4

Robust Control Research of Chaos Phenomenon for Diesel-Generator Set on Parallel Connection

Man-lei Huang
School of Automation, Harbin Engineering University, Harbin, China

1. Introduction

Several diesel-generator sets usually operate on parallel connection in ship power system, which has altitudinal nonlinearity. When operating point of system changes, its dynamic property will change markedly. The oscillation phenomenon of ship power system which is acyclic, random and gusty or paroxysmal will occur on light load working condition, it can result in system sectionalizing when it is serious, this phenomenon is called chaos. Chaos is a very complicated phenomenon which is generated by the interaction of each parameter in the nonlinear system. When it appears in ship power system, following the continuous and random oscillation of system operating parameter, which endangers operation security of system seriously, it must be prevented and eliminated effectively in the system. In order to analyze the chaos phenomenon of ship power system, the nonlinear mathematical model of two diesel-generator sets on parallel connection is built in this paper, which reflects the variation law of ship power system. Then the light load working condition of two diesel-generator sets on parallel connection in ship power station is analyzed by using Lyapunov index method on the base of this, seeking the generating mechanism of chaos. A nonlinear robust synthetic controller is designed which is based on the nonlinear mathematical model of diesel-generator set, then a nonlinear robust synthetic control law is developed for the diesel-generator set, it will be applied to control the chaos phenomena, thus providing desirable stability for ship power system.

2. Mathematic model of diesel-generator set on parallel connection

The mathematical model of diesel-generator set include the mathematical model of electromechanical transient process and electromagnetism transient process, first building the mathematical model of electromechanical transient process, then the mathematical

Foundation item: Supported by the National Natural Science Foundation of China under Grant No.60774072; Fundamental Research Funds for the Central Universities of China under Grant No.HEUCFT1005.

model of electromagnetism transient process, the mathematical model of one diesel-generator set is get on the base of this.

The mathematical model of diesel-generator set electromechanical transient process describes the motion law of diesel-generator set[1-3], reflecting the dynamic change process of power angle and angular speed, its expression is

$$\begin{cases} \dfrac{\mathbf{d}\delta}{\mathbf{d}t} = \omega - 1, \\ \dfrac{\mathbf{d}\omega}{\mathbf{d}t} = \dfrac{T_b}{T_a\omega_0}\omega + \dfrac{1}{T_a\omega_0}c_1 + \dfrac{c_2}{T_a\omega_0}L - \dfrac{1}{T_a\omega_0}\dfrac{E_q'U}{X_d'}\sin\delta - \dfrac{1}{T_a\omega_0}\dfrac{U^2}{2}\dfrac{X_d' - X_q}{X_d'X_q}\sin 2\delta. \end{cases} \quad (1)$$

In the equation: δ is power angle of diesel-generator set, ω electric angular speed of diesel-generator set, U terminal voltage of generator stator winding, E_q' q-axis transient electric potential, X reactance of each winding, L output axis displacement of diesel engine govonor actuator, $\omega_0 = 100\pi\mathbf{rad/s}$, T_a, T_b, c_1, c_2 constants, δ, L real values, other variables per unit values.

From Eq.(1) we know, this equation has nonlinear feature.

The mathematical model of diesel-generator set electromagnetism transient process include stator voltage balance equation of generator and electromagnetism transient equation of field winding[3], omitting the effect of damping winding, its expression is

$$\begin{cases} \dfrac{\mathbf{d}E_q'}{\mathbf{d}t} = \dfrac{1}{T_{d0}}E_{fd} - \dfrac{1}{T_{d0}}E_q' - \dfrac{X_d - X_d'}{T_{d0}}I_d, \\ U_d = -RI_d + \omega X_q I_q, \\ U_q = -RI_q - \omega X_d' I_d + \omega E_q', \\ U = \sqrt{U_d^2 + U_q^2}. \end{cases} \quad (2)$$

In the equation: U is terminal voltage of stator winding, U_d and U_q d-axis and q-axis component of stator winding terminal voltage, R resistance of stator winding, X reactance of each winding, I current of each winding, T time constant of each winding, E_q' q-axis transient electric potential, E_{fd} voltage of exciting winding.

Since E_q' is not easy to measure, we select the terminal voltage of stator winding U as state varible, only needing change E_q' of Eq.(2) into U. According to the relation between varible data, the following form is set up

$$U = E_q' - c_3\delta \quad (3)$$

Substituting Eq.(3) into the first item Eq.(2), we have

$$\frac{\mathbf{d}U}{\mathbf{d}t} = \frac{1}{T_{d0}}E_{fd} - \frac{1}{T_{d0}}U - \frac{c_3}{T_{d0}}\delta - c_3\omega - \frac{X_d - X_d'}{T_{d0}}I_d + c_3 \quad (4)$$

Substituting Eq.(3) into Eq.(1) and combining with Eq.(4), we have

$$\begin{cases} \dfrac{\mathbf{d}\delta}{\mathbf{d}t} = \omega - 1, \\ \dfrac{\mathbf{d}\omega}{\mathbf{d}t} = \dfrac{T_b}{T_a\omega_0}\omega + \dfrac{1}{T_a\omega_0}c_1 + \dfrac{c_2}{T_a\omega_0}L - \dfrac{1}{T_a\omega_0}\dfrac{(U+c_3\delta)U}{X'_d}\sin\delta - \dfrac{1}{T_a\omega_0}\dfrac{U^2}{2}\dfrac{X'_d - X_q}{X'_d X_q}\sin 2\delta, \\ \dfrac{\mathbf{d}U}{\mathbf{d}t} = -\dfrac{c_3}{T_{d0}}\delta - c_3\omega - \dfrac{1}{T_{d0}}U + \dfrac{1}{T_{d0}}E_{fd} - \dfrac{X_d - X'_d}{T_{d0}}I_d + c_3 \end{cases} \tag{5}$$

We know from the expression of current I_d

$$I_d = \frac{E'_q - U\cos\delta}{X'_d} \tag{6}$$

Substituting Eq.(3) into Eq.(6), we have

$$I_d = \frac{U + c_3\delta - U\cos\delta}{X'_d} \tag{7}$$

Substituting Eq.(7) into Eq.(5), we get

$$\begin{cases} \dfrac{\mathbf{d}\delta}{\mathbf{d}t} = \omega - 1, \\ \dfrac{\mathbf{d}\omega}{\mathbf{d}t} = \dfrac{T_b}{T_a\omega_0}\omega + \dfrac{1}{T_a\omega_0}c_1 + \dfrac{c_2}{T_a\omega_0}L - \dfrac{1}{T_a\omega_0}\dfrac{(U+c_3\delta)U}{X'_d}\sin\delta - \dfrac{1}{T_a\omega_0}\dfrac{U^2}{2}\dfrac{X'_d - X_q}{X'_d X_q}\sin 2\delta, \\ \dfrac{\mathbf{d}U}{\mathbf{d}t} = -\dfrac{X_d c_3}{T_{d0}X'_d}\delta - c_3\omega - \dfrac{X_d}{T_{d0}X'_d}U + \dfrac{1}{T_{d0}}E_{fd} + \dfrac{X_d - X'_d}{T_{d0}X'_d}U\cos\delta + c_3 \end{cases} \tag{8}$$

Eq.(8) is the nonlinear mathematical model of one diesel-generator set, which reflects the relationship of interaction and mutual influence among power angle, speed and voltage, describing the variation law of three variables more exactly.

We select *d-q* axis of first synchronous generator as reference frame, building the mathematical model of two diesel-generator sets on parallel connection. Suppose two diesel-generator sets have the same power, type and parameters, *d*,*q* component of load current is I_d, I_q, power anger difference of two synchronous generators is δ_{12}, the mathematic model of diesel-generator set on parallel connection is

$$\begin{cases} \dfrac{\mathbf{d}\delta_i}{\mathbf{d}t} = \omega_i - 1, \\ \dfrac{\mathbf{d}\omega_i}{\mathbf{d}t} = \dfrac{T_b}{T_a\omega_0}\omega_i + \dfrac{1}{T_a\omega_0}c_1 + \dfrac{c_2}{T_a\omega_0}L_i - \dfrac{1}{T_a\omega_0}\dfrac{(U_i+c_3\delta_i)U_i}{X'_d}\sin\delta_i - \dfrac{1}{T_a\omega_0}\dfrac{U_i^2}{2}\dfrac{X'_d - X_q}{X'_d X_q}\sin 2\delta_i, \\ \dfrac{\mathbf{d}U_i}{\mathbf{d}t} = -\dfrac{X_d c_3}{T_{d0}X'_d}\delta_i - c_3\omega_i - \dfrac{X_d}{T_{d0}X'_d}U_i + \dfrac{1}{T_{d0}}E_{fdi} + \dfrac{X_d - X'_d}{T_{d0}X'_d}U_i\cos\delta_i + c_3 \end{cases} \tag{9}$$

In the equation: $i = 1,\ 2$, subscript 1 indicates the first diesel-generator set, subscript 2 indicates the second diesel-generator set.

Current coupling relation of two diesel-generator sets is

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} I_{d1} \\ I_{q1} \end{bmatrix} + \begin{bmatrix} \cos\delta_{12} & \sin\delta_{12} \\ -\sin\delta_{12} & \cos\delta_{12} \end{bmatrix} \begin{bmatrix} I_{d2} \\ I_{q2} \end{bmatrix} \tag{10}$$

Eq.(10) describes the current distribution relation after two diesel-generator sets enter into parallel connection.

Voltage coupling relation of two diesel-generator sets is

$$\begin{bmatrix} U_{d1} \\ U_{q1} \end{bmatrix} = \begin{bmatrix} \cos\delta_{12} & \sin\delta_{12} \\ -\sin\delta_{12} & \cos\delta_{12} \end{bmatrix} \begin{bmatrix} U_{d2} \\ U_{q2} \end{bmatrix} \tag{11}$$

Eq.(11) describes the voltage restriction relation after two diesel-generator sets enter into parallel connection.

