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Study of Deterministic Chaotic Regime of an Electrical System with One Generating Source By the Gradient-Velocity Method of Vector Functions of A.M. Lyapunov

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Abstract. *The method of functions of Lyapunov is the main universal tool for studying stability of linear and nonlinear systems. At the same time, there remains the problem of the absence of a universal approach to structuring functions of Lyapunov. Purpose of work: Carrying out and researching a deterministic chaotic regime of an electrical system with one generating source by gradient-velocity method of vector functions of A.M. Lyapunov. Research methodology: This article presents an approach based on the gradient-velocity method of vector functions of A.M. Lyapunov. A dynamic system is considered as gradient systems, while the function of Lyapunov is considered as potential functions from catastrophe theories. Results: A mathematical description of the robust stability condition for the existing stationary state in the form of a system of inequalities for the undefined parameters of an electrical system with one generating source (ETS GS) has been carried out. The results obtained show that while the uncertain parameters go beyond the boundaries of robust stability in the system, a regime of deterministic chaos is generated with the formation of a «strange attractor», which leads to a decrease in the efficiency of power transmissions. This study is of great importance for ensuring the stability of the functioning of electrical systems.*

Keywords: *nonlinear system, control systems, stability of an electrical system, robust stability, method of vector functions of A.M. Lyapunov.*

Introduction

Chaos is a complex phenomenon for a deterministic nonlinear dynamic system. As a rule, there are two additional attributes for defining chaos in both temporal and spatial aspects: exponentially sensitive dependence on initial conditions and the structure of strange attractor patterns [1]. Because of its theoretical significance and technical applicability, chaos control has received great attention in various fields, such as laser physics, mechanics, communication systems, radio physics, as well as in energy, electrical, biological, mechanical, socio-economic and medical systems.

Studies of recent decades show the rapid development of theories of nonlinear dynamical systems, which led to one of the significant discoveries in nonlinear dynamical systems, deterministic chaos with the generation of a «strange attractor» [1,2,3]. It follows from this that the modes of deterministic chaos are a specific form of behavior of a nonlinear system, and for an electrical system, the study of chaotic modes is an urgent task. The study of chaotic phenomena is an important part of research on the stability of an electrical system. Namely, while fluctuations in the system become chaotic, the system loses its stability, thereby forming an emergency mode of operation in socio-economic, biological, medical, etc. systems in the form of a «crisis». In the modes of deterministic chaos of an electrical system with a generating source, the Umov-Poynting vector degenerates as a carrier of useful power from the generator to the load [4,5] and leads to a decrease in the efficiency of power transmissions. This is due to the fact that with a large amplitude and frequency of chaotic oscillations, all the energy transferred from the generator to the load under certain conditions is converted into chaotic thermal energy. When deterministic chaos occurs, the trajectories of the system are globally limited by the «strange attractor» and are locally unstable inside the «strange attractor». It is important that when the uncertain parameters of the system go beyond the boundaries of robust stability, deterministic chaos is generated in nonlinear systems [6,7].

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Most real nonlinear dynamic systems are created and operate under conditions of uncertainty. In most cases, uncertainty can be caused by ignorance of the true values of the system parameters and their unpredictable changes during the operation of the system. The ability of a dynamic system to maintain stability under uncertainty is understood as the robust stability of the system. In the general setting, the study of the system for robust stability consists in indicating the constraints on the change of uncertain parameters, where the dynamical system remains stable [8,9].

The main universal tool for studying the stability of linear and nonlinear systems is the method of functions of Lyapunov [14]. At the same time, the basic problem is the lack of a universal approach to the construction of Lyapunov functions [14,15]. Currently, this method is mainly a tool for theoretical research and cannot provide answers to all questions regarding sustainability in real conditions.

Therefore, the gradient-velocity method of the vector function of Lyapunov [16,17,18] is proposed for the study of a nonlinear electrical system with one generating source (ETS GS), where the dynamic system is considered as gradient systems, and the Lyapunov function is considered as potential functions from catastrophe theories [19] and the gradient condition of the dynamical system allows to construct the Lyapunov functions analytically. Thus, a universal approach to the construction of Lyapunov functions is proposed. It should be noted that the necessary condition for the existence of Lyapunov functions corresponds to the asymptotic, robust stability of the dynamic system of the ETS GS.

Research method

Nonlinear differential equations of state of ETS GS, necessary for the analysis of chaotic modes, voltage parameters and voltage deviations $U_л(t)$ have the form:

$$\begin{cases}\dot{\delta} = \omega,\\ \dot{\omega} = B\sin(\delta_л - \delta + \alpha)U_л - D\omega + K,\\ \dot{\delta}_л = CU_л^2 - F\cos(\delta_л - \delta - \alpha)U_л -\\ -HU_л - N\cos(\delta_л - \beta)U_л + JQ_{1b} + L,\\ \dot{U}_л = -MU_л^2 + Y\cos(\delta_л - \delta - \gamma)U_л +\\ +ZU_л + V\cos(\delta_л - \tau)U_л - sQ_{1b} - A,\end{cases} \tag{1}$$

where

$\delta(t)$ – fluctuations in the phase angle on the generator buses,

$\delta_л(t)$ – fluctuations in the phase angle in the power line,

$\omega(t)$ – deviation of the angular frequency from the nominal value,

$U_л(t)$ – voltage at the end of the power transmission line (on the load buses),

Q_{1b} – variable value of reactive power,

$B, \alpha, D, K, C, F, H, N, \beta, J, L, M, Y, \gamma, z, V, \tau, s, A$ – a set of parameters of the ES GI,

$x=(\delta,\ \omega,\ \delta_л,\ U_л)$ – is the vector of state variables (1). We introduce the notation: $x_1=\delta$, $x_2=\omega$, $x_3=\delta_л$, $x_4=U_л$.

Then the equations of state of the ES GI can be represented in the form:

$$\begin{cases}\dot{x}_1 = x_2,\\ \dot{x}_2 = B\sin(x_3 - x_1 + \alpha)x_4 - Dx_2 + K,\\ \dot{x}_3 = Cx_4^2 - F\cos(x_3 - x_1 - \alpha)x_4 -\\ -Hx_4 - N\cos(x_3 - \beta)x_4 + JQ_{1b} + L,\\ \dot{x}_4 = -Mx_4^2 + Y\cos(x_3 - x_1 - \gamma)x_4 +\\ +zx_4 + V\cos(x_3 - \tau)x_4 - sQ_{1b} - A.\end{cases} \tag{2}$$

We define stationary states of system (2) as a solution to a system of algebraic equations:

$$\begin{cases}x_2 = 0,\ B\sin(x_3 - x_1 + \alpha)x_4 - Dx_2 + K = 0,\\ Cx_4^2 - F\cos(x_3 - x_1 - \alpha)x_4 - Hx_4 -\\ -N\cos(x_3 - \beta)x_4 + JQ_{1b} + L = 0,\\ -Mx_4^2 + Y\cos(x_3 - x_1 - \gamma)x_4 + zx_4 +\\ +V\cos(x_3 - \tau)x_4 - sQ_{1b} - A = 0.\end{cases} \tag{3}$$

From (3) we obtain stationary states:

$$\begin{aligned} x_{1S}^1 &= \cos\left(-\frac{F\cos(-2\alpha) - H}{N}\right) + \alpha + \beta;\ x_{2S}^1 = 0;\\ x_{3S}^1 &= \cos\left(-\frac{F\cos(-2\alpha) - H}{N}\right) + \beta;\ x_{4S}^1 = 0.\end{aligned} \tag{4}$$

Another stationary state of the system:

$$x_{1S}^2 = \frac{\left(V + Y - \frac{MN}{C} - 2\frac{MF}{C}\right)\alpha -}{V - \frac{MN}{C}}$$

$$\frac{-\frac{MN}{C}\beta + Y\gamma + V\tau + \frac{MH}{C} - z}{V - \frac{MN}{C}};\quad x_{2S}^2 = 0;$$

$$x_{3S}^2 = \frac{\left(V + Y - \frac{MN}{C} - 2\frac{MF}{C}\right)\alpha - \frac{MN}{C}\beta +}{V - \frac{MN}{C}} \tag{5}$$

$$\frac{+Y\gamma + V\tau + \frac{MH}{C} - z}{V - \frac{MN}{C}} - \alpha = x_{1S}^2 - \alpha;$$

$$x_{3S}^2 = \frac{1}{C}[(F\cos(-2\alpha) + H) + N\cos(x_{1S}^2 - \alpha - \beta)].$$

Let us study the stability of the stationary state (4) of system (2). The equation of state of system (2) is expanded in a Taylor's series expansion around the stationary state (4) and is represented in deviations from the stationary state (4) in the form:

$$\begin{cases}\dot{x}_1 = x_2,\\ \dot{x}_2 =- Bx_1 + Bx_3 - Dx_2,\\ \dot{x}_3 =- F\cos(-2\alpha)x_4 - Hx_4 -\\ -N\cos\left(-\frac{F\cos(-2\alpha)-H}{N}+\beta-\tau\right)x_4 +\\ +F\sin(-2\alpha)x_3x_4 -\\ -N\sin\left(-\frac{F\cos(-2\alpha)-H}{N}\right)x_3x_4 + 2Cx_4,\\ \dot{x}_4 = Y\cos(-\alpha-\gamma)x_4 + zx_4 +\\ +V\cos\left(-\frac{F\cos(-2\alpha)-H}{N}+\beta-\tau\right)x_4 +\\ +Y\cos(-\alpha-\gamma)x_1x_4 + Y\cos(-\alpha-\gamma)x_3x_4 -\\ -V\sin\left(-\frac{F\cos(-2\alpha)-H}{N}+\beta-\tau\right)x_3x_4 +\\ +Y\cos(-\alpha-\gamma)x_4 + zx_4 +\\ +V\cos\left(-\frac{F\cos(-2\alpha)-H}{N}+\beta-\tau\right)x_4 - 2Mx_4^2.\end{cases} \tag{6}$$

System (6) can be represented as:

$$\begin{cases}\dot{x}_1 = x_2,\\ \dot{x}_2 = Bx_1 - Dx_2 + Bx_3,\\ \dot{x}_3 = Gx_4 - G_1x_1x_4 + G_2x_3x_4 + Cx_4^2,\\ \dot{x}_4 = Rx_4 + R_1x_1x_4 + R_2x_3x_4 - Mx_4^2,\end{cases} \tag{7}$$

where

$$G =- F\cos(-2\alpha) - H - N\cos\left(-\frac{F\cos(-2\alpha)-H}{N}\right),$$
$$G_1 = F\sin(-2\alpha) - N\sin\left(-\frac{F\cos(-2\alpha)-H}{N}\right),$$
$$R = Y\cos(-\alpha-\gamma) + z + +V\cos\left(-\frac{F\cos(-2\alpha)-H}{N}+\beta-\tau\right),$$
$$R_1 = Y\cos(-\alpha-\gamma),\quad R_2 = Y\sin(-\alpha-\gamma) - -V\sin\left(-\frac{F\cos(-2\alpha)-H}{N}+\beta-\tau\right).$$

A deterministic chaotic regime is generated in system (7) when robust stability is lost. Therefore, we investigate the stability of system (7) using the gradient-velocity method of Lyapunov vector functions. From the gradient of system (7) and the equivalence of the Lyapunov vector functions and the potential function from catastrophe theory [19], we determine the gradient vectors of the Lyapunov vector functions $V(x)=V_1(x), V_2(x), V_3(x), V_4(x)$ according to equation (7):

$$\begin{cases}\frac{\partial V_1(x)}{\partial x_1} = 0, \frac{\partial V_1(x)}{\partial x_2} =- x_2, \frac{\partial V_1(x)}{\partial x_3} = 0, \frac{\partial V_1(x)}{\partial x_4} = 0,\\ \frac{\partial V_2(x)}{\partial x_1} = Bx_1, \frac{\partial V_2(x)}{\partial x_2} = Dx_2, \frac{\partial V_2(x)}{\partial x_3} = Bx_3,\\ \frac{\partial V_2(x)}{\partial x_4} = 0,\\ \frac{\partial V_3(x)}{\partial x_1} = 0, \frac{\partial V_3(x)}{\partial x_2} = 0, \frac{\partial V_3(x)}{\partial x_3} =- G_2x_3x_4,\\ \frac{\partial V_3(x)}{\partial x_4} =- Gx_4 + Cx_4^2,\\ \frac{\partial V_4(x)}{\partial x_1} =- R_1x_1x_4, \frac{\partial V_4(x)}{\partial x_2} = 0, \frac{\partial V_4(x)}{\partial x_3} =- R_2x_3x_4,\\ \frac{\partial V_4(x)}{\partial x_4} = Rx_4 + Mx_4^2.\end{cases} \tag{8}$$

