Optimization Control of Power Supply for Ion Propulsion System in Multi-operating Points Mode

Yuan Jiang[1], Liying Zhu[2(✉)], Zhan Lei[1], Hong Du[2], and Dong Yang[2]

[1] School of Automation and Electrical Engineering, University of Science and Technology Beijing, Beijing 100083, China
[2] Beijing Institute of Spacecraft System Engineering, Beijing 100194, China
350909269@qq.com

Abstract. Space probe is one of the important areas for commercial space industry. In order to make the ion propulsion system have good control performance under the regulation of wide voltage and wide power, a nonlinear controller with adjustable multi-operating points is designed based on the synergetic approach to control (SAC) theory. The duty cycle of DC/DC converter can be calculated by combining the state space equation of DC/DC converter and the evolution law of manifold. In order to ensure that the overshoot of inductor current is small and the response speed is fast when the operating point is switched, according to the convergence characteristics of manifold, the adaptive control parameter is designed based on capacitor voltage error. According to the simulation results, the steady-state error of bus voltage under SAC control is 3.3%, which is less than 6% of PI control. For the transient process of switching, the overshoot of capacitor voltage and inductor current under PI control are close to 30%, much larger than that under SAC control, and the duty cycle under PI control also shows a large oscillation. SAC control has advantages over PI control in terms of steady-state performance, dynamic performance and duty cycle control.

Keywords: Space probe · ion propulsion system · power electronics · Nonlinear control

Commercial spaceflight is now the main battleground in the competition among space powers. Deep space exploration technology is an important field of commercial space industry. In the future, it can be relied on to realize space travel, space mining, space base construction and so on. Ion electric propulsion has the advantages of high efficiency and high specific impulse, so it has become the first choice for deep space exploration spacecraft [1, 2]. For example, The America's "Deep Space One" probe launched in October 1998 is the first deep space probe with electric propulsion as its main propulsion, the ion electric propulsion system completed the main propulsion task in the cruise stage. Launched in May 2003, Japan's Hayabusa probe, the ion electric propulsion system undertook the main task of cruise phase propulsion. The Dawn probe, launched in September 2007, used the ion electric propulsion system to complete the exploration mission in a real sense. It used the solar ion electric propulsion system to realize the rendezvous and orbit exploration of Vesta and Ceres [3–8].

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Ion electric propulsion system uses discharge chamber, discharge cathode, neutralizer and other facilities to achieve ion production, ion acceleration and ion neutralization, and uses ion optical components (grid power supply, acceleration gate power supply) to complete the separation, focus and acceleration of the ions in the discharge chamber, so as to generate thrust. The Power Processing Unit (PPU) is used to convert the spacecraft bus voltage into the electrical power required by each part of the ion electric propeller. Typical power supply structure of ion thruster is shown in Fig. 1. As electrical equipment, ion electric thrusters generally have the characteristics of large power consumption and multiple working modes (wide voltage and wide power range). For example, the PPU of Hayabusa's electric propulsion system has a bus voltage range of 70–120 V. The PPU of Dawn's electric propulsion system bus has a voltage range of 80–120 V and a power range of 600–3000 W [9, 10]. The adjustable multiple operating points put forward higher requirements for the control of spacecraft power system.