Eq.(9), Eq.(10) and Eq.(11) are the nonlinear mathematical model of two diesel-generator sets on parallel connection, which reflects the relationship of interaction and mutual influence between two diesel-generator sets, describing the variation law of power angle, speed and voltage on two diesel-generator sets exactly.

3. Chaos oscillation analysis of diesel-generator set on parallel connection

This paper will make research on the stability of ship power system by the variation law of power angle, speed and voltage on diesel-generator set. Due to the power transmission between the diesel-generator sets on parallel connection, it is apt to produce power oscillation. Power oscillation is the dynamic process of power of diesel-generator set regulating repeatedly under the effect of some periodic interference.

Power oscillation is a chaos oscillation in nature from the point of view of chaos. The fundamental feature of chaotic motion is highly sensitive to initial condition, the track which is produced by two initial values which is very near each other, will separate according to index pattern as time elapses, Lyapunov index is the quantity which describes the phenomenon. Distinguishing methods of time series chaotic character include fix quantity analysis and ocular analysis, first making numerical analysis for Lyapunov index and judging the condition of chaos emerging, then determining if the chaos exists or not under this condition by the method of ocular analysis. The methods of ocular analysis include time course method, phase path chart method, strobe sampling method, Poincare cross section method and power spectrum method. The methods of calculating Lyapunov index include definition method, Wolf method and Jacobian method, Jacobian method is a method of calculating Lyapunov index which develops in real application. This paper will use Jacobian method to calculate Lyapunov index.

Considering following differential equation system

$$\dot{x} = F(x) \tag{12}$$

In the equation: $\dot{x} = \frac{dx}{dt}$, $x \in R^m$. The evolution of tangent vector e of dot $x(t)$ in the tangent space can be expressed by the equation as follow

$$\dot{e} = T(x(t))e \, , T = \frac{\partial F}{\partial x} \tag{13}$$

In the equation: T is Jacobian matrix of F. The solution of equation can be expressed as

$$e(t) = U(t, e(0)) \tag{14}$$

In the equation $U : e(0) \mapsto e(t)$ is mapping of linear operator. The asymptotic behavior of mapping U can be described by index as

$$\lambda(x(0), e(0)) = \lim_{t \to \infty} \frac{1}{t} \ln \frac{\|e(t)\|}{\|e(0)\|} \tag{15}$$

So, the Lyapunov index of system (12) can be formulated as the mean of above repeat process

$$\begin{aligned} \lambda &= \lim_{k \to \infty} \frac{1}{k\Delta t} \sum_{j=1}^{k} \ln \frac{\|e((j+1)\Delta t)\|}{\|e(j\Delta t)\|} \\ &= \lim_{k \to \infty} \frac{1}{k\Delta t} \ln \frac{\|e((k+1)\Delta t)\|}{\|e(k\Delta t)\|} \frac{\|e(k\Delta t)\|}{\|e((k-1)\Delta t)\|} \cdots \frac{\|e(2\Delta t)\|}{\|e(\Delta t)\|} \end{aligned} \tag{16}$$

For a phase space of n dimension, there will be n Lyapunov index, arranging them according to the order from big to small, supposing $(\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_n)$, λ_1 is called maximum Lyapunov index. Generally speaking, having negative Lyapunov index corresponds with contracting direction, the tracks which are near are stable in the part, corresponding periodic motion. The positive Lyapunov index indicates that the tracks which are near separate by index, the strange attractor is formed in phase space, the Lyapunov index λ is bigger, the chaotic nature of system is stronger, vice versa. For a phase space of n dimension, the maximum Lyapunov index is whether bigger than 0 or not is the basis of judging the system if has chaos oscillation or not.

Computing Lyapunov index of two diesel-generator sets on parallel running with light load separately, two diesel-generator sets all use conventional controllers. Fig.1 and Fig.2 give the phase diagram of power angle, speed and voltage of two diesel-generator sets on parallel running with 12.5% load separately.

Two diesel-generator sets run for 100 seconds on parallel connection with 12.5% load, the initial va1ue of No.1 diesel-generator set is: $(\delta, \omega, U) = (0.1017, 1.0662, 0.9762)$, Lyapunov index is: $\lambda_1 = 0.076789$, $\lambda_2 = 0.035235$, $\lambda_3 = -0.197558$; the initial va1ue of No.2 diesel-generator set is: $(\delta, \omega, U) = (0.1022, 1.0662, 0.9762)$, Lyapunov index is: $\lambda_1 = 0.076806$, $\lambda_2 = 0.035230$, $\lambda_3 = -0.197571$.

Fig.3 and Fig.4 give the phase diagram of power angle, speed and voltage of two diesel-generator sets on parallel running with 25% load separately.

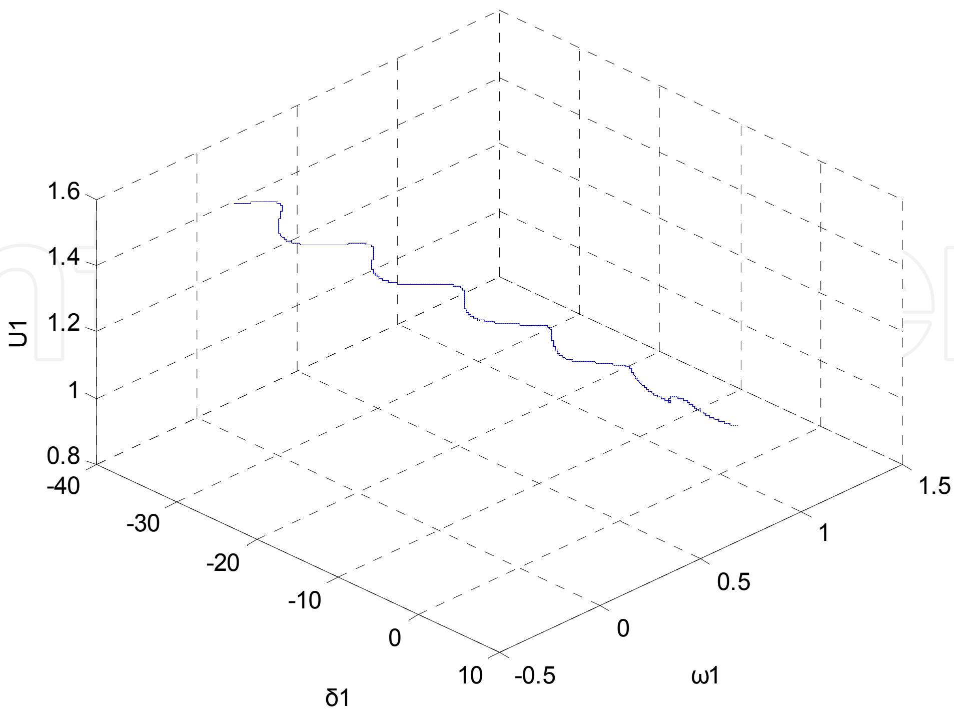


Fig. 1. Phase diagram of No.1 diesel-generator set when two sets load 12.5% on parallel connection

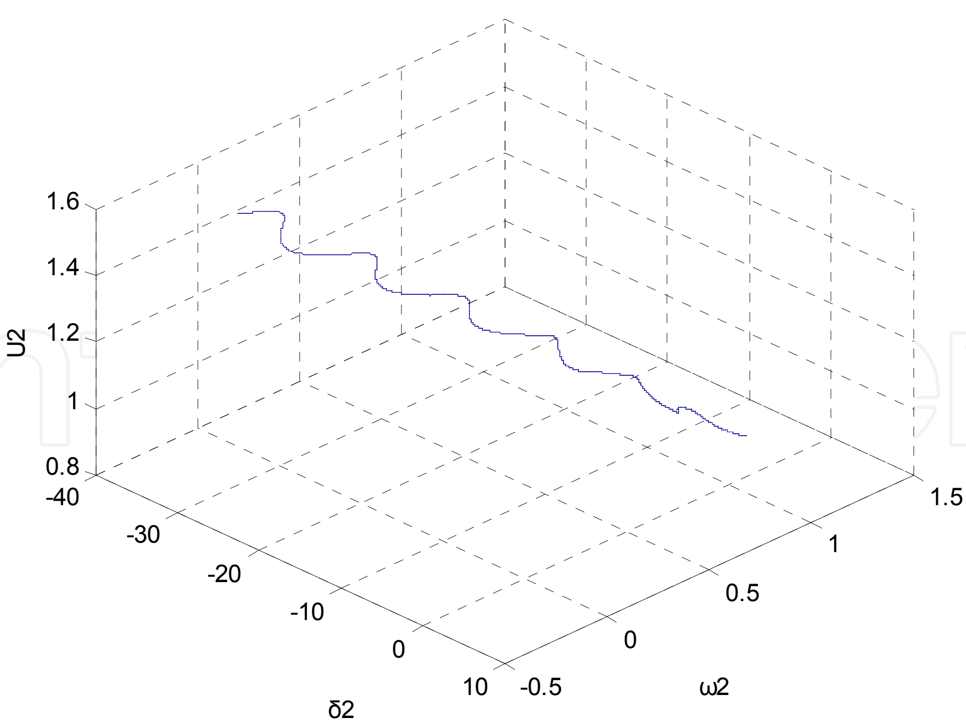


Fig. 2. Phase diagram of No.2 diesel-generator set when two sets load 12.5% on parallel connection

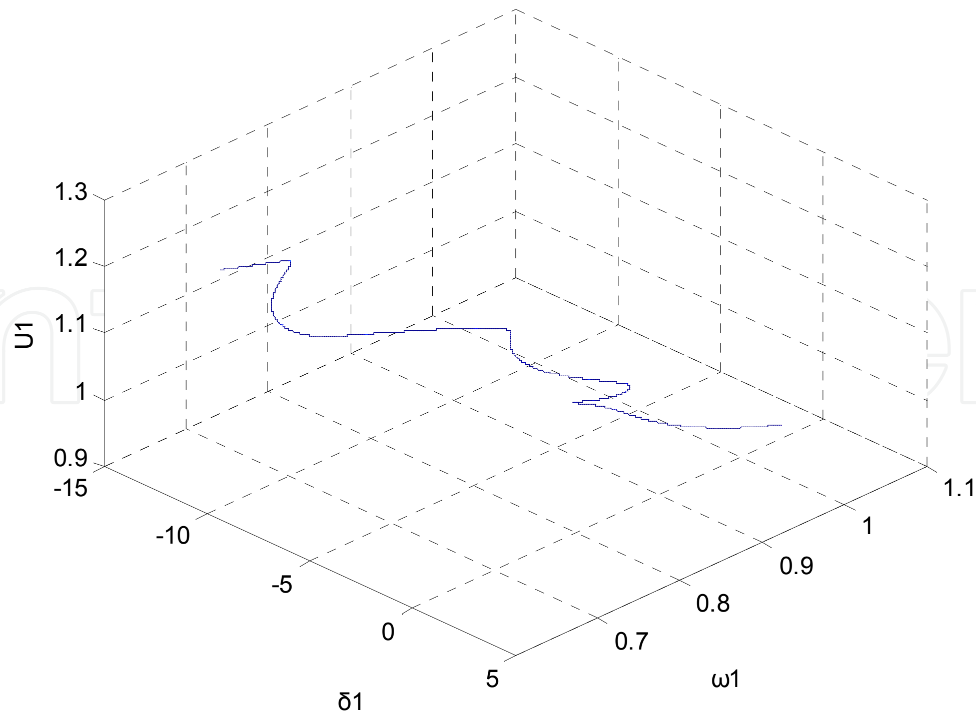


Fig. 3. Phase diagram of No.1 diesel-generator set when two sets load 25% on parallel connection

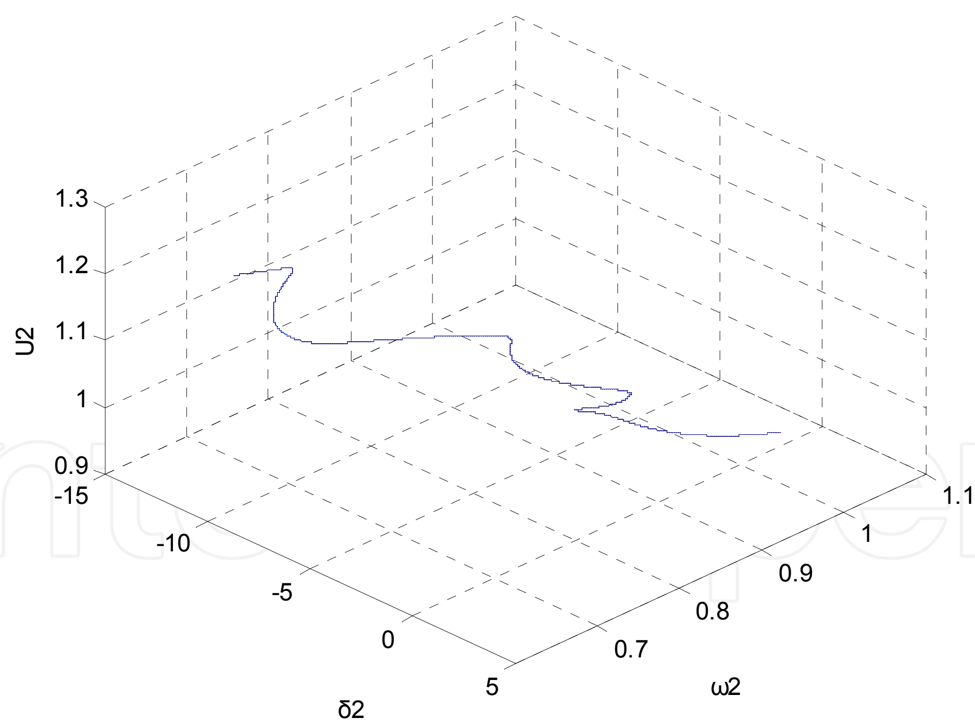


Fig. 4. Phase diagram of No.2 diesel-generator set when two sets load 25% on parallel connection

Two diesel-generator sets run for 100 seconds on parallel connection with 25% load, the initial va1ue of No.1 diesel-generator set is: $(\delta, \omega, U) = (0.1812, 1.0607, 0.9686)$, Lyapunov index is: $\lambda_1 = 0.079251$, $\lambda_2 = 0.034251$, $\lambda_3 = -0.199955$;the initial va1ue of No.2 diesel-generator set is: $(\delta,\omega,U)=(0.1820,1.0607,0.9686)$, Lyapunov index is: $\lambda_1=0.078311$, $\lambda_2=0.034953$, $\lambda_3=-0.199742$.

From Fig.1 to Fig.4 we can see, all maximum Lyapunov indexes of the system are greater than 0, showing that the system exists chaotic phenomenon. Two diesel-generator sets with light load on parallel connection, enter into chaotic state after running a length of time, their specific expression are the oscillation of power angle and speed. Two diesel-generator sets on parallel connection load the lighter, the oscillation of power angle and speed is severer. The oscillation of power angle means the oscillation of power, the reason is the nonlinearity of ship power system and the power transmission between the two diesel-generator sets. The controller in this paper is proportional controller, which is a linear controller. It can't control the nonlinear character of ship power system, it can't average the load in parallel operation control, there is a power angular difference between the diesel-generator sets, thus engendering the power transmission between the sets, which results in the happening of chaotic phenomenon.

Fig.5 and Fig.6 give the phase diagram of power angle, speed and voltage of two diesel-generator sets on parallel running with 25% load plus periodicity load separately. The periodicity load usually appears in ship power system, it is widespread.

Two diesel-generator sets run for 100 seconds on parallel connection with 25% load increasing periodicity load 0.01sint, the initial va1ue of No.1 diesel-generator set is: $(\delta,\omega,U)=(0.1812,1.0607,0.9686)$, Lyapunov index is: $\lambda_1=0.073257$, $\lambda_2=0.031824$, $\lambda_3=-0.191497$; the initial va1ue of No.2 diesel-generator set is: $(\delta,\omega,U)=(0.1820,1.0607,0.9686)$, Lyapunov index is: $\lambda_1=0.073393$, $\lambda_2=0.030161$, $\lambda_3=-0.189995$.

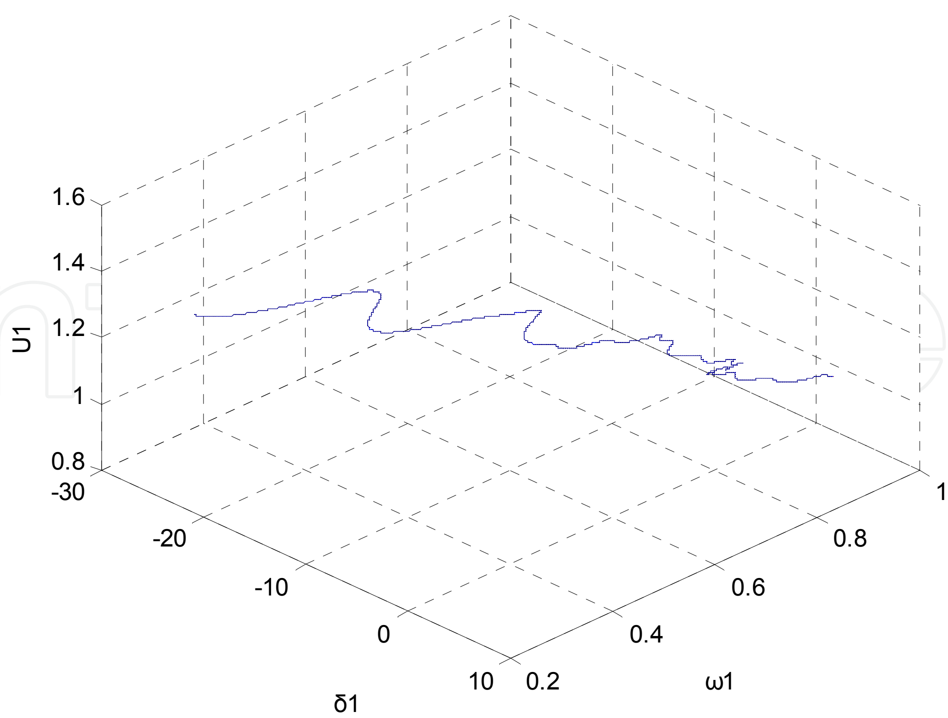


Fig. 5. Phase diagram of No.1 diesel-generator set when two sets increase periodicity load meanwhile load 25% on parallel connection

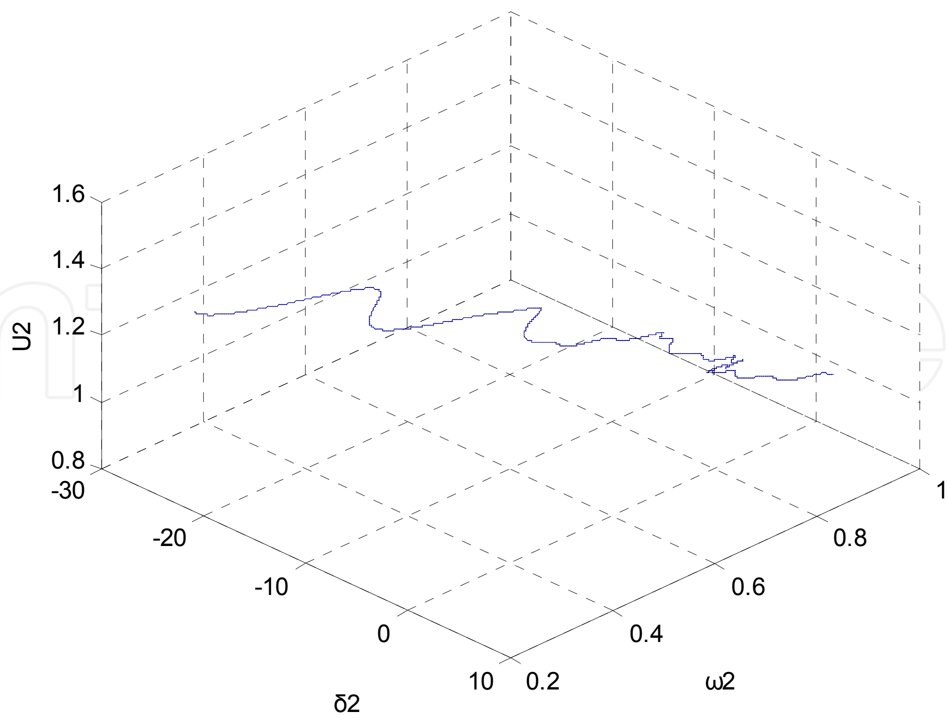


Fig. 6. Phase diagram of No.2 diesel-generator set when two sets increase periodicity load meanwhile load 25% on parallel connection

From Fig.5 and Fig.6 we can see, all maximum Lyapunov indexes of the system are greater than 0, showing that the system exists chaotic phenomenon. The oscillation of power angle and speed in two diesel-generator sets is severer than the state of not increasing periodicity load. Because the periodicity load is nonlinear, increasing periodicity load intensifies the nonlinearity of system, thus aggravating the power oscillation of system[4-6].

The computer simulation results show that it exists chaotic oscillation phenomenon when two diesel-generator sets run on parallel connection with light load. Primary cause of emerging this phenomenon is the nonlinearity of ship power system, minor cause is the power transmission between the two diesel-generator sets. Besides this, using conventional linear controller is also a key factor of generating the chaotic oscillation of system. Only using nonlinear controller, making the nonlinear characteristic of ship power system offset and compensate, can we solve the problem of system chaotic oscillation fundamentally. The chaotic oscillation phenomenon is transition state between stable state and unstable state, it must be prevented in order to ensure the stability of system.

4. Design of nonlinear robust synthetic controller

Mixed H-two/H-infinity control theory is a robust control theory that has speed development from the eighties of 20 century, which can solve the problem of robust stability and robust performance[7-10]. Because diesel-generator set control system is a nonlinear control system, using the method of direct feedback linearization to linearize the nonlinear system, the state feedback controller is designed for linearization system using mixed H-two/H-infinity control theory, thus acquiring nonlinear robust control law in order to reach the purpose of restraining the chaotic phenomenon of ship power system, improving the stability of ship power system.

Because of coupling action between speed and voltage, the nonlinear robust synthetic controller is designed for diesel-generator set in order to control speed and voltage synthetically, making the both interaction in minimum range, thus improving the stability of frequency and voltage in ship power system.

The principle diagram of diesel-generator set synthetic control system based on nonlinear robust synthetic controller is shown in Fig.7. The diesel-generator set synthetic control system is made up of diesel engine, generator, nonlinear robust synthetic controller, actuator, oil feeding mechanism and exciter. Nonlinear robust synthetic controller is made up of two parts, one is nonlinear H-two/H-infinity speed controller, another is nonlinear H-two/H-infinity voltage controller.

The differential equation of actuator is

$$\frac{\mathbf{d}L}{\mathbf{dt}} = -\frac{L}{T_1} + \frac{K_1}{T_1}u_1 \tag{17}$$

The differential equation of exciter is

$$\frac{\mathbf{d}E_{fd}}{\mathbf{dt}} = -\frac{E_{fd}}{T_2} + \frac{K_2}{T_2}u_2 \tag{18}$$

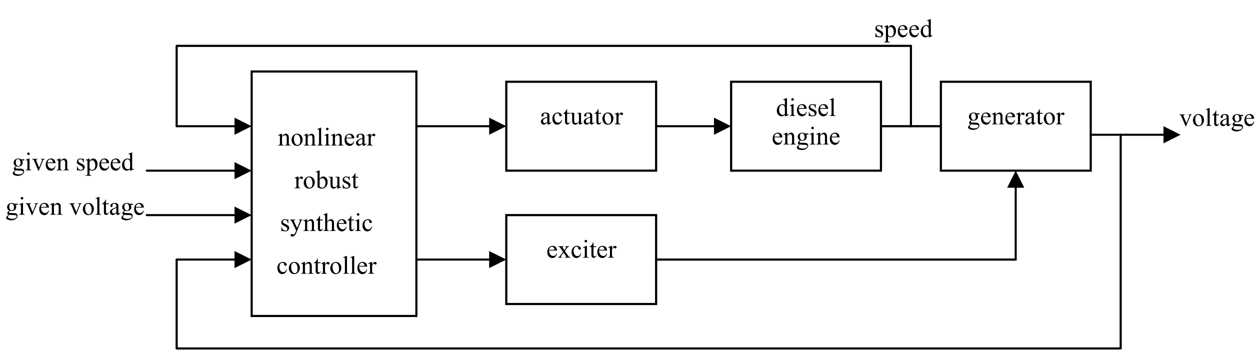


Fig. 7. Principle diagram of diesel-generator set synthetic control system

First step, we design nonlinear H-two/H-infinity speed controller.

Combining Eq.(1) with Eq.(17), we can get the nonliear mathemaical model of diesel engine speed regulation system.

$$\begin{cases} \dfrac{\mathbf{d}\delta}{\mathbf{d}t} = \omega - 1, \\ \dfrac{\mathbf{d}\omega}{\mathbf{d}t} = \dfrac{T_b}{T_a\omega_0}\omega + \dfrac{1}{T_a\omega_0}c_1 + \dfrac{c_2}{T_a\omega_0}L - \dfrac{1}{T_a\omega_0}\dfrac{E'_qU}{X'_d}\sin\delta - \dfrac{1}{T_a\omega_0}\dfrac{U^2}{2}\dfrac{X'_d - X_q}{X'_dX_q}\sin 2\delta, \\ \dfrac{\mathbf{d}L}{\mathbf{dt}} = -\dfrac{L}{T_1} + \dfrac{K_1}{T_1}u_1 \end{cases} \tag{19}$$

Since Eq.(19) has nonlinear feature, the method of direct feedback linearization is used to linearize Eq.(19). Order $x_1 = \delta$, $x_2 = \omega - 1$,

$x_3 = \frac{T_b}{T_a\omega_0}\omega + \frac{1}{T_a\omega_0}c_1 + \frac{c_2}{T_a\omega_0}L - \frac{1}{T_a\omega_0}\frac{E'_qU}{X'_d}\sin\delta - \frac{1}{T_a\omega_0}\frac{U^2}{2}\frac{X'_d - X_q}{X'_dX_q}\sin 2\delta$, so Eq.(19) can be written as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + d_1 w \\ \dot{x}_3 = \dfrac{T_b}{T_a\omega_0}x_3 + \dfrac{c_2K_1}{T_aT_1\omega_0}u_1 - \dfrac{c_2}{T_aT_1\omega_0}L - \dfrac{E'_qU}{T_aX'_d\omega_0}\cos\delta(\omega-1) - \dfrac{U^2(X'_d - X_q)}{T_aX'_dX_q\omega_0}\cos2\delta(\omega-1) \end{cases} \tag{20}$$

In the equation: d_1w is the undesired signal which is assumed for using H-two/H-infinity control method, including equivalence disturbance which is generated by disturbance torque and modeling error.

Assigning virtual controlled variable

$$v = \frac{c_2K_1}{T_aT_1\omega_0}u_1 - \frac{c_2}{T_aT_1\omega_0}L - \frac{E'_qU}{T_aX'_d\omega_0}\cos\delta(\omega-1) - \frac{U^2(X'_d - X_q)}{T_aX'_dX_q\omega_0}\cos2\delta(\omega-1) \tag{21}$$

So Eq.(20) can be changed as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + d_1 w \\ \dot{x}_3 = \dfrac{T_b}{T_a\omega_0}x_3 + v \end{cases} \tag{22}$$

Eq.(22) can be written as matrix form

$$\dot{x} = Ax + B_1w + B_2v \tag{23}$$

In the equation: $x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$, $A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & \dfrac{T_b}{T_a\omega_0} \end{bmatrix}$, $B_1 = \begin{bmatrix} 0 \\ d_1 \\ 0 \end{bmatrix}$, $B_2 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$.

Defining the evaluation signal of dynamic performance as

$$\begin{cases} z_\infty = C_1x + D_{11}w + D_{12}v \\ z_2 = C_2x + D_{21}w + D_{22}v \end{cases} \tag{24}$$

In the equation: $C_1 = \begin{bmatrix} q_{11} & 0 & 0 \\ 0 & q_{12} & 0 \\ 0 & 0 & q_{13} \end{bmatrix}$, $C_2 = \begin{bmatrix} q_{21} & 0 & 0 \\ 0 & q_{22} & 0 \\ 0 & 0 & q_{23} \end{bmatrix}$, $D_{11} = D_{21} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$, $D_{12} = \begin{bmatrix} 0 \\ 0 \\ r_1 \end{bmatrix}$,

$D_{22}=\begin{bmatrix}0\\0\\r_2\end{bmatrix}$, C_1, C_2, D_{11}, D_{12}, D_{21}, D_{22} are weighting matrix, $q_{ij}>0(i=1,2;\ j=1,2,3)$and $r_i>0$ $(i=1,2)$ weighting coefficient. We can select optimal performance combination through changing weighting coefficient, including stability of ship power system, frequency regulation precision and low energy loss of speed regulation system.

For the control system made up of Eq.(23) and Eq.(24), requring design a controller F, making the closed loop system asymptotically stable, moreover H-infinity norm of closed loop transfer function $T_\infty(s)$ from w to z_∞ not more than a given upper bound, in order to ensure the closed loop system have robust stability to uncertainty enter from w; meanwhile making H-2 norm of closed loop transfer function $T_2(s)$ from w to z_2 as small as possible, so as to assure the system performance measured by H-2 norm in a good level, this control problem is called H-two/H-infinity control problem.

