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# Bifurcation Approach to the Emergency Situation Monitoring of Pulse Energy Conversion Systems

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***Abstract:** The new approach to the forecasting and detection of the emergency situations in pulse energy conversion systems based on the bifurcation approach was proposed. The essence of the proposed approach is in the on-line monitoring of "dangerous" bifurcation boundaries in system's parameter space. It is proposed to identify "dangerous" bifurcation situation (emergency) on-line on the basis of state vector analysis.*

## 1. Introduction

Increase of specific energy consumption in so-called "responsible technological processes" stipulates high demands to the reliability and safety of energy conversion and delivering systems. On the other hand the necessity to increase a technological and economical efficiency of energy conversion processes stimulates wide use of pulse energy conversion systems (PECS). The complicated physical nature of the PECS and their operation under conditions of substantial changes in internal and external parameters make prerequisites for the appearance of emergency in their dynamics. The use of agreed-upon approaches to the fault detection and isolation (FDI) for such systems is hindered by some reasons.

A. The high dimension of the state space of the mathematical model (MM) which describe the PECS and incomplete observability of the state vector make difficulties the use of the methods of FDI which are based upon the analysis of the state vector of the system. Again the high order of nonlinear models complicates their realization in real time and causes contradictions between the main criteria of the forecasting efficiency, the adequacy degree and the forecasting time.

B. The substantial nonlinearity of the PECS, which is stipulated by their operation principle, causes the appearance of both the quantitative and qualitative (bifurcation) changes in the dynamics of such systems.

C. The high dimension of the parameter space and a great number of various bifurcation boundaries in the parameter space causes indeterminacy in realization of either scenarios of the development of the dynamics in the PECS when their internal parameters or the operating conditions are changed.

The above-mentioned problems are typical of a different classes of nonlinear systems of various nature and they stimulate the development of radically new approaches to the forecasting and detection of emergency in such systems.

## 2. Description of the Proposed Approach

The proposed approach to the construction of the system for the forecasting and detection of emergency situations in the dynamics of the PECS is based upon the use of bifurcation analysis and the theory of nonlinear observers. The approach involves the following steps.

A. The structural analysis of the PECS that is carrying out to reveal some structural peculiarities which are characteristic of the dynamics of the PECS. The result of this analysis is the decomposition of the PECS into some simpler structural elements, which are studied separately. If it is not possible, an attempt is made to substantially decrease the order of MM by the separation of the most important parts and links (which determine the dynamics) and elimination less significant ones [1].

B. The detection of the main (potentially "expected") scenarios of the development of the dynamics of the PECS and the detection of the interconnection between the detected scenarios and the structural peculiarities of the PECS.

C. The detection of the "dangerous" bifurcation boundaries in the parameter space of the PECS, that is, the location of the boundaries whose intersection leads to emergency, and the formation of quantitative criteria for the detection of either bifurcation boundaries by the use of the state vector of the system.

D. The construction of the FDI system by using the nonlinear observers. In this case any emergency is detected on the basis of the criteria stated in item C by the use of the state vector of the system which was partially reconstructed by the observer.

The problem of the forecasting adequacy of any emergency in the dynamics of the PECS by using the proposed approach is directly connected with the evaluation of the adequacy of simplifications which are used during their analysis (see item A) and during the synthesis of the observers (see item D).

In order to ensure the adequacy degree and forecasting time (for specific aims) it is necessary:

- to study all permissible simplifications in the mathematical models of the PECS depending on the purposes of forecasting and available material resources;
- to place the limits for use of simplifications depending also on the purposes of forecasting.

As an example let us consider the electromechanical PECS (automated d.c. electric drive) whose functional scheme is shown in Fig. 1. This PECS is an automatic system for regulating the current in the armature of a d.c. electric motor and may be represented structurally in the form of three coupled oscillators. The representation of the electromechanical energy conversion systems as some coupled oscillators is sufficiently well known for the researchers of such systems [2, 3].

The mechanical subsystem (the first oscillator) is an equivalent rotating mass, which is reduced to the shaft of the electric motor, and is nonlinearly coupled to the electrical subsystem of the PECS (the second oscillator). There is a passive LC-filter (the third oscillator) between the power source and the electrical subsystem of the PECS. Moreover, the LC-filter and the PECS are coupled through a discrete function of coupling (so-called coupling of the "pulse pumping" type [1]).