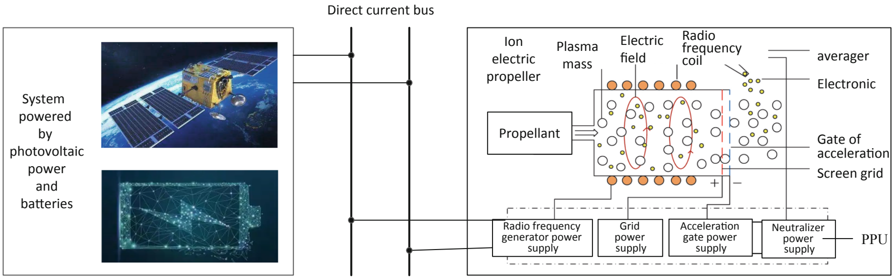

Fig. 1. Power supply structure of ion electric propulsion

According to the requirements of wide range adjustment of ion electric propulsion, the power electronic converter of the spacecraft power supply and distribution unit will show the nonlinear characteristics of discrete and variable structure. Meanwhile, the converter needs to meet the load changes in a wide range and the adjustment process is affected by various disturbances. The above problems make the converter control process and controller design more complicated. Therefore, the linear control method based on the state space average model and the classical cybernetics PI/PID controller are difficult to achieve the expected effect [11, 12]. At present, there are few researches on the control method of spacecraft power supply system with wide voltage and wide power range in China. But in other power systems, some nonlinear control methods, such as theory of differential geometry, robust control, sliding mode variable structure control, adaptive control, cooperative control, etc., are applied to PWM control of power electronic converter. In reference [13], a nonlinear control method based on differential geometry theory and sliding mode was proposed to solve the problems of low accuracy and poor dynamic performance of the compensated current control strategy of active power filter, which realized fast tracking of the command current and accurate control of the output current. In reference [14], aiming at the robustness of grid-connected resonant inverters caused by non-ideal conditions such as weak grid, distortion and imbalance, direct control strategies through feedback robust current with additional unit delay and robust current with suppression of harmonic current were proposed. In reference [15], when the modular multilevel converter is disturbed, PI control and passivity control cannot guarantee the reliability and dynamic performance of the system, so passive sliding mode control which could improve the anti-interference ability and response speed was proposed. In reference [16], an adaptive control strategy that takes into account multiple parameters such as power, frequency and virtual moment of inertia of the virtual synchronous generator was proposed, so that the off-grid switching process has excellent transient characteristics. In reference [17] a method applied the collaborative control theory to DC/DC converter control was proposed, so that the converter output can have a better inhibition effect on the disturbance such as bus voltage and load change.

To sum up, when switching over multiple operating points of ion electric thruster, the power supply is essentially a wide range of output adjustment, so it requires variable structure control of the power converter. In the application of sliding mode variable structure control, chattering and changeful switching frequency are easy to occur [18], which increases the difficulty of design. Therefore, in this paper, the synergetic approach to control (SAC) theory will be used, a variable structure nonlinear control method which can control the spacecraft power system better. The method can directly model and derive the nonlinear control law by using the equation of state, which is especially suitable for the operation mode of wide voltage and wide power regulation.

1 Control Object Mathematical Model

1.1 Deep Space Probe Power Supply Model

The power supply system of the deep space probe generally adopts the mode of combined power supply of photovoltaic cells and batteries, and the DC bus is drawn through the DC/DC converter to supply power to the rear stage load. The control of the power supply system is essentially the control of the DC/DC converter. Therefore, this section only discusses the modeling of the converter. The topology selected is full-bridge DC/DC, and its structure is shown in Fig. 2. In this paper, the following assumptions about the converter will be made. The on-resistance of bridge arm S_1–S_4 and rectifier diode D_1–D_4 is r. The circuit operates in inductance current continuous mode, and the inductance L is linear and unsaturated. Ignoring line impedance.

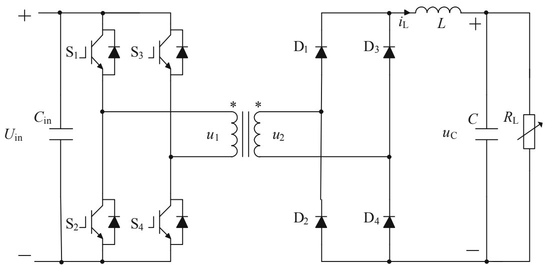

Fig. 2. Model of deep space detector power converter

According to the state of inductance current, the full-bridge converter can be divided into two modes within a full switching cycle. Mode one is that the inductor is in the charged state. At this time, the transformer secondary voltage u_2 is approximately equal to U_{in} (or $-U_{in}$). After the diodes D_1 and D_4 (or D_2 and D_3) are rectified, the inductor L and capacitor C are charged, and the energy of load comes from the transformer primary side. Mode 2 is that the inductor is in a state of follow current, and the transformer secondary voltage u_2 is approximately equal to 0. Diodes D_1 and D_2, D_3 and D_4 are in series and connected into two continuous flow channels. The energy of load comes from inductor L and capacitor C. According to the above physical process, the state space equation with $x_1 = i_L(t)$ and $x_2 = u_C(t)$ as state variables can be constructed as follows:

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}U_{in} \tag{1}$$

Among them, $x(t) = [i_L(t)\ u_C(t)]^T$ is the state vector, $\boldsymbol{A}$ is the system matrix, B is the control matrix, and U_{in} is the input voltage of converter. According to the average model theory, when the duty cycle of S_1–S_4 in a switching period is $d(0 < d < 50\%)$, the following relation can be expressed:

$$\begin{cases} \boldsymbol{A} = \boldsymbol{A}_1 \cdot 2d + \boldsymbol{A}_2 \cdot (1 - 2d) \\ \boldsymbol{B} = \boldsymbol{B}_1 \cdot 2d + \boldsymbol{B}_2 \cdot (1 - 2d) \end{cases} \tag{2}$$