From Eq.(23) and Eq.(24), we can get the augmentation controlled object based on mixed H-two/H-infinity control theory

$$P=\left[\begin{array}{c|cc}A & B_1 & B_2\\\hline C_1 & D_{11} & D_{12}\\C_2 & D_{21} & D_{22}\end{array}\right] \tag{25}$$

controller F can be solved by corresponding augmentation controlled object P.
For controlled object P, existing H-two/H-infinity state feedback controller:

$$v=Fx=[f_1\quad f_2\quad f_3]\cdot\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}=f_1x_1+f_2x_2+f_3x_3 \tag{26}$$

In the equation: F is feedback coefficient, which can be got by using μ-Analysis and Synthesis Toolbox in the MATLAB.

Combining Eq.(21) with Eq.(26), we get

$$u_1=\frac{1}{K_1}L+\frac{T_aT_1\omega_0}{c_2K_1}Fx+\frac{E_q'UT_1}{c_2K_1X_d'}\cos\delta(\omega-1)+\frac{U^2T_1(X_d'-X_q)}{c_2K_1X_d'X_q}\cos2\delta(\omega-1) \tag{27}$$

That is nonlinear H-two/H-infinity speed control law of diesel-generator set. Substituting x_1, x_2, x_3 into Eq.(27), we can get practical form of nonlinear H-two/H-infinity speed control law:

$$\begin{aligned}u_1=&\frac{1}{K_1}L+\frac{T_aT_1\omega_0}{c_2K_1}f_1\delta+\frac{T_aT_1\omega_0}{c_2K_1}f_2(\omega-1)+\frac{T_bT_1}{c_2K_1}f_3\omega+\frac{T_1}{c_2K_1}f_3c_1+\frac{T_1}{K_1}f_3L-\frac{T_1}{c_2K_1}\frac{E_q'U}{X_d'}f_3\sin\delta-\\&\frac{T_1}{c_2K_1}\frac{U^2}{2}\frac{X_d'-X_q}{X_d'X_q}f_3\sin2\delta+\frac{E_q'UT_1}{c_2K_1X_d'}\cos\delta(\omega-1)+\frac{U^2T_1(X_d'-X_q)}{c_2K_1X_d'X_q}\cos2\delta(\omega-1)\end{aligned} \tag{28}$$

Second step, we design nonlinear H-two/H-infinity voltage controller.

Combining Eq.(1), Eq.(4) with Eq.(18), we can get the nonliear mathemaical model of synchronous generator voltage regulation system.

$$\begin{cases} \frac{\mathbf{d}E_{fd}}{\mathbf{dt}} = -\frac{E_{fd}}{T_2} + \frac{K_2}{T_2}u_2 \\ \frac{\mathbf{d}U}{\mathbf{d}t} = \frac{1}{T_{d0}}E_{fd} - \frac{1}{T_{d0}}U - \frac{c_3}{T_{d0}}\delta - c_3\omega - \frac{X_d - X_d'}{T_{d0}}I_d + c_3 \\ \frac{\mathbf{d}\delta}{\mathbf{d}t} = \omega - 1 \\ \frac{\mathbf{d}\omega}{\mathbf{d}t} = \frac{T_b}{T_a\omega_0}\omega + \frac{1}{T_a\omega_0}c_1 + \frac{c_2}{T_a\omega_0}L - \frac{1}{T_a\omega_0}\frac{E_q'U}{X_d'}\sin\delta - \frac{1}{T_a\omega_0}\frac{U^2}{2}\frac{X_d' - X_q}{X_d'X_q}\sin 2\delta \end{cases} \tag{29}$$

We select the error of voltage ΔU as state varible, The relation between U and ΔU is

$$\Delta U = U - U_0 \tag{30}$$

In the equation: U_0 is initial value of stator winding terminal voltage, its value is 1.

We use P_e repalce $\frac{E_q'U}{X_d'}\sin\delta + \frac{U^2}{2}\frac{X_d' - X_q}{X_d'X_q}\sin 2\delta$, regarding P_e as external disturbance, substituting Eq.(30) into Eq.(29), we get

$$\begin{cases} \frac{\mathbf{d}E_{fd}}{\mathbf{dt}} = -\frac{E_{fd}}{T_2} + \frac{K_2}{T_2}u_2 \\ \frac{\mathbf{d}\Delta U}{\mathbf{d}t} = \frac{1}{T_{d0}}E_{fd} - \frac{1}{T_{d0}}\Delta U - \frac{c_3}{T_{d0}}\delta - c_3\omega + (c_3 - \frac{1}{T_{d0}}) - \frac{X_d - X_d'}{T_{d0}}I_d \\ \frac{\mathbf{d}\delta}{\mathbf{d}t} = \omega - 1 \\ \frac{\mathbf{d}\omega}{\mathbf{d}t} = \frac{T_b}{T_a\omega_0}\omega + \frac{1}{T_a\omega_0}c_1 + \frac{c_2}{T_a\omega_0}L - \frac{1}{T_a\omega_0}P_e \end{cases} \tag{31}$$

Eq.(31) can be written as matrix form

$$\dot{x}' = A'x' + B_1'w' + B_2'u_2 \tag{32}$$

In the equation: $x' = \begin{bmatrix} E_{fd} \\ \Delta U \\ \delta \\ \omega \end{bmatrix}$, $A' = \begin{bmatrix} -\frac{1}{T_2} & 0 & 0 & 0 \\ \frac{1}{T_{d0}} & -\frac{1}{T_{d0}} & -\frac{c_3}{T_{d0}} & -c_3 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & \frac{T_b}{T_a\omega_0} \end{bmatrix}$,

$$B_1' = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\dfrac{X_d - X_d'}{T_{d0}} & 0 & 0 & c_3 - \dfrac{1}{T_{d0}} \\ 0 & 0 & 0 & -1 \\ 0 & \dfrac{c_2}{T_a\omega_0} & -\dfrac{1}{T_a\omega_0} & \dfrac{c_1}{T_a\omega_0} \end{bmatrix},\ B_2' = \begin{bmatrix} \dfrac{K_2}{T_2} \\ 0 \\ 0 \\ 0 \end{bmatrix},\ w' = \begin{bmatrix} I_d \\ L \\ P_e \\ 1 \end{bmatrix}.$$

Defining the evaluation signal of dynamic performance as

$$\begin{cases} z_\infty' = C_1'x' + D_{11}'w' + D_{12}'u_2 \\ z_2' = C_2'x' + D_{21}'w' + D_{22}'u_2 \end{cases} \tag{33}$$

In the equation: $C_1' = \begin{bmatrix} q_{14} & 0 & 0 & 0 \\ 0 & q_{15} & 0 & 0 \\ 0 & 0 & q_{16} & 0 \\ 0 & 0 & 0 & q_{17} \end{bmatrix}$, $C_2' = \begin{bmatrix} q_{24} & 0 & 0 & 0 \\ 0 & q_{25} & 0 & 0 \\ 0 & 0 & q_{26} & 0 \\ 0 & 0 & 0 & q_{27} \end{bmatrix}$, $D_{12}' = \begin{bmatrix} r_3 \\ r_4 \\ r_5 \\ r_6 \end{bmatrix}$, $D_{22}' = \begin{bmatrix} r_7 \\ r_8 \\ r_9 \\ r_{10} \end{bmatrix}$,

$D_{11}' = D_{21}' = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$, C_1', C_2', D_{11}', D_{12}', D_{21}', D_{22}' are weighting matrix, q_{ij} >0(i=1,2; j=4-7)and r_i >0(i=3-10)weighting coefficient. We can select optimal performance combination through changing weighting coefficient, including stability of ship power system, voltage regulation precision and low energy loss of excitation system.

From Eq.(32) and Eq.(33), we can get the augmentation controlled object based on mixed H-two/H-infinity control theory

$$P' = \left[\begin{array}{c|cc} A' & B_1' & B_2' \\ \hline C_1' & D_{11}' & D_{12}' \\ C_2' & D_{21}' & D_{22}' \end{array}\right] \tag{34}$$

For controlled object P', existing H-two/H-infinity state feedback controller:

$$u_2 = F'x' = [f_1'\ \ f_2'\ \ f_3'\ \ f_4'] \cdot \begin{bmatrix} E_{fd} \\ \Delta U \\ \delta \\ \omega \end{bmatrix} = f_1'E_{fd} + f_2'\Delta U + f_3'\delta + f_4'\omega \tag{35}$$

That is nonlinear H-two/H-infinity voltage control law of diesel-generator set.

Third step, we design nonlinear robust synthetic controller.

Combining Eq.(28) with Eq.(35), we can get nonlinear robust synthetic controller of diesel-generator set[11-18]

$$\begin{cases} u_1 = \frac{1}{K_1}L + \frac{T_aT_1\omega_0}{c_2K_1}f_1\delta + \frac{T_aT_1\omega_0}{c_2K_1}f_2(\omega-1) + \frac{T_bT_1}{c_2K_1}f_3\omega + \frac{T_1}{c_2K_1}f_3c_1 + \frac{T_1}{K_1}f_3L - \frac{T_1}{c_2K_1}\frac{E'_qU}{X'_d}f_3\sin\delta - \\ \frac{T_1}{c_2K_1}\frac{U^2}{2}\frac{X'_d-X_q}{X'_dX_q}f_3\sin 2\delta + \frac{E'_qUT_1}{c_2K_1X'_d}\cos\delta(\omega-1) + \frac{U^2T_1(X'_d-X_q)}{c_2K_1X'_dX_q}\cos 2\delta(\omega-1) \\ u_2 = f'_1E_{fd} + f'_2\Delta U + f'_3\delta + f'_4\omega \end{cases} \quad (36)$$

Eq.(36) considers the coupling function of speed and voltage, which controls both synthetically. It can increase dynamic precision of speed and voltage, improving the stability of ship power system.

5. Results of computer simulation

The key parameters of diesel-generator set control system in this paper are as follow:

The power of diesel-generator set is 1250kW; the rated speed n =1500r/min; the rotary inertia of set J=71.822kg·m²; the damping coefficient of set D =5.54;the magnetic pole pair number of generator p=2; the rated torque of diesel engine 11.9kN·m; the maximum troke of output axis 10mm.

The rated voltage of synchronous generator is 390V; the rated current 2310A; the power factor 0.8; the rated frequency 50Hz; the exciting voltage of exciter 83V; the exciting current 7.7A.

