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The diagnostics of the emergency modes of the variable-frequency electric drive of the pumping complex

***Abstract**. The paper deals with the demonstration of the fact that the emergency modes that occur in the pipeline networks are accompanied by wave processes resulting in the variation of all parameters of the hydrosystem. We worked out the mathematical model of the automatic control system with the function of the pressure stabilization at the consumer. We obtained the curves representing the alteration of the dynamic processes in the pumping complex during emergency modes occurrence. We formulated the diagnostic signs and proposed the algorithm of the determination of the emergency modes.*

Streszczenie.** W artykule wskazano na fakt, iż tryby awaryjne występujące w sieci rurociągowej związane są z procesami falowymi wynikłym ze zmiany wszystkich parametrów hydrosystemu. Opracowany został model matematyczny systemu sterowania automatycznego z funkcją stabilizacji ciśnienia u odbiorcy. Otrzymano krzywe, reprezentujące zmienność procesów dynamicznych w układzie pompowania podczas wystąpienia trybów awaryjnych. Sformułowane zostały oznaczenia diagnostyczne oraz opracowano algorytm określający tryby awaryjne.* ***(Diagnostyka trybu awaryjnego zmienno-częstotliwościowego napędu elektrycznego w układzie pompowania)

Keywords: emergency mode, pumping complex, diagnostics, frequency analysis.
Słowa kluczowe: tryb awaryjnt, zespół pompowy, diagnostyka, analiza częstotliwościowa

Introduction

At frequent switch on/off of the pumps, sharp shutting the stopcock, switch of the pipelines, unplanned change of the schedule of water consumption, etc. in PC pipeline network there appear wave processes of different amplitude and frequency. They may result in the occurrence of emergency modes such as water hammer, leakage, cavitation, pipeline clogging and others. Papers [1 – 4] contain a rather wide analysis of the wave processes in PC pipeline network. Therefore, paper [1] analyzes the problem of the diagnostics and localization of leakages in pipeline networks; paper [2] research the wave processes in the head pipeline at the water hammer; papers [3, 4] describe the cavitation phenomena in the impellers of the centrifugal pumps and the pipeline network. One should keep in mind that in most cases the above mentioned emergency modes are considered only from the point of view of hydrodynamics and do not take into account the pipeline network wave processes influence on the characteristics of the electrohydraulic complex on the whole.

The above said determines the topicality of the problems related to the diagnostics of the emergency modes in PC variable-frequency electric drive for the timely response to the development of the contingency situations in the pipeline network and warning the maintenance staff.

Research method

To research the emergency modes of PC operation we created a mathematical model of the automatic control system (ACS) for the pump variable-frequency electric drive with the function of the stabilization of the pressure in the consumer's network. The block diagram (Fig. 1) of the proposed model includes: a model of the frequency converter (FC); a PI-regulator; a model of an induction motor (IM) in *u,v,*0-coordinates; a model of the pump with a block of setting the coefficients of the turbomechanism published characteristics; a block of forming the moment of resistance of the turbomechanism; a model of the pipeline network represented by *n* number of sections in the form of *RLC* – contours; a model of the consumer at the input of which the hydraulic resistance equivalent to the current water consumption is formed; a pressure sensor; a block of the frequency analysis of the hydraulic power, and a block of emergency mode modeling (BEMM).

Paper [5] contains the mathematical description of PC with VFED, a pipeline network represented by 20 sections and a consumer at the end.

As the basic emergency modes occur in the pipeline network, we consider BEMM in more detail. It enables the formation of a certain unsteady state.

Therefore, a leakage is a process of sudden decompression of the pipeline network, characterized by the change of hydraulic resistance $R_{leak}(t)$ of the pipeline section, equivalent to the volume of the lost liquid. In the model, the leakage block is described by *RLC* – contour with the parameters different from the parameters of the pipeline network and can be connected to any of its section.

At the water hammer, the pressure sharply fluctuates because of a sudden increase of the local resistance $R_{wh}(t)$ of the pipe, which is performed by the installation of a stopcock at the corresponding section of the hydronetwork.

The cavitation processes are caused by the growth of liquid consumption in the consumer's network, which results in the decrease of the pressure in the pumping main. Cavitation caverns – cavities filled with steam or gas in the liquid flow – form and collapse during cavitation. They cause periodic fluctuations of pressure in the hydronetwork. In case when the pressure value H_j at the *j*- th section of the pipeline is less or equal to the value of critical pressure H_{kj} in the liquid flow, there is increase of cavitation cavities of the volume: $V_{kav} = V_0 + V'_{kav}$, where V_0, V_{kav}' – the initial and current value of the volume of the cavitation cavern, respectively. In this case, the critical value of the pressure corresponding to the start of the development of the cavitation processes at the j-th section of the pipeline is determined by expression described in paper [4].

For PC with the following parameters: motor $P_n = 7500$ W, $U_n = 220$ V, $\omega_n = 303.7$ s^{-1}, $I_n = 15$ A, $M_n = 24.7$ Nm; pump $Q_n = 0.012691$ m^3/s, $H_p = 22.4$ m; pipeline network $d = 0.1$ m, $L = 1000$ m, $n = 20$, $S = \pi d^2/4 = 0.00785$ m^2, $R_0 = 0.0183$ s/m^2, $C_0 = 2038.7$ m^2, $L_0 = 0.1962$ s^2/m^2, $R_{con} = 9.855$ we obtained the curves representing the alteration of technological $H(t)$, $Q(t)$, mechanical $\omega(t)$, $M(t)$, electromechanical $I(t)$ and energy $p_{el}(t)$, $p_{hp}(t)$, $p_{hcon}(t)$ characteristics at the occurrence of the above mentioned emergency modes in the pipeline network (Fig. 2 – 4).

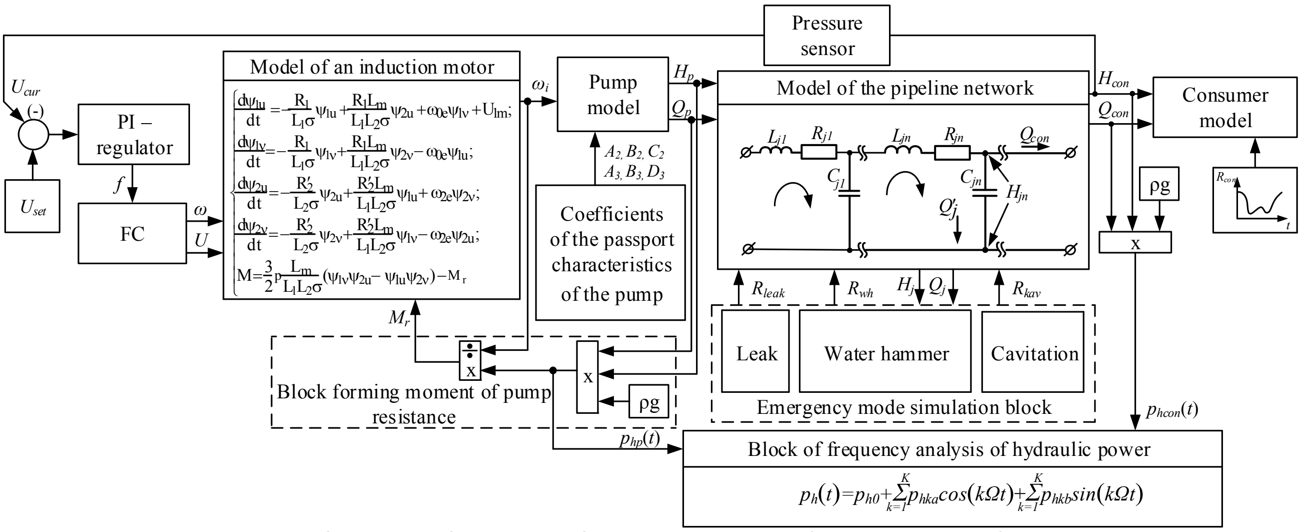


Fig.1. The block diagram of the model of the system of the automatic control of the pump variable-frequency electric drive

In the first case we analyzed the occurrence of a leakage of volume $Q_{leak} = 0.14Q_n$ in the pipeline network at time moment $t = 120$ s (Fig.2).

The analysis of the obtained curves reveals that at the occurrence of a leakage in the pipeline network at time moment $t = 120$ s the pressure at the consumer's network reduces (Fig.2, a). The closed-loop system compensates for the pressure deviation by increasing the rotation frequency on the motor shaft (Fig.2, b). It results in the increase of the losses and the pressure at the pump output and in insignificant growth of IM current and electromagnetic moment (Fig.2, b).

Fig.3 contains the curves representing the alteration of PC technological, electromechanical and energy parameters at sharp shutting of the stopcock at the 19[th] section of the pipeline at time moment $t = 120$ s. As a result, there occurs a considerable pressure jump in the pipeline accompanied by fluctuations spreading along the whole length of the main until they decline completely. In this case, the pressure and the losses at the consumer decrease to zero. ACS increases the pump unit rotation frequency (Fig. 3, b), which results in an inconsiderable growth of the pressure at the output of the turbomechanism (Fig.3, a), the current and IM electromagnetic moment significantly reduce (Fig. 3, b).

Fig.4. shows PC parameter alteration curves at the occurrence of cavitation. The analysis revealed that at time moment $t = 80$ s one can observe the reduction of the hydraulic resistance of the pipe, which results in the increase of the liquid loss in the main. The pressure in the pipeline decreases and there is lower pressure of the saturated steam, which results in the generation of self-oscillations in the head system (Fig. 4, a). PC ACS forms the signal for the increase of the rotation frequency of the pump IM (Fig.4, b), which causes the increase of the pressure and loss at the output of the pump and the decrease of the amplitude values of the cavitation oscillations.

The wave processes in PC pipeline network in emergency modes are accompanied by the alteration of the energy parameters of the analyzed system [6]:

the electric power supplied to IM stator windings:
$p_{el}(t) = u_{1u}(t)i_{1u}(t)+u_{1v}(t)i_{1v}(t)$, where $u_{1u}(t)$, $i_{1u}(t)$, $u_{1v}(t)$, $i_{1v}(t)$ – the voltage and the current of the electric machine by coordinates u and v, respectively;

the hydraulic power at the output of pump unit: $p_{hp}(t) = \rho g Q_p(t) H_p(t)$;

the hydraulic power at the j-th section of the pipeline: $p_{hj} = \rho g Q_j(t) H_j(t)$;

the hydraulic power of the consumer: $p_{hcon}(t) = \rho g Q_{con}(t) H_{con}(t)$, where ρ – the density of the liquid.

Using the method of the frequency analysis of the hydraulic power [7], one can obtain the frequency characteristic of the energy processes at the development of the unsteady situation in PC pipeline network:

$$p_h(t) = P_{h0} + \sum_{k=1}^{K} P_{hka} \cos(k\Omega t) + \sum_{k=1}^{K} P_{hkb} \sin(k\Omega t) \tag{1}$$

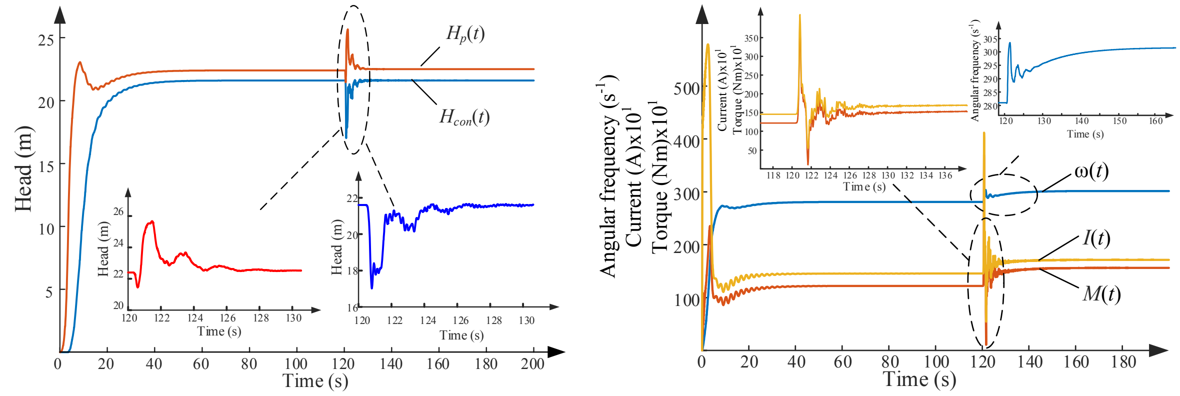
where $P_{h0} = \frac{1}{T_{pe}} \int_0^{T_{pe}} p_h(t)dt$; $P_{hka} = \frac{1}{T_{pe}} \int_0^{T_{pe}} p_h(t)\cos(k\Omega t)dt$;

$P_{hkb} = \frac{1}{T_{pe}} \int_0^{T_{pe}} p_h(t)\sin(k\Omega t)dt$ – the constant and the variable (cosine and sine) components of the hydraulic power signal; T_{pe} – the period of the expansion represented by the duration of the transient process in the hydronetwork; $\Omega = 2\pi f$ – the circular frequency of the power signal; K, k – the quantity and the number of harmonics of the hydraulic power, respectively.

The analysis of the amplitude spectra of the hydraulic power revealed the presence of low frequency (up to 10 Hz) components characterizing different emergency modes. We obtained that in the power frequency spectrum in the presence of a leakage the low-frequency components up to 1 Hz prevail and the higher harmonic appears at the frequency of 0.5 Hz corresponding to the surge phase $T_{ph} = 2l/s = 2$ s – the time of waves passing along the pipeline in the direct and reverse direction. At the water hammer, the harmonics with higher amplitude focus in the frequency range of 0.1 ÷ 0.5 Hz. At the occurrence of the cavitation oscillations in the amplitude spectrum of the hydraulic power there occur periodic surges of harmonics in the frequency intervals of 0 ÷ 0.5 Hz and 1.5 ÷ 4.2 Hz, respectively.

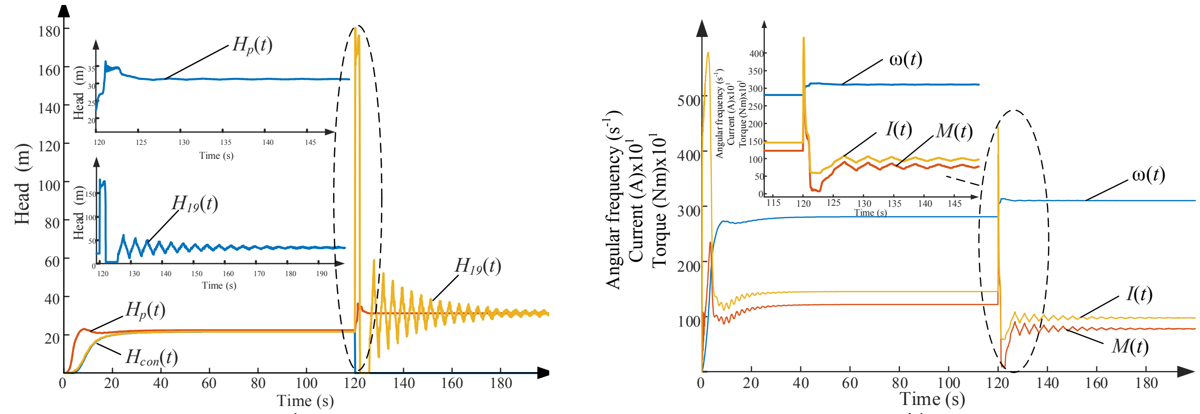
Table 1 contains the information signs of emergency situations (ES), obtained based on the analysis of the signs of PC main parameters derivatives, according to the curves of transients.

Fig.5 contains a generalized algorithm of the operation of the system of the diagnostics of PC unsteady operation modes. The first stage consists in the reading of the signals of the technological parameters from the sensors at the pump output and at the consumer. In case of deviation, the algorithm initiates the procedure of the identification of the emergency mode taking place in the pipeline based on the previously determined information signs of unsteady processes. Then the diagnostics system proposes a complex of organizational and technical measures to prevent the development of the emergency situation.



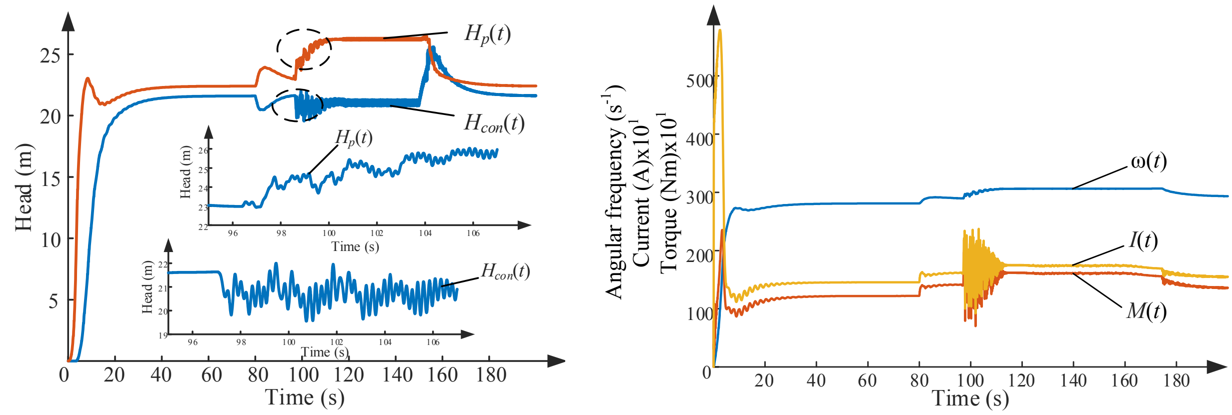
a) b)

Fig.2. The curves representing the alteration of technological (a) and electromechanical (b) parameters of PC at the occurrence of a leakage in the pipeline network at time moment t=120 s



a) b)

Fig.3. The curves representing the alteration of technological a) and electromechanical (b) parameters of PC at a sharp shutting of the stopcock at time moment t=120 s



a) б)

Fig.4. The curves representing the alteration of technological (a) and electromechanical (b) parameters of PC at the occurrence of cavitation in the hydronetwork

Table 1. The diagnostic signs of the emergency states (ES) based on technological and electromechanical parameters of the PC

ES type	Diagnostic signs
Leakage	$dH_p/dt>0$; $dQ_p/dt>0$; $d\omega/dt>0$; $dI/dt>0$; $dM/dt>0$.
Water hammer	a sharp pressure jump before the stopcock; $dH_p/dt>0$; $Q_p(t)\rightarrow 0$; $d\omega/dt>0$; $dI/dt<0$; $dM/dt<0$.
Cavitation	presence of periodic oscillations of head and discharge signals; $dH_p/dt>0$; $dQ_p/dt>0$; $d\omega/dt>0$; $dI/dt>0$; $dM/dt>0$.

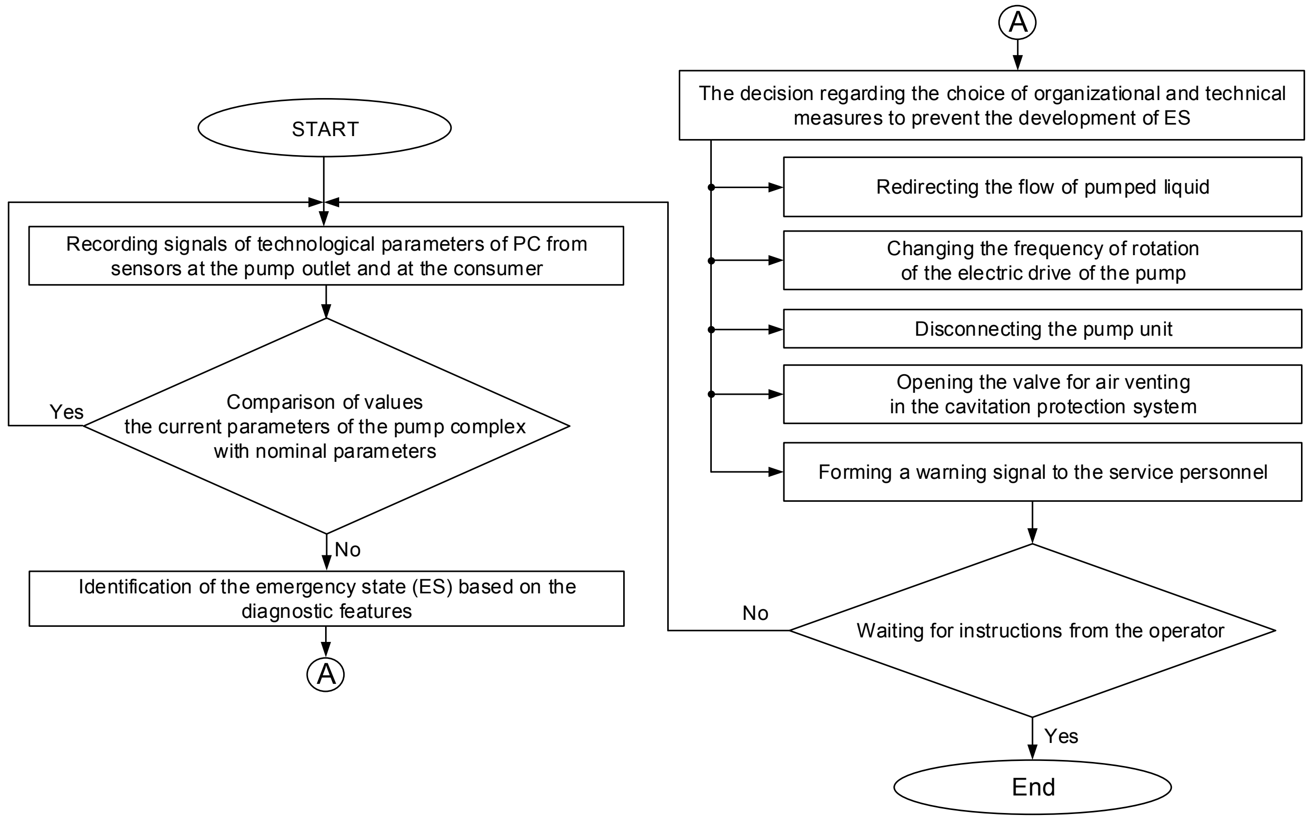


Fig.5. The generalized algorithm of the operation of the system of the diagnostics of unsteady modes of PV operation

Conclusions

We have worked out the mathematical model of the system of the automatic control of the variable-frequency electric drive of the pump with the function of the stabilization of the pressure in the consumer's network. It includes the block of modeling emergency modes enabling the formation of a leakage, a water hammer and cavitation in the pressure pipeline network. We have formulated the diagnostic signs of the emergency modes based on the obtained curves representing the alterations of the technological, electromechanical and energy parameters of the pumping complex for identification kind of the unsteady mode. We have proposed the generalized algorithm of the operation of the diagnostics system allowing the determination of the development of the emergency modes aiming at the timely response to the contingency situations in the pipeline networks of the pumping complex.

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