The mechanical subsystem of the PECS and the input filter may be considered as linear oscillating elements to a first approximation. Moreover, for relatively powerful drives (more than dozens of kW) the resonance frequency of the mechanical subsystem is much less than the modulation frequency of the electrical subsystem. Therefore, when analyzing such systems the

known simplification may be the method of dividing motions into fast motions (in the electrical subsystem) and low motions (in the mechanical subsystems) [3]. In this case the equations of the mechanical subsystem may be eliminated from the dynamic MM of the PECS, and the mechanical subsystem itself may be accounted for by the parameter  $\omega$  – the rotation frequency of the motor shaft. While making a bifurcation analysis the  $\omega$  is considered as varying parameter.

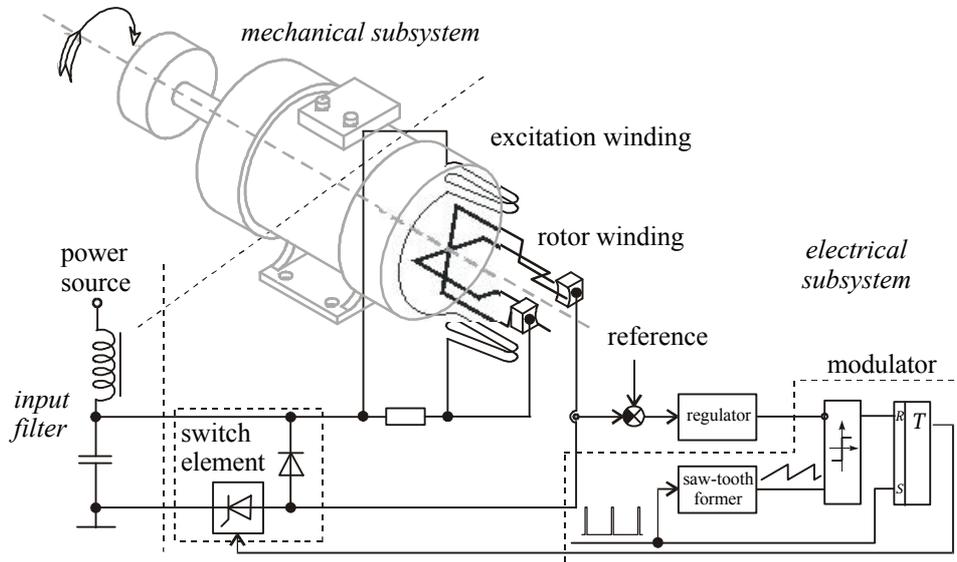


Fig. 1. Functional scheme of the considered electromechanical system

The resonance frequency of the input filter on the contrary may be comparable with the modulation frequency of the electrical subsystem of the PECS. Consequently the interaction between the input filter and the electrical subsystem of the PECS determines largely the dynamics of the PECS on the whole [3].

Finally, the mathematical model of the PECS under consideration is a system of five differential equations with the discontinuous right-hand part [3]. The components of the state vector  $\mathbf{X}$  are: the current fed from the power source  $i_c$ ; the voltage at the capacitor of the input filter  $U_c$ ; the armature current  $i_r$  and the magnetic flux  $\hat{O}$  of the electric motor and the variable describing the PI-element of the regulator.

The instants of switching of the switch element for the PECS with pulse-width modulation is described by a scalar commutation function of the state vector  $\mathbf{X}$  and time  $t$  [3-5]. The parameters of the mathematical model correspond to the electric motor drive of a tram or a trolley bus having the equivalent power of the electric motors of 160 kW. The control frequency of the PECS  $f_0$  is equal to 400 Hz.

At this design step of the PECS it is assumed that its stationary motion should be periodic oscillations with the frequency  $f_0$ , but experimentally and on models it is determined that the variations in the parameters of the PECS may result in the appearance of more complicated motions in it, subharmonic (with frequency of  $f_0/m$ ), quasiperiodic and chaotic (see for example [3]). Fig. 2 shows two parametric bifurcation diagram of stationary motions (from [3]). The rotation frequency of the motor shaft,  $\omega$  and the resonance frequency of the input filter,  $f_r$  are considered in Fig. 2 as varying parameters. In the diagram the domains, where the periodic motions with the frequency  $f_0/m$  exist, are denoted by  $P_m$  and the domains, where quasiperiodic or chaotic motions exist, are marked by  $Q$  and  $Ch$  respectively.