Among them, $\boldsymbol{A_1}$ and $\boldsymbol{B_1}$ are the system matrix and control matrix of mode 1, and $\boldsymbol{A_2}$ and $\boldsymbol{B_2}$ are the system matrix and control matrix of mode 2. According to the circuit equation, the matrix $\boldsymbol{A}$ and $\boldsymbol{B}$ can be written as: $A = \begin{bmatrix} -\frac{[k^2+(2k^2+4)d]r}{Lk^2} & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{R_L C} \end{bmatrix}$, $B = \begin{bmatrix} \frac{2d}{kL} \\ 0 \end{bmatrix}$, k is the primary secondary side ratio of the transformer. Thus, the mathematical model of full bridge DC/DC can be written as follows:

$$\begin{cases} \dot{x}_1 = -\dfrac{\left[k^2 + \left(2k^2 + 4\right)d\right]r}{Lk^2}x_1 - \dfrac{1}{L}x_2 + \dfrac{2d}{kL}U_{in} \\ \dot{x}_2 = \dfrac{1}{C}x_1 - \dfrac{1}{R_L C}x_2 \end{cases} \tag{3}$$

1.2 PPU Equivalent Model of Ion Electric Thruster

In the mission of far-reaching detection, due to the limited energy supply, the ion electric thruster mostly adopts the mode of multi-operating point adjustment, that is, the supply voltage and power of the PPU (including the screen grid power supply, acceleration grid power supply, etc.) can be adjusted. From the power side, a PPU with adjustable voltage and power is equivalent to a variable resistance, so in this paper, the PPU is equivalent to a variable load RL.

2 Design of Controller

2.1 Synergetic Approach to Control Theory

Synergetic approach to control (SAC) is a state-space method for designing nonlinear controllers. The control law can be obtained according to the selected macro variables and the defined manifold functions. The basic process is shown in Fig. 3. After establishing the state space of the controlled object, macro variables are selected in the space and manifold functions are constructed to realize the indexes of steady-state and dynamic control. In addition, the higher order system can be reduced by increasing the number of manifolds. If the mathematical model of the system is obtained, the calculation process of deducing the control law based on the synergetic control theory is simple, with the characteristics of strong nonlinear adaptability and strong control followability. Results show that the nonlinear synergetic controller has strong robustness to the system parameters and can obtain better performances of steady-state and dynamic.

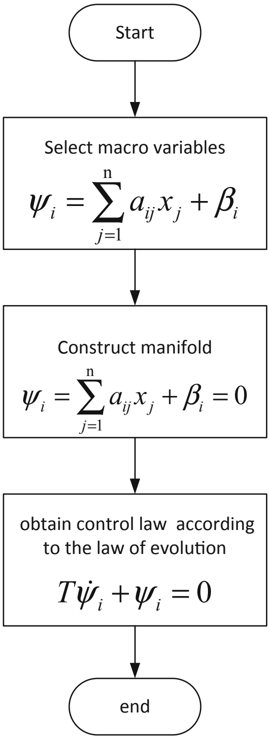

Fig. 3. Design flow of synergetic approach to control

Selecting macro variables is the first but key step in the design of synergetic controller, which requires the macro variables to contain the steady-state characteristics of the system. Macro variables are usually defined as linear combinations of state variables $x(t)$:

$$\boldsymbol{\psi} = \boldsymbol{\psi}(\boldsymbol{x}, t) = \boldsymbol{\alpha}\boldsymbol{x}(t) + \boldsymbol{\beta} \tag{4}$$

