, 18]. The principle of the Zhukovsky's method is to derive the forces balance equation that is applied to a conditionally balanced system:

$$\sum_{i=1}^{n} P_i v_i \cos(\widehat{\vec{P_i},\vec{v_i}})=0\,, \tag{3}$$

where: P_i - forces applied to a balanced system, v_i - the speed of the points to which the forces are applied, $\vec{P}_i,\vec{v}_i$ - angle between vectors force and speed.

The diagram of forces at various points of PJ with double-working beam is shown in Fig. 4.

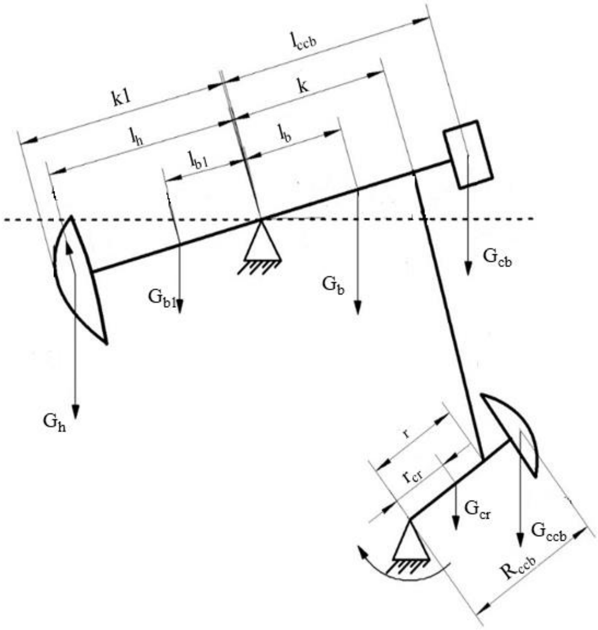


Fig. 4. The diagram of forces at various point of PJ with double-working beam, where: G_h, G_{b1}, G_b, G_y, G_{cb}, G_{cr}, G_{ccb} – weight of the horsehead, the walking beam front arm, the walking beam back arm, the yoke, the counterbalance, the crank, the crank counterbalance;. l_h, l_{b1}, l_b, l_{cb} – distance from the oscillation pin of walking beam to the mass center of horsehead, to the walking beam front arm, walking beam back arm, the counterbalance; R_{ccb} - distance from the axis of rotation to mass center of the crank counterbalance; r_{cr} – distance from the axis of rotation to mass center of the crank

The moment on the crank shaft is calculated as:

$$M_c=P_r r \tag{4}$$

The drive shaft is connected to the PJ crank through V-belt transmission having a transfer factor i_t and efficiency η_f. Therefore, the moment of resistance on the drive shaft and the net engine power W_p is defined as [19]:

$$M_d=\frac{M_c}{i_t\eta_f}, \tag{5}$$

$$W_p=\frac{M_c\omega_c}{\eta_f}. \tag{6}$$

The asynchronous electric drive simulation model.

To develop and test control methods, it is necessary to identify the dependency between the change in the dynamic level and the power consumed by the drive, depending on the frequency change of the control signal. To determine the power consumed by the drive, it is necessary to introduce mathematical description of subsystem "gear - electric drive – control system". In this case, the control action is the frequency change of the control signal (frequency of the phase voltage across the electric drive stator windings), the disturbing action is the change in the moment of resistance on the drive shaft, the reaction of the system to the input actions change is the change in the frequency of drive shaft rotation.

To determine the power consumed by the drive, depending on the change in moment on the drive shaft, it is necessary to implement L-shaped equivalent circuit (Fig. 5).

Parameters of the equivalent circuit, such as: X1, R1, Xμ, X2, R2' are calculated according to the parameters from the asynchronous electric drive documentation by using the method described in article [20].

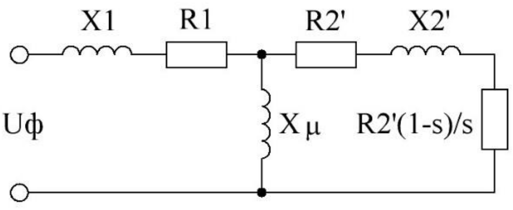


Fig. 5. L-shaped equivalent circuit of asynchronous electric drive

The slip change s depending on the change in the asynchronous electric drive resistance moment Mc is determined by the Kloss formula [21, 22].

IV. RESULTS

The given dependencies and methods formed the basis of the SRPU simulation model (Fig. 6) implemented in MATLAB / Simulink.

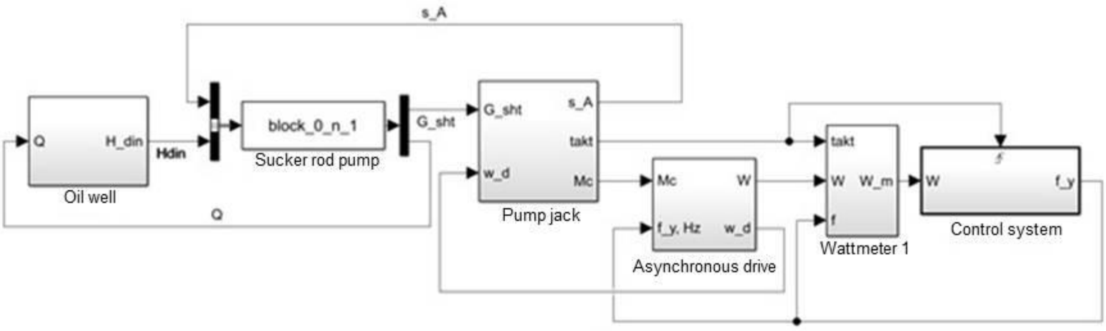


Fig. 6. SRPU model consisting of blocks describing the blocks of the SRPU: simulation models of well and oil reservoir (Oil well), SRP (Sucker rod pump), PJ (Pump jack) Electromechanical drive (Asynchronous drive)

The presented model is necessary both for the development of flowrate control algorithm and for the development of a method for diagnosing SRP faults based on the wattmeter card signal processing.

A. Simulation modeling of the SRP.

To develop a control algorithm, it is necessary to consider the behavior of the system when control object and control system parameters remain unchanged. Namely, when the influx speed and the pump speed do not match each other.

The dependence diagram of various parameters on time obtained using the developed model are presented in fig. 7

In order to conduct simulation, the well parameters and pump speed remained unchanged. The initial position of the dynamic liquid level corresponds to the static liquid level. The bottom pressure is equal to reservoir pressure. The pump speed equals zero and the system is in equilibrium (Fig. 7).

The dependence diagrams illustrate the situation when the pump speed is smaller than the flow speed (Fig. 7b).

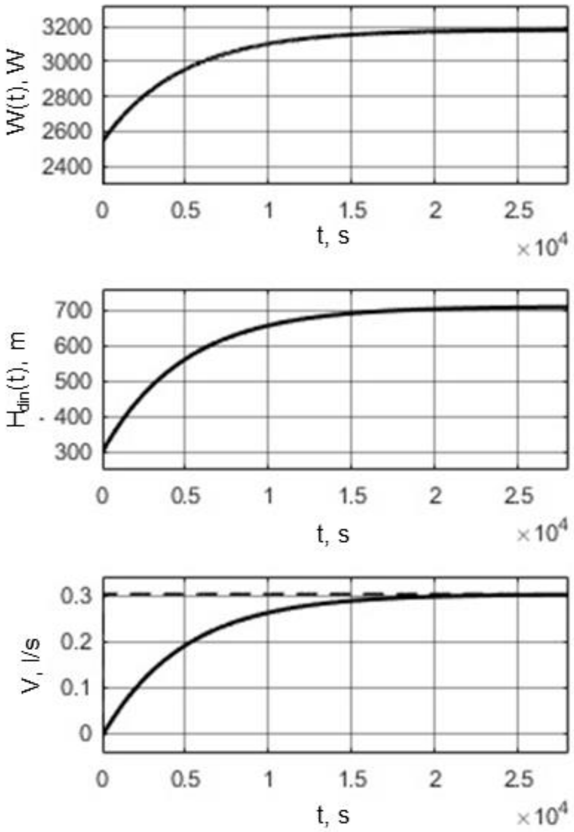


Fig. 7. The dependence diagrams of the average power consumed during the period W(t), the dynamic liquid level Hdin(t), the influx speed V (solid line) and the pump speed (dashed line)

The given dependences prove the conclusions presented in [23]. The subsystem "oil reservoir - well - sucker rod pump" is self-organizing. The dynamic liquid level changes when the influx speed does not correspond to the pump speed. The change in dynamic liquid level leads to a change in the bottomhole pressure and influx speed. After some time, a natural alignment of these speeds occurs. However, the new steady-state value of the dynamic liquid level may differ from the optimal. This situation can lead to negative consequences.

With a decrease in the dynamic level, the pressure drop ΔP decreases, which leads to a decrease in fluid flow and an artificial lowering of the well's debit.

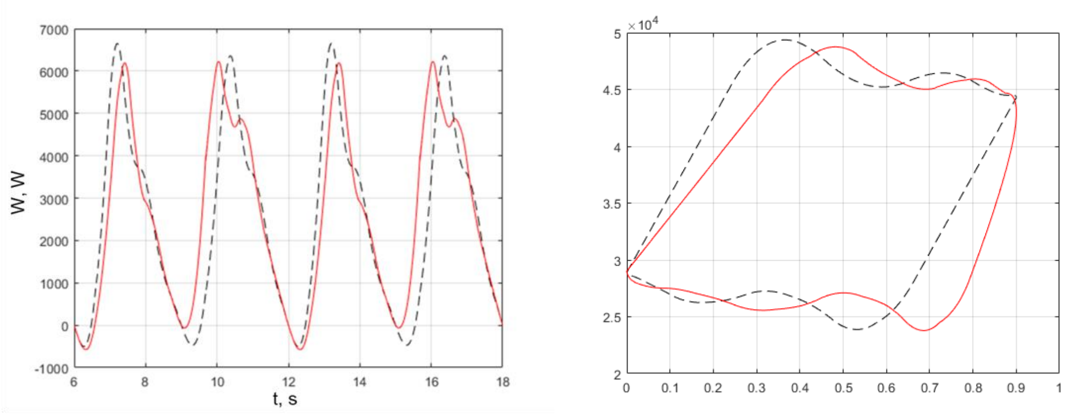
An increase in the dynamic liquid level leads to a decrease in bottomhole pressure and an increase in the polished rod load. A significant excess of the pump speed over the influx speed can cause a decrease in the liquid level before the pump intake, which can lead to a pump underload [24]. The above dependences also show that the value of the average power consumed during the period reflects a change in the dynamic level. The presented conclusions suggest that the control algorithm of this system should take into account the features of the system's behavior when the well is put on stream.

B. Simulation of SRP faults

The dependence of the change in the wattmeter card shape in case of leakage in the SRP pressure valve was investigated using the developed simulation model.

The shapes of wattmeter card and the dynamogram corresponding to the SRPU normal operation (dashed line) and the fault signals (solid line) are shown in Fig. 8.

It should be noted that currently the wattmetry method for faults diagnostics is not studied well. For that reason, the auxiliary dynamograms were obtained to study the features that led to faults (Fig. 8b).



a) b)

Fig. 8. Wattmeter cards (a) and dynamograms (b) obtained using the simulation model

The analysis of results (Fig. 8a) showed that change in the shape of the wattmeter card corresponds to a simulated SRP fault (leak in the pressure valve). Thus, the developed simulation model also allows investigating the control object operation at various well and equipment parameters. Also this model allows studying the dependence of the change in shape of wattmeter card for various SRP faults.

V. CONCLUSION

The developed simulation model describes SRPU blocks in detail and allows investigating the system with various parameters of the equipment and the well. The model provides the logic of the closed loop system, which is necessary to develop control algorithms based on the study of the obtained dependencies. This model also allows simulating different faults of the well equipment in order to study the influence of these faults on the shape of the wattmeter card and to develop diagnostic algorithms.

The developed model is needed to conduct an analysis of SRPU and to develop universal sensorless control systems. The conducted simulation of the SRPU operation showed that if the pump speed of well fluid is less than the influx speed, then subsystem "oil reservoir - well - sucker-rod pump" is self-organizing. There is a natural alignment of these speeds after a long time.

The study of the dependence of the change in the wattmeter card shape for leakage in the pressure valve was investigated using the developed simulation model.

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REFERENCES

1. V.N. Ivanovskii, "Povyshenie interesa k shtangovym nasosnym ustanovkam - v chem prichina?" [Increasing interest in sucker rod pumping units — what is the reason for?]. Territoriya Neftegaz [Oil and Gas Territory], 8, 2013, pp. 48-49.
2. A.I. Ismagulova, "Systems for automatic control of the dynamic fluid level in the well in sucker rod installations", Inzhenernyi vestnik Dona, 22(4-1), 2012. Available at: http://ivdon.ru/magazine/archive/n4p1y2012/1325
3. M.I. Khakim'yanov, "Controllers for automation of sucker rod pump installations", Neftegazovoe delo, 12(1), 2014, pp. 78-85. Available at: http://ogbus.ru/files/ogbus/authors/Hakimyanov/Hakimyanov_3.pdf
4. M.I. Khakim'yanov, "Modern control stations for downhole sucker-rod suction pump installations", Neftegazovoe delo, 12(1), 2014, pp. 78-85. Available at: http://ngdelo.ru/files/old_ngdelo/2014/1/ngdelo-1-2014-p78-85.pdf
5. A.F. Sakaev, "Monitoring and diagnostics of the state of the equipment of sucker rod pumps by the indirect method according to the wattmeter program using artificial neural networks", Notes of the Mining Institute, 173, 2007, pp. 101-104.

