Research on Nonlinear Control for Power Supply Control Device in Space-borne Full Regulation Power Bus Platform

YONGLIANG ZHU  
Nanjing Research Institute of Electronics Technology  
Nanjing, CHINA  
zhuylxq@163.com

LIAN HUANG  
Nanjing Research Institute of Electronics Technology  
Nanjing, CHINA  
huanglian@buaa.edu.cn

ZHIHAO ZHANG  
Key Laboratory of Space Utilization, Technology and Engineering Center for space Utilization, Chinese Academy of Sciences.  
Beijing, CHINA  
zzh@csu.ac.cn

Abstract: - As the power level of the power system with fully regulated power bus in space-borne distribution system increases and the load scale and diversity becomes more and more complicated, the investigation of control for power supply control device has gradually been in a hot research topic. In this paper, a nonlinear model of non-isolated bi-directional DC/DC converter used in battery charge and discharge control was established, and nonlinear state space description was derived by adopting large signal modeling. Then, a linear space mapping was deduced by virtual output construction according to condition of state feedback linearization, and design of state feedback controller was implemented by analyzing the influence of circuit parameters to system characteristics based on two-order classical control system of linear space. Finally, simulation and experiment are implemented respectively by using simulation platform and developing an experimental prototype. The control method proposed in this paper could implement accurate and fast track power instruction function when battery charges or discharges, and has strong robustness against power bus voltage disturbances, load sudden change and deviation of system parameters, etc.

Key-Words: - Fully regulated power bus platform, Power supply control device, Large signal modeling, Nonlinear control

1 Introduction

Power supply mode with fully regulated power bus which has introduced battery charge and discharge regulator makes Space-borne distribution system setting more flexible, makes modularization and generalization easier, and is suited for different on-orbit operation mode and system with variable load during on-orbit period. The Power supply mode with fully regulated power bus has been adopted in both domestic large and medium sized spacecraft [1-3]. Under the premise of ensuring the safe and stable operation of the Space-borne distribution system, design and control of power electronics converter has become key technology in power supply technology development [4-5].

This paper proposed a state-space feedback control method based on large signal nonlinear model of non-isolated bi-directional DC/DC converter. The system structure is proposed and the mathematical model of control system is established. The affine nonlinear model was built based on CCM (Continuous Conduction Model). Then nonlinear transformation matrix was built according to nonlinear control theory and mapping was created between nonlinear space and linear space. The method proposed in this paper was verified to make system accurately and fast tracing power instruction, have good start-up characteristics and strong robustness, and effectively meet the demand of control power flow in space-borne distribution system.

2 Fully Regulated Power Bus Platform in Space-Borne System

2.1 Power supply control device

Due to the diversity of system power levels and demands, the control methods for power supply in full regulation power bus platform are different. This paper focuses on one kind of full regulation power bus structure that shown in Fig.1.

Fig. 1 Structure of power distribution system
During light period, the solar energy is transformed to electric energy through solar panels, which is supplied to electric unit, and the rest is for battery charging. If there exists enough electric power, shunting is necessary, otherwise, storage batteries needs to be charged. During shadow period, the chemical energy is transformed to electric energy through storage batteries, and the electric energy is supplied to the load of space-borne system by power control device [6-8].

2.2 Bi-directional DC/DC converter

The topology of non-isolated bi-directional DC/DC converter which suited in full regulation power bus platform is illustrated in Fig.2. For such kind of converter, the structure is simple, number of component is small, and the control method is easy to realize.

![Fig. 2 Topology of non-isolated bi-directional DC/DC converter](image)

2.3 Large signal modeling

Euler-Lagrange dynamic system is the traditional states space comment model for power switching converter. For pulse width modulation (PWM) DC/DC converter, the states space comment method is the common way for modeling. According to the bi-directional DC/DC converter topology and modeling equation for states space comment method, the nonlinear model of non-isolated and bi-directional DC/DC converter can be deduced as the following:

\[
\begin{align*}
L \frac{di_L}{dt} &= (1-d)U_{dc} - U_b \\
C \frac{dU_{dc}}{dt} &= dU_b - \frac{U_{eq} - U_{dc}}{R} 
\end{align*}
\]

Where, \(i_L\) and \(U_{dc}\) are average inductor current and capacitor voltage during one switching period, respectively. \(d\) is the duty cycle of \(S_2\), and \((1-d)\) is the duty cycle of \(S_1\).