Among them, $\boldsymbol{\psi} = [\psi_1\ \psi_2\ \ldots\ \psi_{\mathrm{m}}]^{\mathrm{T}}$, $\boldsymbol{x}(\mathrm{t}) = [x_1(\mathrm{t})\ x_2(\mathrm{t})\ \ldots\ x_{\mathrm{n}}(\mathrm{t})]^{\mathrm{T}}$, $\boldsymbol{\alpha}$ is coefficient matrix $[\alpha_{ij}]_{\mathrm{m}\times\mathrm{n}}$, $\boldsymbol{\beta}$ is vector of intercept $[\beta_1\ \beta_2\ \ldots\ \beta_m]^{\mathrm{T}}$. In the synergetic approach to control theory, the essence of the control process is to make the system go from any initial state to the manifold $\boldsymbol{\psi} = 0$ and finally to the steady state. For a system whose state-space equation is $\dot{x} = f(\boldsymbol{x}, \boldsymbol{u}, t)$, the dynamic evolution law of its manifold is:

$$T\dot{\boldsymbol{\psi}} + \boldsymbol{\psi} = T\frac{\partial \boldsymbol{\psi}}{\partial \boldsymbol{x}}\dot{\boldsymbol{x}} + \boldsymbol{\psi} = 0, \quad T > 0 \tag{5}$$

T is the time constant of the differential equation, which can characterize the convergence rate of the system tending to the manifold $\boldsymbol{\psi} = 0$. The control law can be derived by using the Eq. (5). Since manifold $\boldsymbol{\psi} = 0$ contains all the control information of the system, when the system runs on manifold $\boldsymbol{\psi} = 0$, if control variables are added to stabilize the system, the system will converge to the steady-state equilibrium point along the manifold. According to Lyapunov and the sliding mode stability theorem, the sufficient and necessary condition for the manifold $\boldsymbol{\psi} = 0$ to be stable is that there is a continuously differentiable function $\boldsymbol{V}(t, \boldsymbol{x}, \boldsymbol{\psi})$ in the subspace of x where (1) $\boldsymbol{V}(t, \boldsymbol{x}, \boldsymbol{\psi})$ is positive definite about $\boldsymbol{\psi}$; (2) The full derivative of $\boldsymbol{V}(t, \boldsymbol{x}, \boldsymbol{\psi})$ against t is negative by dividing by $\boldsymbol{\psi} = 0$ [19].

We can construct a function $V(t, \boldsymbol{x}, \boldsymbol{\psi}) = \boldsymbol{\psi}^{\mathrm{T}}\boldsymbol{\psi}$. Obviously, $\boldsymbol{V}(t, \boldsymbol{x}, \boldsymbol{\psi})$ is positive definite about $\boldsymbol{\psi}$. Then, find the full derivative of $\boldsymbol{V}(t, \boldsymbol{x}, \boldsymbol{\psi})$ with respect to t:

$$\dot{V} = \frac{\partial \boldsymbol{x}}{\partial t}\sum_{i=1}^{\mathrm{m}} 2\psi_i \frac{\partial \psi_i}{\partial \boldsymbol{x}} = 2\sum_{i=1}^{\mathrm{j}} \psi_i \dot{\psi}_i \tag{6}$$

According to the variable definition in formula (4) and (5), it can be obtained:

$$\begin{cases} \dot{\psi}_i = -\dfrac{\psi_i}{T}, & T > 0 \\ \dot{\psi}_i \cdot \psi_i < 0, & T > 0 \end{cases} \tag{7}$$

When the time constant $T > 0$, the full derivative of $\boldsymbol{V}(t, \boldsymbol{x}, \boldsymbol{\psi})$ with respect to t is negative except where $\boldsymbol{\psi} = 0$. In conclusion, it can be proved that the system is stable about manifold $\boldsymbol{\psi} = 0$ and the control law exists.

2.2 Synergetic Controller of Deep Space Detector Power Supply

For the full-bridge DC/DC mathematical model defined by the formula (3), the macro variable selected in this paper is:

$$\psi = (x_2 - x_{2\mathrm{ref}}) + \alpha \cdot (x_1 - x_{1\mathrm{ref}}) \tag{8}$$

Among them, $x_{2\mathrm{ref}}$ is the given value of the output voltage of the converter. $x_{1\mathrm{ref}}$ is the steady-state value of the inductance current, which can be calculated according to the given value of the output power P_{ref} and the given value of the output voltage. α is the synergetic control parameter. Then, the dynamic evolution trajectory expressed in formula (5) can be expressed as:

$$T\dot{\psi} + \psi = T \cdot (\dot{x}_2 + \alpha\dot{x}_1) + (x_2 - x_{2\mathrm{ref}}) + \alpha\left(x_1 - \frac{P_{\mathrm{ref}}}{x_{2\mathrm{ref}}}\right) \tag{9}$$