As it is readily noticed in the diagram of Fig. 2, the domains of periodicity alternate with the domains of quasiperiodicity (at variation in  $f_r$ ). It is explained by the interaction of two oscillators with rationally not coupled frequencies (of the input filter and the electrical subsystem of the PECS).

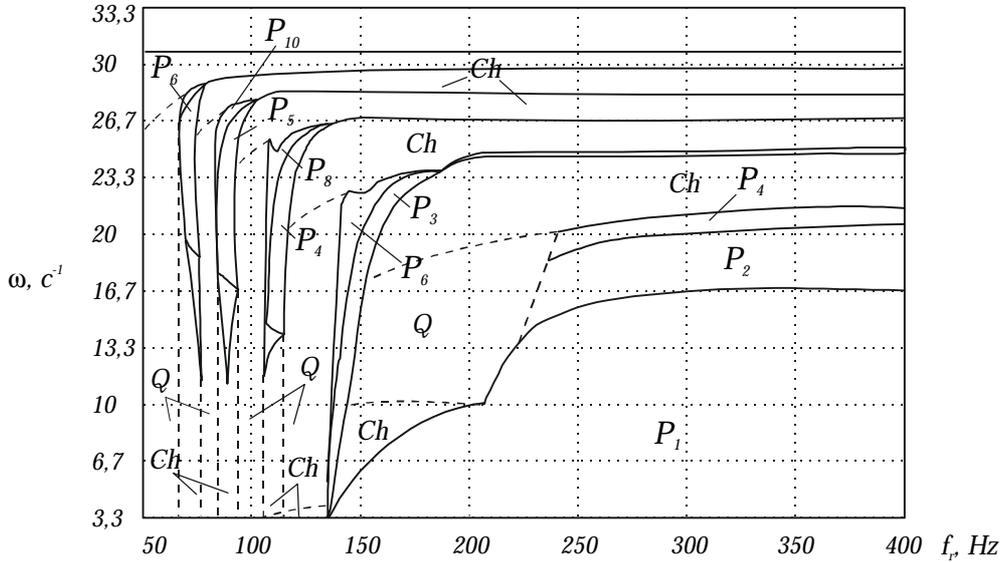


Fig. 2. Two parametric bifurcation diagram of stationary motions

Thus, the main type of stationary motion in the PECS under consideration are quasiperiodic oscillations which are characterized by two-dimensional torus in the state space. In this case, the periodic motions in the domains  $P_m$  may be considered as the motions which are synchronized on the torus.

The "stepwise" change in system's state during corresponded bifurcation boundary intersection can be considered as the criteria to separation of "dangerous" bifurcation boundaries in Fig.2. The essence of bifurcation boundaries separation with "dangerous" and "non-dangerous" may be illustrated with the consideration of specific period doubling bifurcation boundary (the boundary between  $P_1$  and  $P_2$  in Fig. 2). Let us consider that the systems dynamics is described by stroboscopic mapping  $X_{k+1}=F(X_k)$  [3-5]. Here  $X_k=X(kT)$  is a state vector of the system,  $k=0,1,2,\dots$ ,  $T=1/f_0$ . If one looks upon discrete sequence  $X_k$ ,  $k = 0,1,2,\dots$  the motion with period equals to the  $1/f_0$ , corresponds to the equation  $X_k = F(X_k)$ . Similarly, the equation  $X_k=F(F(X_k))$ ,  $X_k \neq F(X_k)$  corresponds to the motion with period doubled to the  $1/f_0$  (see Fig.3).

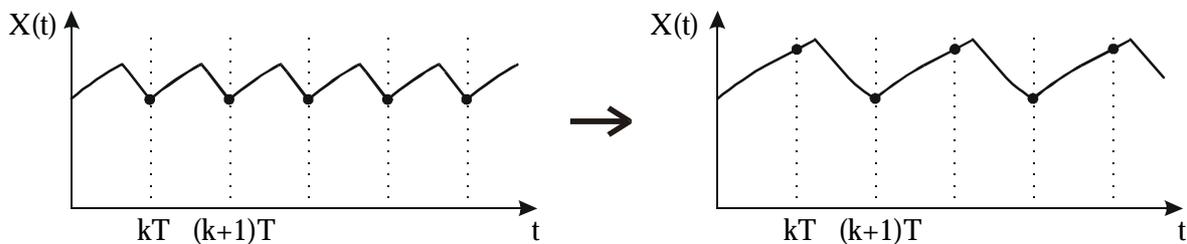


Fig.3. Illustration of period doubling phenomenon.