From (7) we determine the expansion in the coordinates of the components of the velocity vector:

$$\begin{cases}\left(\frac{dx_1}{dt}\right)_{x_1} = 0, \left(\frac{dx_1}{dt}\right)_{x_2} = x_2, \left(\frac{dx_1}{dt}\right)_{x_3} = 0, \left(\frac{dx_1}{dt}\right)_{x_4} = 0,\\ \left(\frac{dx_2}{dt}\right)_{x_1} =- Bx_1, \left(\frac{dx_2}{dt}\right)_{x_2} =- D_1x_2, \left(\frac{dx_2}{dt}\right)_{x_3} = Bx_3,\\ \left(\frac{dx_2}{dt}\right)_{x_4} = 0,\\ \left(\frac{dx_3}{dt}\right)_{x_1} = 0, \left(\frac{dx_3}{dt}\right)_{x_2} = 0, \left(\frac{dx_3}{dt}\right)_{x_3} = G_2x_3x_4,\\ \left(\frac{dx_3}{dt}\right)_{x_4} = Gx_4 - Cx_4,\\ \left(\frac{dx_4}{dt}\right)_{x_1} = R_1x_1x_4, \left(\frac{dx_4}{dt}\right)_{x_2} = 0, \left(\frac{dx_4}{dt}\right)_{x_3} = R_2x_3x_4,\\ \left(\frac{dx_4}{dt}\right)_{x_4} = Rx_4 - Mx_4.\end{cases} \tag{9}$$

According to the theorem of A.M. Lyapunov's total time derivative of the Lyapunov vector-function is defined as the scalar product of the velocity vector (9) by the gradient vector (8)

$$\frac{dV(x)}{dt} = \sum_{i=1}^{4}\sum_{j=1}^{4}\frac{\partial V_i(x)}{\partial x_j}\left(\frac{dx_i}{dt}\right)_{x_j} =- x_2^2 - B^2x_1^2 - -Dx_2^2 - Bx_3^2 - G_2^2(x_3x_4)^2 - (Gx_4 - Cx_4^2)^2 - -R_1^2(x_1x_4)^2 - R_2^2(x_3x_4)^2 - (Rx_4 + Mx_4^2)^2. \tag{10}$$

It follows from (10) that the total time derivative of the Lyapunov vector function is a sign-negative function.

Using the components of the gradient vector (8) of the Lyapunov vector function, we determine the Lyapunov vector functions in scalar form:

$$V(x) = V_1(x) + V_2(x) + V_3(x) = \frac{1}{2}Bx_1^2 + +\frac{1}{2}(D_1-1)x_2^2 - \frac{1}{2}x_3^2 + Bx_3^2 - \frac{1}{2}(G+R)x_4^2 - -\frac{1}{2}R_1x_1^2x_4 - (G_2+R_2)x_3^2x_4 + \frac{1}{3}(C+M)x_4^3. \tag{11}$$

Function (11), according to the Morse lemma from catastrophe theory [19], can be represented in the form of a quadratic form:

$$V(x) \approx Bx_1^2 + (D_1-1)x_3^2 - (G+R)x_4^2. \tag{12}$$

The conditions for the positive definiteness of Lyapunov vector functions (11) are written:

$$(D-1) > 0, -F\cos(-2\alpha) - H - -N\cos\left(-\frac{F\cos(-2\alpha)-H}{N}\right) + Y\cos(-\alpha-\gamma) + +z + V\cos\left(-\frac{F\cos(-2\alpha)-H}{N}+\beta-\tau\right) > 0. \tag{13}$$

The stability of the stationary state (5) of the system (2) is investigated by the gradient-rate method of Lyapunov vector functions and we determine that the stationary state (5) is unstable and we make sure that when the stationary state (4) becomes unstable, a deterministic chaotic regime is generated in the system.

Conclusion

Real unregulated electrical systems of generating sources operate under conditions of uncertainty. The functioning of the ES GI as a nonlinear dynamic system in the regime of deterministic chaos with the formation of «strange attractors» is considered a basic property.

In the regime of deterministic chaos of an electrical system with one generating source, the Umov-Poynting vector degenerates as a carrier of useful power from the generator to the load, which, as a result, leads to a decrease in the efficiency of power lines.

This article proposes an approach to the study of the deterministic chaotic regime of an uncontrolled ETS GS by the gradient-velocity method of Lyapunov vector functions. In this case, the equations of state of an uncontrolled ES GI are presented in the form of gradient systems, and the Lyapunov function – in the form of potential functions from catastrophe theories.

As a result of the study, the condition for the robust stability of the existing stationary state of the ETS GS is presented in the form of a system of inequalities for uncertain parameters. Thus, we have confirmation that when the parameters go beyond the boundaries of robust stability, a regime of deterministic chaos is generated in the system with the formation of a «strange attractor», therefore, the energy passing from the generator to the load under certain conditions is converted into chaotic energy and, as a consequence, leads to a decrease in the efficiency of power lines. Thus, this study is of great importance for ensuring the stability of the functioning of electrical systems.

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А.М. Ляпунов векторлық функцияларының градиенттік-жылдамдық әдісін қолдану арқылы бір генераторлық көзі бар электр жүйелерінің детерминистік хаотикалық режимін зерттеу

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Аңдатпа. *Ляпунов функцияларының әдісі – сызықтық және сызықты емес жүйелердің тұрақтылығын зерттейтін негізгі әмбебап құрал. Сонымен қатар, Ляпунов функцияларын құруға әмбебап көзқарастың жоқтығы проблемасы қалады. Жұмыстың мақсаты: А.М. Ляпуновтың векторлық функцияларының градиент-жылдамдық әдісімен бір генератор көзі бар электр жүйесінің детерминистикалық хаотикалық режимін зерттеу. Зерттеу әдістемесі: Бұл мақалада А.М. Ляпуновтың векторлық функциялардың градиент-жылдамдық әдісіне негізделген тәсіл ұсынылған. Динамикалық жүйе градиент жүйелері ретінде қарастырылады, ал Ляпунов функциясы апаттар теориясының потенциалды функциялары ретінде қарастырылады. Нәтижелер: бір генератор көзі бар электрлік жүйенің анықталмаған параметрлері үшін теңсіздіктер жүйесі түрінде бар стационарлық күйдің берік тұрақтылық жағдайының математикалық сипаттамасы жүргізілді. Алынған нәтижелер көрсеткендей, белгісіз параметрлер берік тұрақтылық шегінен шығып кетсе де, жүйеде «оғаш тартқыш» пайда болатын детерминистикалық хаос режимі пайда болады, бұл электр беру тиімділігінің төмендеуіне әкеледі. Бұл зерттеудің электр жүйелерінің жұмысының тұрақтылығын қамтамасыз етуде маңызы зор.*

Кілт сөздер: *сызықты емес жүйе, басқару жүйелері, электр жүйесінің тұрақтылығы, робасты тұрақтылық, А.Л. Ляпуновтың векторлық функциясының әдісі.*

Исследование детерминированного хаотического режима электротехнической системы с одним генерирующим источником градиентно-скоростным методом вектор-функций А.М. Ляпунова

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Аннотация. *Метод функций Ляпунова является основным универсальным средством исследования устойчивости линейных и нелинейных систем. В то же время остается проблема отсутствия универсального подхода к построению функций Ляпунова. Цель исследования: Проведение исследования детерминированного хаотического режима электротехнической системы с одним генерирующим источником градиентно-скоростным методом вектор-функций А.М. Ляпунова. Методология исследования: В данной статье представлен подход, основанный на градиентно-скоростном методе вектор-функций А.М. Ляпунова. В качестве градиентных систем рассматривается динамическая система, в то время как функция Ляпунова – в качестве потенциальных функций из теорий катастроф. Результаты: Выполнено математическое описание условия робастной устойчивости существующего стационарного состояния в виде системы неравенств для неопределенных параметров электротехнической системы с одним генерирующим источником (ЭТС ГИ). Полученные результаты показывают, что в то время, как неопределенные параметры выходят за границы робастной устойчивости, в системе порождается режим детерминированного хаоса с образованием «странного аттрактора», что приводит к снижению КПД электропередач. Данное исследование имеет большое значение для обеспечения устойчивости функционирования электротехнических систем.*

Ключевые слова: *нелинейная система, системы управления, устойчивость электротехнической системы, робастная устойчивость, метод вектор-функций А.М. Ляпунова.*

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