According to the formula (9), the duty cycle d of $S_1 - S_4$ within a switching cycle can be written as:

$$d = \left[\begin{array}{l} \dfrac{(RLC\alpha + TRL - RCT\alpha r)x_1 - (LT + RCT\alpha - RLC)x_2}{RLC} \\ -x_{2\mathrm{ref}} - \dfrac{\alpha P_{\mathrm{ref}}}{x_{2\mathrm{ref}}} \end{array} \right] \Bigg/ \frac{(2k^2 + 4)rT\alpha x_1 - 2kU_{\mathrm{in}}T\alpha}{k^2 L} \tag{10}$$

The parameter α affects the dynamic performance of manifold convergence: when the value is larger, the overshoot can be reduced, and when the value is smaller, the dynamic response can be accelerated, but it may cause overshoot. The principle of parameter α influencing the convergence process is shown in Fig. 4.

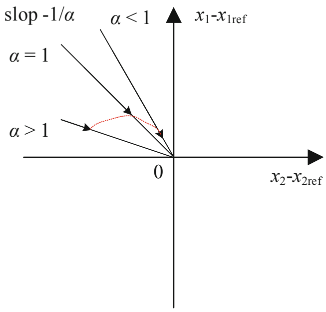

Fig. 4. Geometric representation of the dynamic process of the system by α

As shown in Fig. 4, when the system is in the initial stage of convergence, the capacitor voltage error $(x_2 - x_{2\mathrm{ref}})$ is large. If α is large, -1/α is small, and the slope of the corresponding line is small, which makes the inductive current overshoot $(x_1 - x_{1\mathrm{ref}})$ small and not easy to cause system oscillation. When the system approaches the steady state, the capacitor voltage error $(x_2 - x_{2\mathrm{ref}})$ is small. If the value of α is small, the value of $-1/\alpha$ is large, and the slope of the corresponding straight line is large. As a result, the adjustment speed of the inductor current $(x_1 - x_{1\mathrm{ref}})$ is accelerated, and the time of approaching the equilibrium point is shortened. Therefore, the ideal value of parameter α can be dynamically adjusted according to the capacitor voltage error $(x_2 - x_{2\mathrm{ref}})$: when the capacitor voltage error is large, it can amplify the error. And when the capacitor voltage error is small, it can attenuate the error. Taking advantage of the property of quadratic function, α chosen in this paper is:

$$\alpha = a(x_2 - x_{2\mathrm{ref}})^2 + b \tag{11}$$

3 Simulation Analysis

3.1 Simulation Parameter Setting

In order to verify the superiority of the proposed synergetic control method in the multi-operating point control of the power supply of ion electric propulsion system, the simulation model is built in the Matlab Simulink, compared with the classical PI controller to analyze the dynamic response of the output voltage and the inductive current overshoot of the full-bridge converter under wide voltage and wide power regulation. The simulation parameters are shown in Table 1.

Table 1. The simulation parameters

Symbol of parameter	Parameter value	Unit	Physical meaning
U_{in}	80	V	DC/DC converter input voltage
U_{o} ($x_{2\text{ref}}$)	60,100,120	V	DC/DC converter output voltage (bus voltage)
P_{ref}	4800, 6600,7200	W	DC/DC converter output power given value
R_{L}	0.5,1.5,3	Ω	The operating point of simulated ion thruster is adjustable
L	4	mH	DC/DC converter rectifier side inductance
C	200	μF	DC/DC converter output side capacitance
r	0.005	Ω	On - state equivalent resistance of switching tube
k	1:2	1	Ratio of turns of primary secondary side of transformer
f	20	kHz	DC/DC converter switching frequency
T	6	ms	Synergetic controller time constant
a	0.0002	$\text{V}^{-1}{\cdot}\text{A}^{-1}$	Synergetic control parameter 1
b	0.03	$\text{V}{\cdot}\text{A}^{-1}$	Synergetic control parameter 2

3.2 Simulation Results

In the simulation time of 0.3 s, there are two switching points. At 0 s, the converter is required to work in high voltage mode, the bus voltage is 120 V, the output power is 4800 W. At 0.1 s, the operating point of the converter is required to be switched to the rated operating point, the bus voltage is 100 V, and the output power is 6600 W. At 0.2 s, the converter is again required to switch to the low-voltage working mode, the bus voltage is 60 V, and the output power is 7200 W.

Figure 5 shows the dynamic response process of the bus voltage at the output side when the DC/DC converter is respectively controlled by PI control and synergetic control in multi-operating point switching mode. It can be seen that the steady-state performance of the two controllers is similar, both can make the converter work in the required voltage mode, but in low-voltage mode, the steady-state value of the PI controller is lower than 56 V, and that of the SAC controller is about 58.2 V. In terms of dynamic performance, the overshoot of PI controller at 0 s is 26.7% and that is 27% at 0.1 s. While that of SAC controller is 4.8%. The first two adjustment time of PI control is about 0.01 s and 0.014 s, which are also longer than SAC controller.

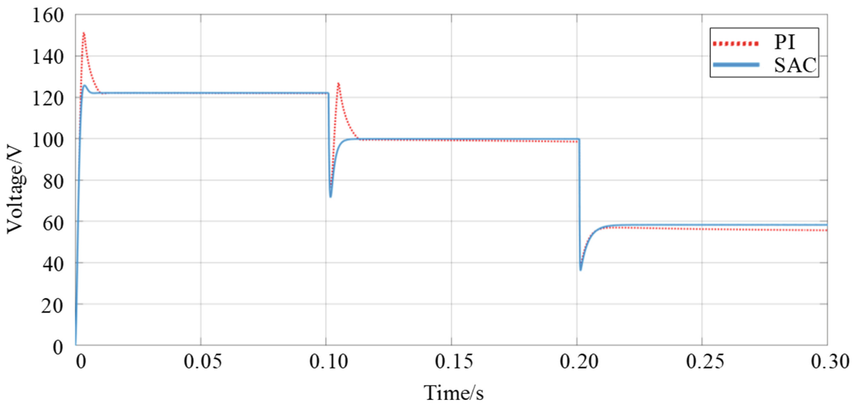

Fig. 5. Dynamic response process of capacitor voltage in multi-operating point mode

Figure 6 shows the overshooting state of inductance current on the rectification side when the DC/DC converter is respectively controlled by PI and coordinated control in multi-operating point switching mode. At 0 s and 0.1 s switching, the inductance current under PI control is overshot, which is 28.7% and 30.6%, respectively. Although there is no overshoot at 0.2 s switching, there is obvious steady-state error. In contrast, due to the adaptive adjustment of parameter α according to capacitor voltage error designed in Sect. 2.2, the overshoot of SAC control is smaller than that of PI control when the operating point is switched, and the adjustment time of 0s initial state is also faster than that of PI control.

In conclusion, compared with traditional PI control, SAC control has certain advantages in steady-state performance and dynamic performance.

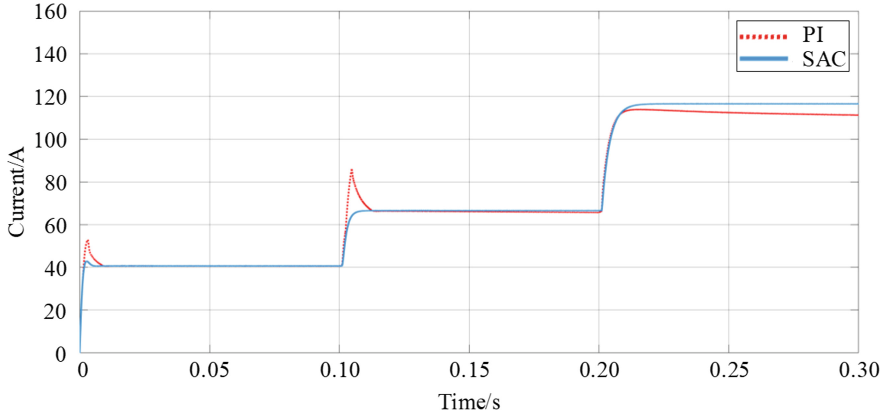

Fig. 6. Overshoot state of inductor current in multi-operating point mode

4 Conclusion

In order to make the deep space detector ion electric propulsion system have good control performance under wide voltage and wide power regulation, the state space model of full-bridge DC/DC converter is established by using the idea of state average. And then, a nonlinear controller based on the cooperative control theory is designed and its stability is proved. The control law of the converter can be obtained by combining the state equation of capacitor voltage, inductor current and manifold function. In order to ensure that the inductor current overshoot is small and the adjustment speed is fast, adaptive collaborative control parameters based on capacitor voltage error feedback are also designed in this paper. It is proved by Matlab simulation that the synergetic control has certain advantages over the traditional PI control in steady-state performance and dynamic performance. The synergetic controller designed in this paper provides an effective method to solve nonlinear control problems such as multi-point switching of power electronic converters in deep space detectors and other scenarios.

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