Designing nonlinear synthetic controller based on mixed H-two/H-infinity control theory, assuming disturbance signal coefficient of Eq.(23) d_1 =0.1, assuming weighting coefficient of Eq.(24) q_{11} =0.002, q_{12} =0.4, q_{13} =0.5, r_1 =0.01, q_{21} =0.002, q_{22} =0.4, q_{23} =0.5, r_2 =0.01.

Corresponding matrix are

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -0.0014 \end{bmatrix}, B_1 = \begin{bmatrix} 0 \\ 0.1 \\ 0 \end{bmatrix}, C_1 = C_2 = \begin{bmatrix} 0.002 & 0 & 0 \\ 0 & 0.4 & 0 \\ 0 & 0 & 0.5 \end{bmatrix}, D_{12} = D_{22} = \begin{bmatrix} 0 \\ 0 \\ 0.01 \end{bmatrix}.$$

Using LMI toolbox, we get state feedback controller:

$$F = [-0.3582 \quad -35.1042 \quad -157.7578] \quad (37)$$

Assuming weighting coefficient of Eq.(33) q_{14} =0.1, q_{15} =2800, q_{16} =0.1, q_{17} =0.1, q_{24} =0.1, q_{25} =2800, q_{26} =0.1, q_{27} =0.1, $r_3 = r_4 = r_5 = r_6$ =1, $r_7 = r_8 = r_9 = r_{10}$ =1.

Corresponding matrix are

$$A' = \begin{bmatrix} -0.4545 & 0 & 0 & 0 \\ 0.0011 & -0.0011 & -0.0002 & -0.2043 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -0.0014 \end{bmatrix}, \; B'_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -0.0021 & 0 & 0 & 0.2032 \\ 0 & 0 & 0 & -1 \\ 0 & -0.0004 & -0.0028 & 0.0042 \end{bmatrix},$$

$$C_1' = C_2' = \begin{bmatrix} 0.1 & 0 & 0 & 0 \\ 0 & 2800 & 0 & 0 \\ 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.1 \end{bmatrix}, D_{12}' = D_{22}' = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}.$$

Using LMI toolbox, we get state feedback controller:

$$F' = [-0.027 \quad -697.798 \quad -0.023 \quad -0.025] \tag{38}$$

Substituting Eq.(37) and Eq.(38) into Eq.(36), we get nonlinear robust synthetic controller of diesel-generator set.

Optimization of weighting function is difficult point of H-two/H-infinity control, needing select repeatedly. After each selection, using LMI toolbox to get state feedback coefficient, substituting simulation model, making charactrsitc test in order to get best combination property index. Fig.8 give the block diagram of the system simulation.

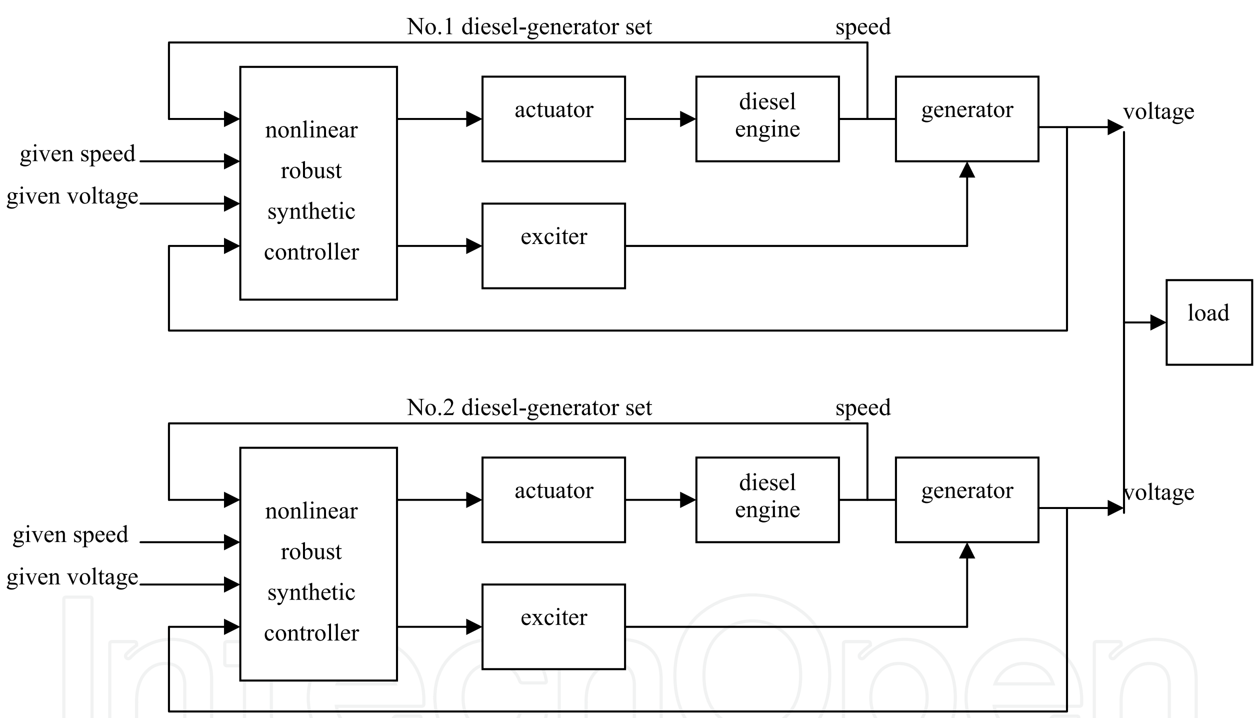


Fig. 8. Block diagram of the system simulation

In order to test and verify the effect of nonlinear robust synthetic controller for restraining the chaotic oscillation of ship power system, Fig.9 and Fig.10 give the phase diagram of power angle, speed and voltage of two diesel-generator sets on parallel running with 12.5% load separately after using nonlinear robust synthetic controller. The initial va1ues of two sets are same as that of generating chaotic oscillation, the running time is also 100 seconds. Calculating the Lyapunov index of two diesel-generator sets on parallel operation, we get the following results. Lyapunov index of No.1 diesel-generator set is: $\lambda_1 = -0.003435$, $\lambda_2 = -0.104389$, $\lambda_3 = -0.230524$; Lyapunov index of No.2 diesel-generator set is: $\lambda_1 = -0.003442$, $\lambda_2 = -0.104382$, $\lambda_3 = -0.230524$.

Fig.11 and Fig.12 give the phase diagram of power angle, speed and voltage of two diesel-generator sets on parallel running with 25% load separately after using nonlinear robust synthetic controller. The initial va1ues of two sets are same as that of generating chaotic oscillation, the running time is also 100 seconds. Calculating the Lyapunov index of two diesel-generator sets on parallel operation, we get the following results. Lyapunov index of No.1 diesel-generator set is: $\lambda_1 = -0.003983$, $\lambda_2 = -0.103822$, $\lambda_3 = -0.230553$; Lyapunov index of No.2 diesel-generator set is: $\lambda_1 = -0.003993$, $\lambda_2 = -0.103811$, $\lambda_3 = -0.230554$.

Fig.13 and Fig.14 give the phase diagram of power angle, speed and voltage of two diesel-generator sets on parallel running with 25% load plus periodicity load separately after using nonlinear robust synthetic controller. The initial va1ues of two sets are same as that of generating chaotic oscillation, the running time is also 100 seconds. Calculating the Lyapunov index of two diesel-generator sets on parallel operation, we get the following results. Lyapunov index of No.1 diesel-generator set is: $\lambda_1 = -0.004331$, $\lambda_2 = -0.103293$, $\lambda_3 = -0.230741$; Lyapunov index of No.2 diesel-generator set is: $\lambda_1 = -0.004341$, $\lambda_2 = -0.103283$, $\lambda_3 = -0.230742$.

From Fig.9 to Fig.12 we can see, all maximum Lyapunov indexes of the system are less than 0, showing that the system doesn't exists chaotic phenomenon and works in a stable range. Two diesel-generator sets with light load on parallel connection, run after using nonlinear robust synthetic controller, their chaotic phenomenon disappears, power angle, speed and voltage run nearby the desired values. It shows that nonlinear robust synthetic controller can control the nonlinear character of ship power system effectively and make the nonlinear characteristic of ship power system offset and compensate, it can solve the problem of system chaotic oscillation fundamentally.

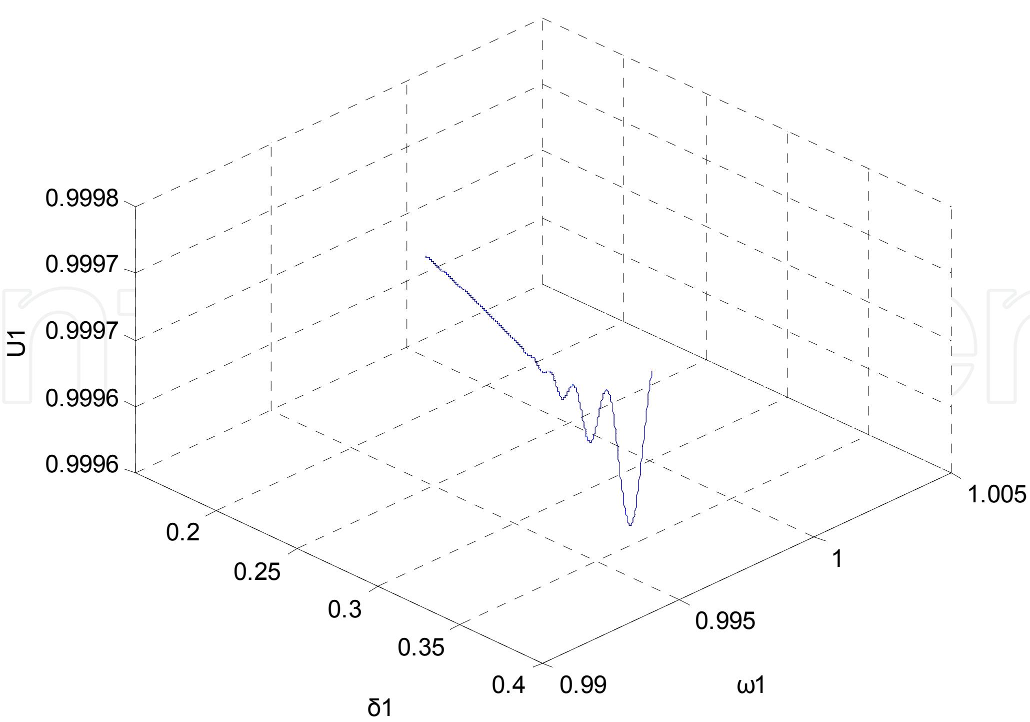


Fig. 9. Phase diagram of No.1 diesel-generator set when two sets load 12.5% on parallel connection after using nonlinear robust synthetic controller

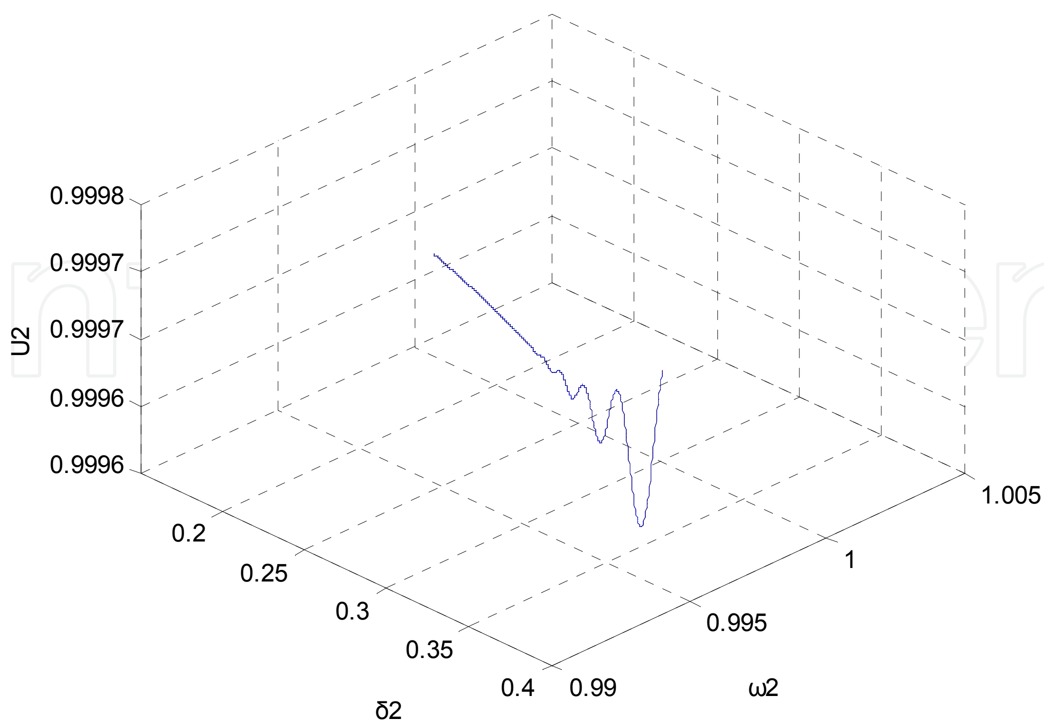


Fig. 10. Phase diagram of No.2 diesel-generator set when two sets load 12.5% on parallel connection after using nonlinear robust synthetic controller

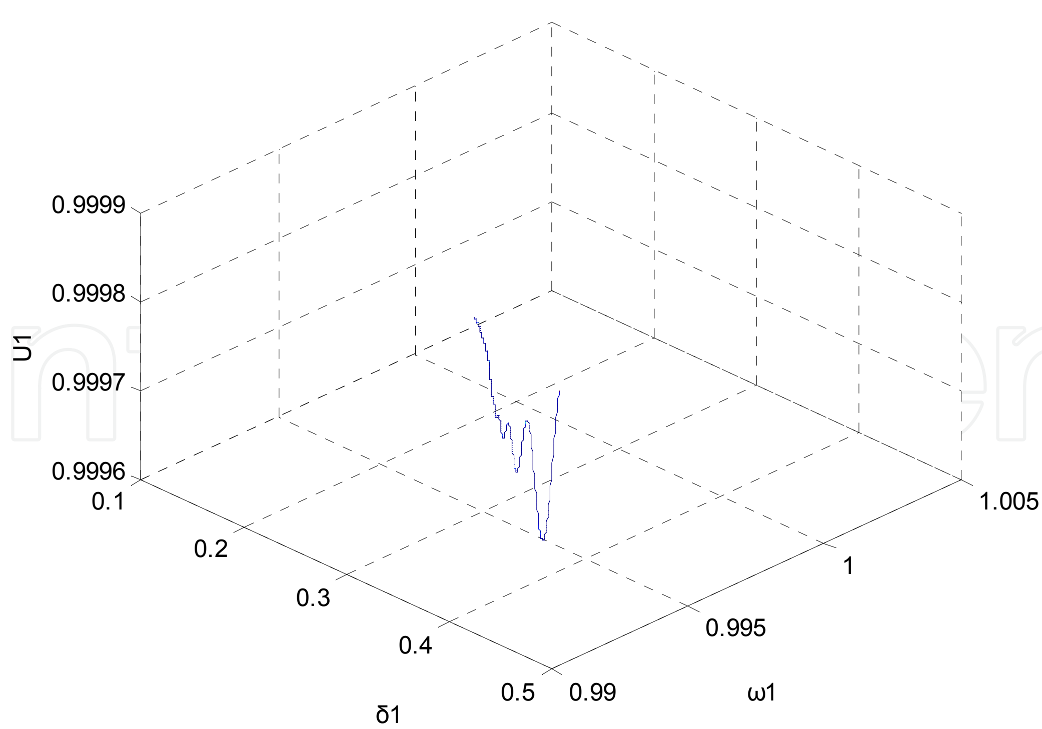


Fig. 11. Phase diagram of No.1 diesel-generator set when two sets load 25% on parallel connection after using nonlinear robust synthetic controller

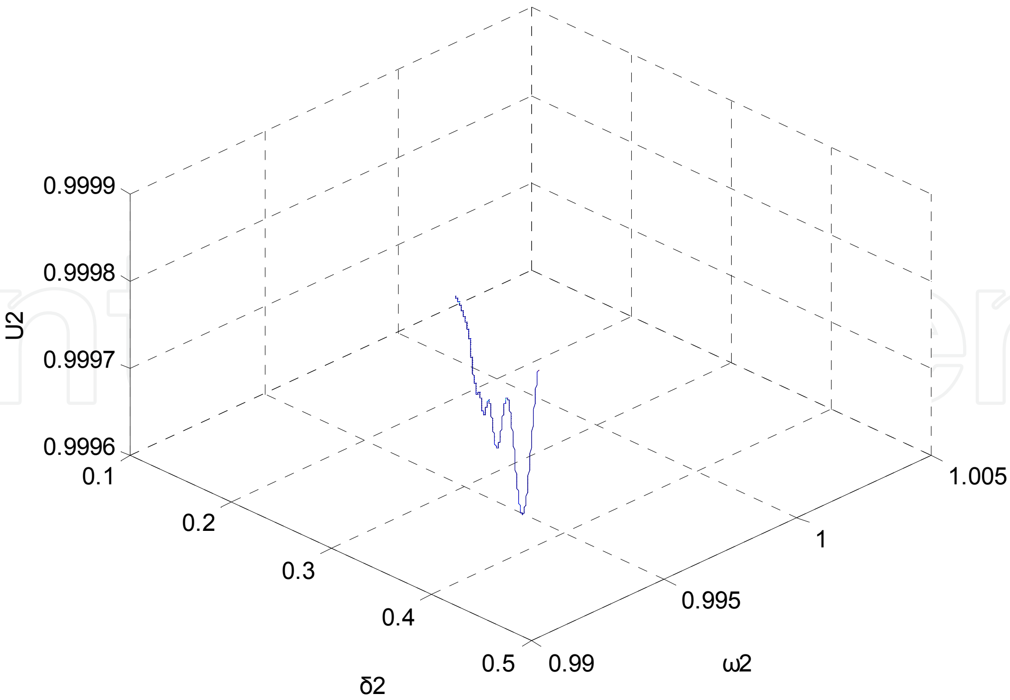


Fig. 12. Phase diagram of No.2 diesel-generator set when two sets load 25% on parallel connection after using nonlinear robust synthetic controller

From Fig.13 to Fig.14 we can see, all maximum Lyapunov indexes of the system are also less than 0, showing that the system also doesn't exists chaotic phenomenon and works in a stable range. Although after adding periodicity load intensifying the nonlinearity of system, nonlinear robust synthetic controller can restrain the chaotic phenomenon of ship power

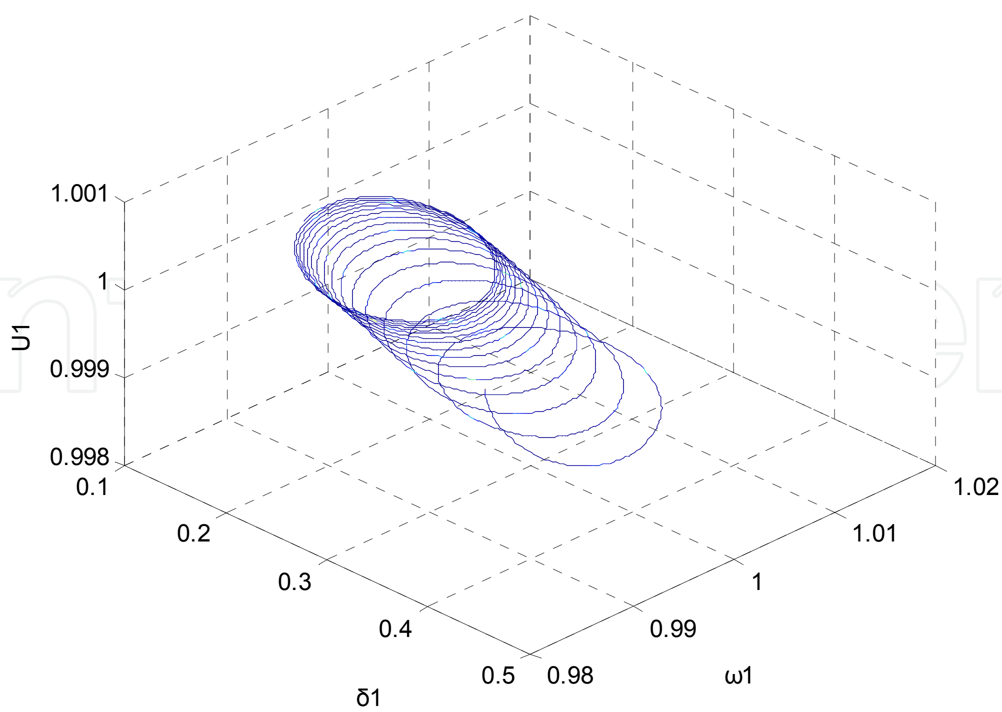


Fig. 13. Phase diagram of No.1 diesel-generator set when two sets load 25% plus periodicity load on parallel connection after using nonlinear robust synthetic controller