6. A.M. Sagdatullin, “Razrabotka matematicheskoi modeli sistemy avtomatizatsii elektroprivoda shtangovoi skvazhinnoi nasosnoi ustanovki” [Development of a mathematical model of an automation system for an electric drive of a sucker rod pumping unit]. Territoriya Neftegaz [Oil and Gas Territory], 4, 2014, pp. 28-35.
7. A.F. Sakaev, “Sistemy i algoritmy energosberegayushchego upravleniya chastotno-reguliruemymi elektroprivodami shtangovykh skvazhinnykh nasosnykh ustanovok” [Systems and algorithms for energy-saving control of variable-frequency electric drives of sucker-rod pumping units. Cand. Diss.] . Peterburgskii gosudarstvennyi gornyi institut im. GV Plekhanova, 2009.
8. M. Khakim'yanov, “Upravlenie elektroprivodami skvazhinnykh nasosnykh ustanovok” [Control of electric drives of downhole pumping units]. Moscow, Infra- Engineering Publ., 2017, pp. 139.
9. S.G. Voronin, D.A. Kurnosov, M.I. Korabel'nikov, D.V. Korobatov, V.V. Zapunnyi, “Matematicheskoe modelirovanie ekspluatatsionnoi skvazhiny v protsesse optimizatsii neftedobychi” [Mathematical modeling of a production well in the process of oil production optimization]. Vestnik YuUrGU. Seriya: Energetika [Bulletin of YuUrGU. Series: Energy], 9, 2005, pp. 70-74.
10. O.A. Miklina, “Otsenka pritoka nefti v gidrodinamicheski sovershennuyu skvazhinu” [Estimation of oil flow into a hydrodynamically perfect well]. Ukhta, UGTU Publ., 2016, pp. 22.
11. V.B. Sadov, “Parameter estimation of an oil extracting and pump installation control with use of dynamometer cards”, Bulletin of the south Ural state university series “Computer technologies, automatic control, radio electronics”, 13(2), 2014, pp. 33-41.
12. A.S. Topol'nikov, “Modelirovanie dinamicheskikh nagruzok na polirovannyi shtok stanka-kachalki pri neispravnostyakh v rabote shtangovogo nasosa” [Simulation of dynamic loads on a polished rod of a pumping unit in the event of a malfunction in the rod pump]. Trudy Instituta mekhaniki im. R.R Mavlyutova [Proceedings of the Institute of Mechanics. R.R Mavlyutova], 10, 2014, pp. 95-101.
13. K.R. Urazakov, V.A. Molchanova, A.S. Topol'nikov, “Matematicheskaya model' shtangovoi ustanovki s ezhektorom dlya otkachki gaza iz zatrubnogo prostranstva” [Mathematical model of a rod installation with an ejector for pumping gas from the annulus]. Interval. Peredovye neftegazovye tekhnologii [Interval. Advanced oil and gas technology], 6, 2007, pp. 54-60.
14. A.S. Virnovskii, “Teoriya i praktika glubinno-nasosnoi dobychi nefti: Izbrannye Trudy” [Theory and Practice of Downhole Oil Production: Selected Works]. Moscow, Nedra Publ., 1971, pp. 183.
15. N.D. Dregotesku, “Glubinonasosnaya dobycha nefti” [Deep pump oil production]. Moscow, Nedra Publ., 1966, pp. 417.
16. V.N. Ivanovskii, “Skvazhinnye nasosnye ustanovki dlya dobychi nefti” [Oil well pumping units]. Moscow, GUP «Neft' i gaz» RGU nefti i gaza im. IM Gubkina Publ, 2002.
17. L.G. Chicherov, G.V. Molchanov, A.M. Rabinovich, “Raschet i konstruirovanie neftepromyslovogo oborudovaniya” [Calculation and design of oilfield equipment]. Moscow, Nedra Publ., 1987, pp. 422.
18. A.S. Korenyako, “Teoriya mekhanizmov i mashin” [Theory of mechanisms and machines]. Vishcha shk. Publ., 1976, pp. 438.
19. A.G. Molchanov, V.L. Chicherov, “Neftepromyslovye mashiny i mekhanizmy” [Oilfield machines and mechanisms]. Moscow, Nedra Publ., 1976.
20. V.S. Safaryan, S.G. Gevorgyan, “Ascertainment of the Equivalent Circuit Parameters of the Asynchronous Machine”, Energetika. Proc. CIS higher educ. inst. and power eng. assos., 6, 2015, pp. 20-34.
21. A.D. Likhodedov, “Construction of the mechanical characteristic of the asynchronous engine and its approbation”, Modern problems of science and education, 5, 2012, pp. 99.
22. V.A. Solov'ev, “Raschet kharakteristik trekhfaznogo asinkhronnogo dvigatelya” [Calculation of the characteristics of a three-phase induction motor]. Moscow, MGTU im. N.E. Baumana Publ., 2014, pp. 44.
23. V.B. Sadov, “Selection and research of two-factor model for conversion function of vortex sonic flowmeters”, Bulletin of the south Ural state university series “Computer technologies, automatic control, radio electronics”, 13(3), 2013, pp. 46–53.
24. B.M. Latypov, “Progressing cavity pump for oil production under complicated conditions”, Oil and gas business, 10(1), 2012, pp. 13-15.