When the specified power \(P_{ref}\) is positive, the storage system is charging, which is discharging otherwise. By analyzing the topology, tracing \(P_{ref}\) can be replaced by tracing the output voltage \(U_{dc}\) as equation.

\[
U_{dc} = U_{ref} = \frac{1}{2}U_{eq} + \frac{1}{4}U_{eq}^{2} - RP_{ref} \tag{2}
\]

\[
I_{ref} = \frac{U_{eq} - U_{ref}}{R} \times U_{ref} \tag{3}
\]

Let \([e_1,e_2] = [i_L - i_{ref}, U_{dc} - U_{ref}]\) as the status variables, the SISO (single input and single output) affine nonlinear system of non-isolated and bi-directional DC/DC converter can be deduced as following:

\[
\begin{align*}
\dot{x} &= f(e) + g(e)u \\
y &= h(e) = e_2
\end{align*}
\]

Where the status space dimension for this SISO system is \(n=2\), \(u=1-d\):

\[
f(e) = \begin{bmatrix}
-1 & 0 \\
\frac{1}{RC} & \frac{1}{RC}
\end{bmatrix},
g(e) = \begin{bmatrix}
\frac{1}{C}(e_1 + U_{ref}) \\
\frac{1}{L}(e_2 + U_{ref})
\end{bmatrix}
\]

3 Nonlinear Controller Method

In differential geometry theory [9-11], the exact linearization theorem for state feedback description of SISO affine nonlinear system as following.

Assume that in nonlinear system \(\Sigma\), \(f(e)\) and \(g(e)\) are smooth vector fields, the following condition can be met when only in \(\Omega\):

1) Vector field \(\{g(e) \ ad_jg(e) \ ... \ ad_{j-1}g(e)\}\) is linear independent in \(\Omega\), namely, the matrix \(G\) consisting of the vectors mentioned above , the rank is invariant and equals to \(n\);

2) Since the vector field \(\{g(e) \ ad_jg(e) \ ... \ ad_{j-1}g(e)\}\) is involutory in \(\Omega\), there is necessarily a function \(\omega(e)\), which makes the relative degree \(r\) equals to system degree \(n\). If \(\omega(e)\) is the system output matrix, the nonlinear system can be exact linearized through state feedback.
3.1 State feedback linearization for Bi-directional DC/DC converter

According to the state space description illustrated by equation (4), there is a necessarily output function $\omega(e)$, which makes the nonlinear system be exact linearized through state feedback. According to non-linear control theory and equation (4), $L_x \omega(e) = 0$ must be met when re-construct output $\omega(e)$.

$$L_x \omega(e) = \frac{\partial \omega}{\partial e} g(e) = \frac{\partial \omega}{\partial e_1} (Le_2 + U_{ref}) + \frac{\partial \omega}{\partial e_2} (C \xi) = 0 \quad (5)$$

The solution of equation as following:

$$\omega(e) = Le_1^2 + Ce_2^2 + 2Le_1I_{ref} + 2Ce_2U_{ref} \quad (6)$$

The new state space description of system $\Sigma$ can be deduced as the following:

$$\begin{bmatrix} e = f(e) + g(e)u \\ \dot{z} = \omega(e) \\ z = g(e) \\ \dot{L}_x \omega(e) = \left[ L_1e_1C_1L_2 + C_2L_4 + 2C_2L_2U_{ref} + 2C_2U_{ref} \right]$$

Through non-coordinate transformation to output equation, the equation (8) can be deduced.

$$z = g(e) = \begin{bmatrix} \omega(e) \\ Le_1^2 + Ce_2^2 + 2Le_1I_{ref} + 2Ce_2U_{ref} \\ 2L_4e_1 + 2L_2e_2 + 2C_2e_2U_{ref} \end{bmatrix}$$

(8)

The process of mapping nonlinear system into linear system under new coordinate system is shown as equation (9), where Z is state variable and V is control variable in linear system.

$$\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

(9)

3.2 Controller design

It is assumed that state feedback control rate is $\nu = -(k_1z_1 + k_2z_2)$ , where $k_1$ and $k_2$ are feedback coefficients of corresponding feedback quantities. Feedback coefficients $k_1$ and $k_2$ can influence the stability as well as static and dynamic characteristics of system. According to state feedback rate, $z_1$ is a state variable of two-order linear system as equation.

$$z_1 + k_1 z_2 + k_2 z_1 = 0 \quad (10)$$

The natural oscillation frequency of LC circuit is $\omega_n = 1/\sqrt{LC}$, and the system energy can be stored and transmitted mainly by inductor L and capacitor C. When the system oscillation frequency is $\omega_n$, damped coefficient is $\xi$, and $\omega_n$ is $\sqrt{k}$ times of $\omega_n$, the feedback system can be counted out as equation:

$$\begin{cases} k_1 = \omega_n^2 = (\sqrt{k} \omega_n)^2 = k / (LC) \\ k_2 = 2\xi \omega_n = 2\xi \sqrt{k} \end{cases} \quad (11)$$

According to equations (8), (11) and $\nu = -(k_1z_1 + k_2z_2)$, the analysis equation of control variable $u$ can be derived.