Now suppose, the doubling of the period in the system in question is the result of change of some parameter  $\alpha$ . As shown in [4] in application to the PECS with PWM the above mentioned doubling of period of stationary motion may occur by two ways:

- so-called "smooth" doubling (supercritical bifurcation of period doubling);
- "rigorous" doubling (subcritical bifurcation of period doubling).

These both cases are illustrated by bifurcation diagrams in Fig.4 a,b. On the ordinate  $X_k$  values are plotted which determine stationary motions with a specific value of  $\alpha$ . In Fig.4 the stable motions are shown by solid lines and unstable motion by dashed lines. The point of bifurcation of period doubling of stationary motion is denoted as  $\alpha^*$ .

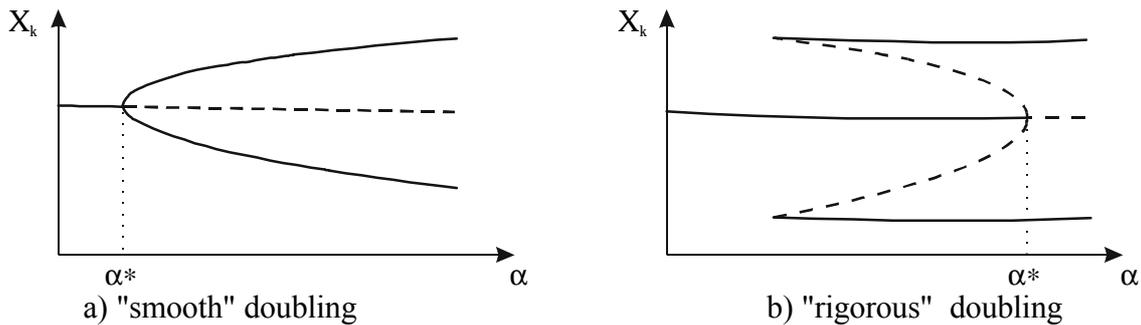


Fig.4. Bifurcation diagrams of stationary motions

Are the situations in Fig.4a and Fig.4b emergency from the point of view of operation of the system? In the first case the change of stationary motion in the system occurs "smoothly" and therefore it may be detected and compensated some how. This is not a type of "dangerous" bifurcation boundary. In the second case a "stepwise" change of stationary motion is observed and this is an emergency conditions undoubtedly. Moreover, the presence of hysteresis domain in Fig.4b creates preconditions for phenomenon of alternation (in a definite time interval) of stationary motion, for example, by impact of external noise. This bifurcation boundary is "dangerous". Similarly we can characterize the bifurcation boundary between the domain of periodic motion existence  $P_1$  and the domain of chaos  $Ch$  as a "dangerous" boundary.

The correlation function both with the static error signal are proposed to consider as a qualitative criteria of on-line monitoring of "dangerous" bifurcation boundaries intersection (an emergency situation) in PECS. The static error signal in common case is proposed to be reconstructed with the observer. With the help of this criteria one can easily detect emergency situation in the PECS' dynamics.

### 3. Conclusions

In practice, the use of the results of the bifurcation analysis for the purposes of FDI is complicated by a number of mathematical problems.

1. To obtain a pattern of division of the parameter space is such a process which requires very large computing expenditures. This process can not be realized in real time.
2. For "direct" use of the results of the bifurcation analysis for FDI it is necessary to solve the problem of parametric identification of the PECS but to do it is practically impossible.

Hence the authors of the paper offer an approach to FDI for the PECS which uses not the pattern of division of the parameter space into the domains with different types of motions, but

the mathematical criteria based upon the use of the state vector of the PECS which describe the bifurcation boundaries of the domain having the given motion. The nonobserved components of the state vector of the PECS is proposed to restore by nonlinear observers. At present the problems of the formation of mathematical criteria which describe the bifurcation boundaries of the PECS on the basis of its state vector and the problems of the formation of nonlinear observers of the PECS are not completely solved and determine the directions of further investigations.

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