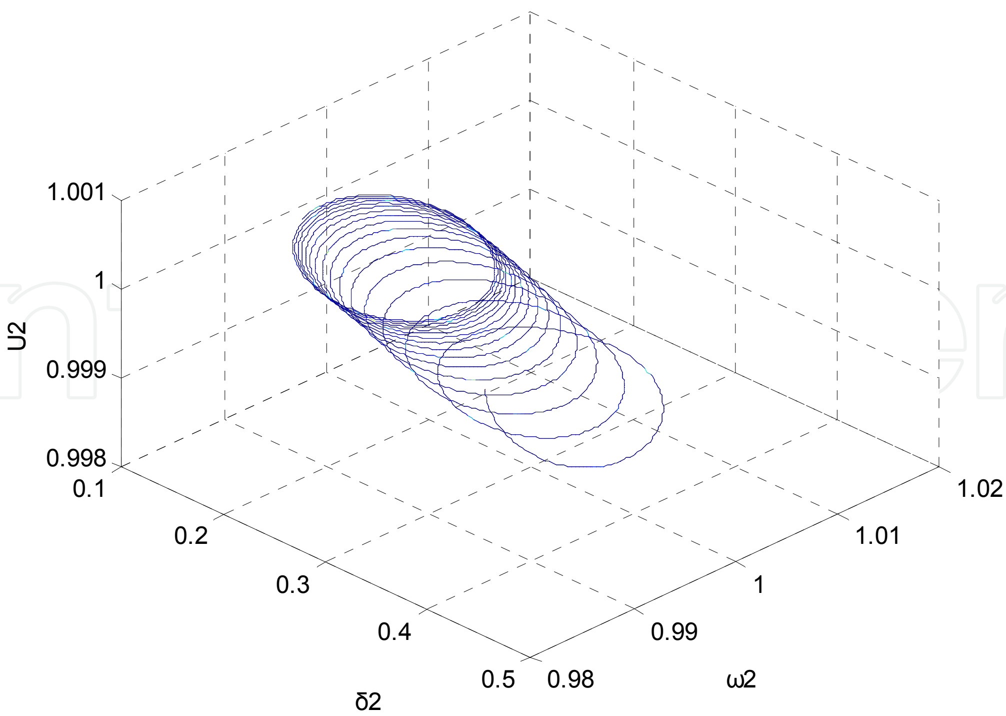


Fig. 14. Phase diagram of No.2 diesel-generator set when two sets load 25% plus periodicity load on parallel connection after using nonlinear robust synthetic controller

system, making the nonlinear characteristic of ship power system offset and compensate, thus improving the stability of ship power system.

Because ship power system made up of diesel-generator sets is a nonlinear system, using nonlinear robust synthetic controller can offset and compensate the nonlinear characteristic of ship power system, it can average the load in parallel operation control, there is no power angular difference between the diesel-generator sets, thus avoiding the power transmission between the sets, solving the problem of system chaotic oscillation fundamentally, improving the voltage and frequency stability of ship power system. The research on nonlinear robust synthetic controller of diesel-generator set provides a new control method for ship power system, having important practical significance and extensive using prospect.

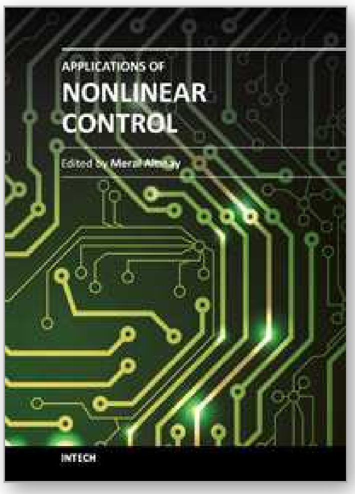
6. Conclusion

In order to analyze the chaos phenomenon of ship power system, the nonlinear mathematical model of two diesel-generator sets on parallel connection is built in this paper, which reflects the relationship of interaction and mutual influence between two sets. The light load working condition of two diesel-generator sets on parallel connection in ship power station is analyzed by using Lyapunov index method, which proves the presence of chaos phenomenon. A nonlinear robust synthetic controller is designed which is based on the nonlinear mathematical model of diesel-generator set. In combining the direct feedback linearization with robust control theory to design the synthetic controller for the diesel-generator set, then a nonlinear robust synthetic control law is developed for the diesel-generator set. The computer simulation results show that the nonlinear robust synthetic controller effectively suppresses the chaos phenomenon of ship power system, thus providing desirable stability for ship power system.

7. References

[1] Huang Manlei, Tang Jiaheng, Guo Zhenming · The Mathematical Model of Diesel Engine Speed Regulation System[J] · Journal of Harbin Engineering University, 1997, 18(6):20~25
[2] Huang Manlei, Li Dianpu, Liu Hongda · Simulation Research on Double-pulse Speed Governor of Diesel Engine[J] · SHIP ENGINEERING, 2002, 24(3):36~38
[3] Huang Manlei, Wang Changhong · Nonlinear mathematical model of diesel-generator set on ship[J] · Journal of Harbin Engineering University, 2006, 27(1):15-19, 47.
[4] Yang Zhengling, Lin Kongyuan · Study on the relation between classical swing equations and chaos[J] · Automation of Electric Power Systems, 2000, 24(7):20~22,45
[5] Jia Hongjie,Yu Yixin,Wang Chengshan · Chaotic phenomena in power systems and its studies [J] · Proceedings of the CSEE, 2001, 21(7):26~30
[6] Wang Baohua, Yang Chengwu, Zhang Qiang. Summary of bifurcation and chaos research in electric power system[J] · Transactions of China Electrotechnical Society, 2005, 20(7):1~10
[7] Bernstein D S, Hadded W M · LQG control with an H_∞ performance bound: A Riccati equation approach · IEEE Trans on Automatic Control, 1989, 34(3):293-305
[8] Zhou K, Glover K, Bodenheimer B, et al · Mixed H_2 and H_∞ performance objectives I: Robust performance analysis · IEEE Trans on Automatic Control, 1994, 39(8):1564-1574
[9] Doyle J, Zhou K, Glover K, et al · Mixed H_2 and H_∞ performance objectives II: Optimal Control · IEEE Trans on Automatic Control, 1994, 39(8):1575-1587
[10] Khargonekar P P, Rotea M A · Mixed H_2/H_∞ control: A convex optimization approach · IEEE Trans on Automatic Control, 1991, 36(7):824-837
[11] Sun Yu-song, Sun Yuan-zhang, Lu Qiang, Shao Yi-xiang · Research on Nonlinear Robust Control Strategy for Hydroelectric Generator's Valve[J] · Proceedings of the CSEE, 2001,21(2):56-59,65
[12] Li Wen-lei, Jing Yuan-wei, Liu Xiao-ping · Nonlinear robust control for turbine main steam valve[J] · Control Theory and Applications, 2003,20(3):387-390
[13] Wang Jin-hua · Design of mixed H_2/H_∞ controller[J] · Control Theory and Applications, 2004,21(1):45-53
[14] Robert Lashlee, Vittal Rao and Frank Kern · Mixed H_2 and H_∞ Optimal Control of Smart Structures · Proceedings of the 33th conference on decision and control, Lake Buena Vista, FL, December 1994:115-120
[15] Curtis P. Mracek and D. Brett Ridgely · Normal Acceleration Command Following of the *F*-16 Using Optimal Control Methodologies: A Comparison
[16] Kap Rai Lee, Do Chang Oh, Kyeong Ho Bang and Hong Bae Park · Mixed H_2/H_∞ Control for Underwater Vehicle with Time Delay and Parameter Uncertainty · Proceedings of the American Control Conference, Albuquerque, New Mexico, June 1997:3225-3229

[17] Kap Rai Lee, Do Chang Oh, Kyeong Ho Bang and Hong Bae Park · Mixed H_2/H_∞ Control with Regional Pole Placement for Underwater Vehicle Systems · Proceedings of the American Control Conference, Chicago, Illinois, June 2000:80-84
[18] Feng Wu, Keat-Choon Goh and Steve Walsh · Robust H_2 Performance Analysis for A High-Purity Distillation Column · Computers Chem. Energy, 1997, 21:8161-8166



Applications of Nonlinear Control
Edited by Dr. Meral Altınay

ISBN 978-953-51-0656-2
Hard cover, 202 pages
Publisher InTech
Published online 13, June, 2012
Published in print edition June, 2012

A trend of inverstigation of Nonlinear Control Systems has been present over the last few decades. As a result the methods for its analysis and design have improved rapidly. This book includes nonlinear design topics such as Feedback Linearization, Lyapunov Based Control, Adaptive Control, Optimal Control and Robust Control. All chapters discuss different applications that are basically independent of each other. The book will provide the reader with information on modern control techniques and results which cover a very wide application area. Each chapter attempts to demonstrate how one would apply these techniques to real-world systems through both simulations and experimental settings.

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821