From the equations above, it can be concluded that $u$ is directly determined by feedback parameters, and $k_1$, $k_2$ is determined by two-order system parameter $k$ and damping ratio $\xi$. It is a remarkable fact that as the control parameters can influence the value of $u$, which is a control variable in former system and represents duty cycle is according to power electronics theory, it is necessary to constraint control parameters’ values to make $u$ in the range of $[0,1]$, on the base of analysis mentioned above.

4 Simulation Analysis

To testify the superiority of state feedback linearizing method in order to control battery charge and discharge to tracking the given power, the Simulation circuit is established on the base of non-isolated DC/DC converter topology shown in Fig.2 and Matlab/Simulink simulation platform, in which specific parameters are illustrated in Table 1. Firstly the control effect of parameters $k$ and $\xi$ are confirmed. Then simulation are carried on against system start-up, bus voltage fluctuation, load change (i.e. power flow direction, amplitude change, battery charge and discharge), change of system parameters to testify the effectiveness and robustness of such method. The solid line represents instruction while the dashed line represents tracking curve and the parameters are illustrated in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power bus voltage (V)</td>
<td>30</td>
</tr>
<tr>
<td>Rated battery voltage (V)</td>
<td>12</td>
</tr>
<tr>
<td>Rated battery power (W)</td>
<td>500</td>
</tr>
<tr>
<td>Battery capacity (Ah)</td>
<td>20</td>
</tr>
<tr>
<td>Inductor value (mH)</td>
<td>0.2</td>
</tr>
<tr>
<td>Capacitor value (uF)</td>
<td>200</td>
</tr>
<tr>
<td>Equivalent resistance of power bus (Ω)</td>
<td>2</td>
</tr>
<tr>
<td>Switching frequency (kHz)</td>
<td>50</td>
</tr>
</tbody>
</table>

4.1 The effect of control parameters

According to the experimental condition shown in Table 1, simulation is carried on based on different control parameters, in which it is assumed that the power instruction is 100W at 0.5s. The influence of the control parameters on system response characteristic is shown in Fig.3 and Fig.4.
It can be inferred that when power bus $U_{eq}$ suddenly changes or random high-frequency disturbance occurs, the output voltage of the non-isolated bi-directional DC/DC converter can still rapidly and accurately trace the power instruction, which shows that the controller has strong anti-interference ability.

### 4.3 Load disturbance

Load disturbance mentioned in this paper refers to the change of battery power instruction to control charge and discharge, i.e., the change of battery charge and discharge condition. The power instruction is required to have a period of 0.1s and changes at $[100 \ -100 \ 60 \ -30]$W to simulate control on battery charge and discharge. The effect is shown in Fig.6.

![Fig. 6 Voltage tracking, power tracking effect in load disturbance](image)

It can be inferred from Fig.6 that the bi-directional DC/DC converter can control power flow direction by charge or discharge battery, and rapidly and accurately trace instruction even when the battery voltage changes, which shows that the controller has strong anti-interference ability.

### 4.4 Inaccurate system parameters

Actually, there usually exists deviation between actual value and set value in capacitors and inductors design, which results from the change of components after long working time, distributed system parameters, or production deviation of electronic product. It is supposed that the design of state feedback accurate linearization controller accords with Table 1, while the actual values of inductor $L$, capacitor $C$ are 60%, 100% or 150% of
the set values, and the power instruction becomes +100W instead of -100W, the control effect is shown in Fig.7, where only one parameter changes in (a) or (b).

![Fig. 7 Power tracking effect in inaccurate system parameters](image)

(a) system parameter C

(b) system parameter L

It can be inferred from Fig.7 that when finite deviation of component values occurs (still meet CCM requirement), the energy bidirectional flow of the battery charge and discharge control system can still be accurately and effectively implemented using state feedback accurate linearization method, by which the power instruction can be rapidly and specifically traced, and strong robustness is reflected.

4 Conclusion

This paper has proposed non-linear control method for non-isolated DC/DC converter in power supply control device of space-borne full-regulated power bus platform, and it can be concluded as the following:

1) For non-isolated and bi-directional DC/DC converter, the state feedback controller, resulting from state feedback linearization and large signal modeling, has no requirement for quiescent operation point and is suit for frequent charging and discharging situation of battery charge-discharge control system.

2) The controller design is not sensitive to system parameters, which has strong robustness and anti-interference ability towards power bus voltage disturbances, load sudden change, etc.

3) The control method could implement fast, accurate and no-overshooting power instruction tracking function and power bi-directional flow between energy store unit and power bus. As a result, the method has excellent control effect and good application prospect in space-borne full-regulation power bus platform.

References:


