Research on Linear Active Disturbance Rejection Control in DC/DC Boost Converter

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Abstract: This paper proposes a cascade control strategy based on linear active disturbance rejection control (LADRC) for a boost DC/DC converter. It solves the problem that the output voltage of boost converter is unstable due to non-minimum phase characteristics, input voltage and load variation. Firstly, the average state space model of boost converter is established. Secondly, a new output variable is selected, and a cascade control is adopted to solve the problems of narrow bandwidth and poor dynamic performance caused by non-minimum phase. LADRC is used to estimate and compensate the fluctuations of input voltage and loads in time. Linear state error feedback (LSEF) is used to achieve smaller errors than traditional control method, which ensures the stability and robustness of the system under internal uncertainty and external disturbance. Subsequently, the stability of the system is determined by frequency domain analysis. Finally, the feasibility and superiority of the proposed strategy is verified by simulation and hardware experiment.

Keywords: DC/DC boost converter; LADRC; LESO; cascade control

1. Introduction

With the vigorous promotion of renewable energy such as photovoltaics and wind turbines, the DC microgrid has received extensive attention [1–3]. Compared with the AC microgrid, the DC microgrid has the advantages of high efficiency and simple control structure [4]. In addition, the DC microgrid avoids some of the problems in the AC microgrid. For instance, reactive power flow, harmonic current, and synchronization [5]. Therefore, the DC microgrid will become the main power architecture for buildings, parks, and power electronic loads. The instability of the output voltage will cause some problems, including protection device malfunction and damage to the electrical equipment, so it is important to ensure the stability of the DC output voltage.

In a DC microgrid, renewable energy units, loads, and other units are connected by inverters, such as DC/DC converters, DC/AC converters, AC/DC converters, etc. Moreover, it can be connected to the AC microgrid or the large grid through bidirectional DC/AC. Not only can the AC side disturbance and fault be effectively isolated, but also the DC side load can be reliably powered [6]. The DC/DC boost converter is an important part of the connection between each unit and the bus. It achieves voltage boost by a specific circuit structure and adjusting the on-off time of the switching device [7]. Open loop control is a simple method of controlling a step-up DC/DC converter that calculates the PWM pulse duty cycle from the input voltage and the output voltage. However, this method is extremely sensitive to external disturbances and changes from parameters. Moreover, it is easy to cause problems such as large overshoot of the output voltage and high amplitude of the inductor current. Therefore, most of the DC/DC converter control uses a closed-loop control method.
Scholars and researchers have done a lot of work on the control of DC/DC converters. In [8,9], the isolated converter is used to increase the output voltage by adjusting the turns ratio. However, the excessive number of turns leads to a large leakage inductor, which makes it difficult to improve the efficiency. In [10,11], a cascade converter is used, which can control the voltage by adjusting the duty ratio of the two parts of the switch tube, but the converter is inefficient and difficult to control. In [12], a high boost converter with a switched capacitor is proposed. High voltage gain is achieved at the appropriate duty cycle by introducing a switched capacitor into the switched mode DC-DC converter. However, the switched capacitor introduces a pulsating input current that can cause poor line and load regulation issues. In [13], state feedback control is adopted, which has strong suppression of load disturbance, but does not consider input voltage disturbance. In [14], the high-order synovial observer is used to estimate the load change in advance and cancel it in the feedforward channel, and combine it with the feedback control loop. It not only improves the transient characteristics of the system, but also improves the stability margin of the system. However, the calculation method of this method is too large and sensitive to noise.

By analyzing the transfer function of the step-up DC/DC converter, it can be seen that the system has a zero point in the right half plane. Capacitance voltage is directly controlled as an output, which causes the bandwidth to be narrowed and the dynamic performance of the system to deteriorate, which increases the control difficulty [15,16]. In [17], an input–output feedback linearization technique is proposed and applied to an AC/DC converter. In [18], an internal model control with a conditional integrator is proposed for the robust output regulation of a DC/DC buck converter. Due to the nonlinearity and unstable zero dynamics of the boost converter, a novel nonlinear control strategy based on input–output feedback linearization is proposed in [19]. In [20], a wide series of control techniques are presented for well-known power electronics converters, including the conventional DC-DC boost converter. In response to this problem, two main solutions can be obtained from the perspective of control and system: (1) changing the topology of DC/DC booster converter to eliminate the unstable zero dynamic; and (2) indirect control of the output voltage. By selecting a new output variable, the unstable zero dynamics of the converter are eliminated, and the relationship between the new output variable and the output voltage is used for control. The former directly controls the output voltage and easily satisfies the control effect, but increasing the power electronic switching device leads to an increase in cost. The latter does not change the topology of the converter, and the output voltage is controlled by indirect control, but the output voltage is susceptible to input voltage and resistance changes. The classical PI control relies on the error between the control target and the actual output to determine the control strategy to eliminate this error [21], so the design is simple and the applicability is good. However, this method designs the output feedback control according to the target error, so that the dynamic response characteristic is slow, and the system is adjusted only when the output has changed.

Based on the in-depth study of PID, active disturbance rejection control (ADRC) attributes all the uncertain factors acting on the controlled object to “unknown disturbances”, which are estimated and compensated by the extended state observer. This method is based on process error to reduce the error [22]. The active disturbance rejection control consists of three parts: tracking differentiator (TD), extended state observer (ESO), and nonlinear state error feedback (NLSEF) control law. To make the design of the controller simpler and easier to promote the application, Gao et al. simplified the self-disturbance control to linear active disturbance rejection control (LADRC) [23].

The parameters' setting of controller is simplified by using proportional-derivative (PD) control and establishing the proportional coefficient and differential time constant to the controller bandwidth [24]. Linearization of the ESO, conversion to a linear extended state observer (LESO), and the establishment of a link between the observer bandwidth and parameters, simplifies the design of the LESO. Since the active disturbance rejection controller does not depend on the system model and the algorithm is simple, it is applied in many fields. In [25], ADRC is applied to solve industrial problems. Industrial automation equipment was tested. In the worst case, performance improvement from just under 20% to
in the control algorithm itself, the ease of adjustment and operation, this improvement makes ADRC a viable alternative to existing industrial controller in manufacturing industry. In [26], from the perspective of ADRC, the design of the control algorithm and the controller is carried out, and the effectiveness of the control algorithm is verified. In [27], a fixed-time ADRC control method is proposed to solve the problem of instability of output voltage caused by the load disturbance. In [28], the ADRC method is applied to the control of the double-switch buck-boost converter. In [29], the ADRC method is applied to the control of the four-rotor unmanned aerial vehicle. In [30], the ADRC method is applied to the inverter control of the speed control system. In [31], the ADRC method is applied to the control of the four-rotor unmanned aerial vehicle. In [32], the ADRC method is applied to the control of the four-rotor unmanned aerial vehicle. In [33], the ADRC method is applied to the control of the four-rotor unmanned aerial vehicle.

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The pulse function $\mu(t)$ can be expressed as:

$$\mu(t) = \begin{cases} 
1, & nT < t \leq (n + d)T \\
0, & (n + d)T < t \leq (n + 1)T 
\end{cases}$$

Switching frequency $f_{sw}$ is 10 kHz in this paper, where $T = 1/f_{sw}$ is the switching period, $d$ is the duty cycle, $0 < d < 1$ and $n = 0, 1, 2...$.

To establish the average model of the DC/DC boost converter. The waveform of switch function $\mu(t)$ is shown in Figure 2.

![Figure 2. Impulse waveform.](image)

The pulse function $\mu(t)$ can be expressed as:

As can be seen from the above pulse function, the DC/DC boost converter has two operating states:

1. Switch conduction mode, $\mu(t) = 1$: When the switch is turned on, the input voltage $U_i$ charges the inductor $L$, and the charging current is kept substantially constant. At the same time, the voltage of capacitor $C$ supplies power to load $R$.

   Switch conduction model equation:

   $$\begin{align*}
   L \frac{di}{dt} &= U_i \\
   C \frac{dU}{dt} &= \frac{1}{R} U_o
   \end{align*}$$

2. Switch cutoff mode, $\mu(t) = 0$: When the switch is turned off, the input voltage $U_i$ and the inductor $L$ together charge the capacitor $C$ and supply power to the load resistor.

   Switch cutoff model equation:

   $$\begin{align*}
   L \frac{di}{dt} &= U_i \\
   C \frac{dU}{dt} &= \frac{1}{R} U_o
   \end{align*}$$

The average mathematical model equations of the DC/DC boost converter can be obtained by combining Equations (2) and (3):

$$\begin{align*}
\frac{dU_i}{dt} &= \frac{1}{R} U_o - \frac{1}{C} U_i \\
\frac{dU_o}{dt} &= \frac{1}{R} U_o - \frac{1}{RC} U_i
\end{align*}$$

3. Control Method Design

3.1. Cascade Control

According to the analysis of Equation (4), when the output voltage is directly controlled, the system is a non-minimum phase system. This will lead to narrow bandwidth and slow dynamic response to the system, which increases the difficulty of control. The output redefinition method is one of the methods to solve the non-minimum phase problem. By selecting a new output variable, a new output function is established, so that the zero dynamic subsystem is stable.

For the control of the DC/DC boost converter, a new output variable can be selected to eliminate the unstable zero dynamics and achieve the effect of change the non-minimum phase characteristics of the system. According to the model in Equation (4), if the inductor current is the system output, the new subsystem is the minimum phase system. Therefore, the output voltage control problem of
The output redefinition method is rolling the inductor current. According to the model in Equation (4), if the inductor current is the system output, the new subsystem is the minimum phase system. Therefore, the output voltage control problem of the system can be converted into an inductor current control problem. Further consideration is given to how to achieve the desired output voltage value by controlling the inductor current. There is a relationship between the output voltage and the inductor current, which can be written as:

\[ I_{t}(\infty) = U_{\text{ref}}^2(\infty) / RU_i \]

where \( I_{t}(\infty) \) and \( U_{\text{ref}}(\infty) \) are the steady state values of \( I_t \) and \( U_{\text{ref}} \), respectively.

According to Equation (6), \( I_{\text{ref}}(\infty) \) is the reference value of the inductor current, and \( U_{\text{ref}}(\infty) \) is the reference value of the output voltage.

A cascade control system is formed by designing an output voltage controller in the front stage of the current controller. The output voltage cannot be obtained directly from the input voltage observation. The uncertain factors of the system are estimated in advance by designing an output voltage controller in the front stage of the current controller. The output voltage can be obtained according to Equation (6):

\[ I_{\text{ref}}(\infty) = U_{\text{ref}}^2(\infty) / RU_i \]

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\[ I_{\text{ref}}(\infty) = U_{\text{ref}}^2(\infty) / RU_i \]

According to Equation (6), \( I_{\text{ref}}(\infty) \) is calculated from \( U_{\text{ref}}(\infty) \), and there are two problems: (1) The relationship between the inductor current and the output voltage is based on the stability of the system. If there is an unknown disturbance of the system, the dynamic performance of the output voltage cannot be achieved. (2) The input voltage of the system is uncertain, such as the DC/DC boost converter. The uncertain factors are estimated in advance by designing an output voltage controller in the front stage of the current controller. The uncertainty factors of the system are estimated in advance by designing an output voltage controller in the front stage of the current controller.

### 3.2. Linear Active Disturbance Rejection Control

LADRC consists of a linear extended state observer (LESO), and a linear state error feedback (LSEF) control law. LADRC is composed of disturbance suppression loop and feedback control loop. The structure is shown in Figure 3. The uncertain factors of the system are estimated in advance by the LESO and eliminated by the disturbance suppression loop, which is combined with the feedback control loop to improve the transient and stability performance of the system.

![Figure 3: Structure of first-order LADRC](image)

**Figure 3:** Structure of first-order LADRC.

- \( r \) is the input reference; \( u_0 \) is the controlled quantity; \( \omega \) is external disturbance of the system; \( G_p \) is the controlled object; \( y \) is the system output; \( \hat{y} \) is the estimated value of system output; \( f \) is the estimated value of the total disturbance; \( k_p \) is the controller parameter; and \( b_0 \) is the system gain.

The first-order single-input single-output system is analyzed as follows:

\[ y = b_0u_0 + f(y, u_0) \]

where \( f \) is the total disturbance of the system.

Let \( x_1 = y, x_2 = f \), then

\[ \begin{cases} \dot{x} = Ax + Bu_0 + Ef \\ y_1 = Cx \end{cases} \]
where \( A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B = \begin{bmatrix} b_0 \\ 0 \end{bmatrix}, E = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 \end{bmatrix}, x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}. \)

The corresponding continuous LESO is

\[
\begin{align*}
\dot{x} &= Ax + Bu_0 + L_0(y - \hat{y}) \\
\hat{y} &= C\hat{x}
\end{align*}
\]

where \( L_0 = \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} \) (9)

For first-order system, proportional control is adopted:

\[
u = k_p(r - \dot{x}_1) \tag{11}\]

The total disturbance action is observed by the LESO as the expansion state of the system. To achieve automatic compensation of the total disturbance, the final control law is designed as

\[
u_0 = u - \dot{x}_2 = \frac{k_p(r - \dot{x}_1) - \dot{x}_2}{b_0} = K_p(\hat{R} - \hat{x}) \tag{12}\]

where \( \hat{R} = \begin{bmatrix} r \\ 0 \end{bmatrix} \) is the input reference and \( K_p = \begin{bmatrix} k_p & 1 \end{bmatrix}/b_0 \) is gain of controller.

Substitute Equation (12) into Equation (6) to get

\[
y = -\dot{x}_2 + u + f \approx u \tag{13}\]

In summary, LADRC can be described as the form of state space as follows:

\[
\begin{align*}
\dot{x} &= (A - L_0C)\dot{x} + Bu_0 + L_0y \\
u_0 &= K_p(\hat{R} - \dot{x})
\end{align*}\tag{14}\]

The gain \( L_0 \) of the LESO and \( K_p \) of the LSEF are designed. By introducing the concept of bandwidth, the setting of \( L_0 \) and \( K_p \) is converted into the observer’s bandwidth \( \omega_o \) and the controller’s bandwidth \( \omega_c \), which simplifies the parameter tuning process.

The characteristic equation of LESO can be obtained from Equation (14)

\[
|sI - (A - L_0C)| = \begin{bmatrix} s + \beta_1 & -1 \\ \beta_2 & s \end{bmatrix} = s(s + \beta_1) + \beta_2 = s^2 + \beta_1s + \beta_2 \tag{15}\]

All poles of the observer are assigned to \(-\omega_o\), then

\[
s^2 + \beta_1s + \beta_2 = (s + \omega_o)^2 \tag{16}\]

where \( \omega_o \) is the bandwidth of observer.

The closed-loop characteristic equation of the feedback control system is as follows:

\[
|sI - (A - BK_p)| = \begin{bmatrix} s + k_p & 0 \\ 0 & s \end{bmatrix} = s(s + k_p) \tag{17}\]

All poles of the controller are assigned to \(-\omega_c\), where \( \omega_c \) is the controller bandwidth. Combining Equations (15) and (16), the equivalent equation are obtained as

\[
\beta_1 = 2\omega_o, \beta_2 = \omega_o^2, k_p = \omega_c \tag{18}\]
4. Controller Design

For the average model of the DC/DC boost converter established by Equation (3), this paper designs inner-loop current controller and outer-loop voltage controller based on LADRC. It has the characteristics of two-channel control with interference suppression and control feedback. LESO can be used to estimate the fluctuations of input voltage and loads in advance, which can be eliminated by disturbance suppression loop to improve the rapidity of the system. To avoid the problem of controlled quantity delay caused by error feedback from PI control, capacitive voltage signal and inductive current signal are, respectively, obtained by the LESO, which are used as the feedback quantity of voltage outer loop and current inner loop. Moreover, LESO has a filter function, which can suppress the noise in the system and reduce the low-pass filtering in the traditional cascade control.

4.1. Design of Current Controller

Design the current controller according to the first formula in Equation (4); the current controller is designed as follows:

\[
\frac{dI_L}{dt} = -(1-d)\frac{U_o}{L} + \frac{U_i}{L} \tag{19}
\]

Let \( I_L = y_1 \), \( d = u_1 \), then

\[
y_1 = \frac{U_o}{L}u_1 + \frac{U_i}{L} = b_1u_1 + f_1(y_1, u_1) \tag{20}
\]

where \( b_1 = \frac{U_o}{L} \) is the object gain, \( y_1 \) is the system output, \( u_1 \) is the system input, and \( f_1 = \frac{U_i}{L} - \frac{U_o}{L} = \frac{U_i - U_o}{L} \) is the total disturbance of the system.

Let \( x_1 = y_1, x_2 = f_1 \), then

\[
\begin{aligned}
\dot{x} &= A_1x + B_1u_1 + E_1f_1 \\
y_1 &= C_1x
\end{aligned} \tag{21}
\]

where \( A_1 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \), \( B_1 = \begin{bmatrix} b_1 \\ 0 \end{bmatrix} \), \( E_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \), \( C_1 = \begin{bmatrix} 1 & 0 \end{bmatrix} \), and \( x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \).

Second-order LESO is

\[
\begin{aligned}
\dot{x} &= A_1\dot{x} + B_1\dot{u}_1 + L_{o1}(y_1 - \dot{y}_1) \\
\dot{y}_1 &= C_1\dot{x}
\end{aligned} \tag{22}
\]

where \( L_{o1} = \begin{bmatrix} \beta_{11} \\ \beta_{12} \end{bmatrix} \).

According to Equation (19), the relative of the current is first-order, and proportional control is used:

\[
u = k_1(r_1 - \dot{x}_1) \tag{23}\]

According to the expansion state \( \dot{x}_2 = \dot{f}_1 \) given by the LESO. To achieve automatic compensation of the total disturbance, the final control law is designed as

\[
u_1 = \frac{u - \dot{x}_2}{b_1} = \frac{k_1(r - \dot{x}_1) - \dot{x}_2}{b_1} = K_1(\dot{R}_1 - \dot{x}) \tag{24}\]

where \( \dot{R}_1 = \begin{bmatrix} r_1 \\ 0 \end{bmatrix} \) is the input reference and \( K_1 = \begin{bmatrix} k_1 & 1 \end{bmatrix} / b_1 \) is gain of controller.

Substituting Equation (24) into Equation (20),

\[
\dot{y}_1 = -\dot{x}_2 + u_1 + f_1 \approx u_1 \tag{25}\]
The tuning of $L_{o1}$ and $K_1$ is converted to the tuning of the observer bandwidth $\omega_{o1}$ and the controller bandwidth $\omega_{c1}$. All poles of the observer are configured to $-\omega_{o1}$, and all poles of the controller are configured to $-\omega_{c1}$.

$$\beta_{11} = 2\omega_{o1}, \beta_{12} = \omega_{o1}^2, k_1 = \omega_{c1}$$ (26)

4.2. Design of Voltage Controller

Design a voltage controller according to the second formula in Equation (4); the voltage controller is designed as follows:

$$\frac{dU_o}{dt} = \left(1 - \frac{d}{C}\right)I_L - \frac{1}{RC}U_o$$ (27)

Let $U_o = y_2, I_L = u_2$, then

$$y_2 = \frac{1}{C} - \frac{d}{C}u_2 - \frac{y_1}{RC} = b_2u_2 + f_2(y_2, u_2)$$ (28)

where $b_2 = \frac{1}{RC}$ is the object gain, $y_2$ is the system output, $u_2$ is the system input, and $f_2 = -\frac{y_2}{RC}$ is the total disturbance of the system.

Let $x_1 = y_2, x_2 = f_2$, then

$$\begin{cases}
  \dot{x} = A_2x + B_2u_2 + E_2f_2 \\
  y_2 = C_2x
\end{cases}$$ (29)

where $A_2 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B_2 = \begin{bmatrix} b_2 \\ 0 \end{bmatrix}, E_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, C_2 = \begin{bmatrix} 1 & 0 \end{bmatrix}, x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$.

Second-order LESO is

$$\begin{cases}
  \dot{x} = A_2\dot{x} + B_2u_2 + L_{o2}(y_2 - \dot{y}_2) \\
  \dot{y}_2 = C_2\dot{x}
\end{cases}$$ (30)

where $L_{o2} = \begin{bmatrix} \beta_{21} \\ \beta_{22} \end{bmatrix}$.

According to Equation (27), the dynamic characteristics of the voltage is first-order, so proportional control is used:

$$u = k_2(r_2 - \dot{x}_1)$$ (31)

To achieve automatic compensation of the total disturbance, the final control law is designed as

$$u_2 = u - \dot{x}_2 = \frac{k_2(r - \dot{x}_2) - \dot{x}_2}{b_2} = K_2(\dot{R}_2 - \dot{x})$$ (32)

where $\dot{R}_2 = \begin{bmatrix} r_2 \\ 0 \end{bmatrix}$ is the input reference and $K_2 = \begin{bmatrix} k_2 & 1 \end{bmatrix}/b_2$ is the controller gain.

Substituting Equation (32) into Equation (28),

$$\dot{y}_2 = -\dot{x}_2 + u_2 + f_2 \approx u_2$$ (33)

The $L_{o2}$ and $K_2$ tuning is converted to the tuning of the observer bandwidth $\omega_{o2}$ and the controller bandwidth $\omega_{c2}$. All poles of the observer are configured to $-\omega_{o2}$, and all poles of the controller are configured to $-\omega_{c2}$.

$$\beta_{21} = 2\omega_{o2}, \beta_{22} = \omega_{o2}^2, k_2 = \omega_{c2}$$ (34)

Based on the above controller, the structure of the proposed controller is shown in Figure 4.
The bandwidth tuning is converted to the tuning of the observer bandwidth. The observer bandwidth and the controller bandwidth are tuned to -ωc. All poles of the observer are configured to -ωc, and all poles of the controller are configured to -ωc.

$$\beta_{21} = 2\omega_{c2}, \beta_{22} = \omega_{c2}^2, \beta_2 = \omega_{c2}$$  \hspace{1cm} (34)

Based on the above controller, the structure of the proposed controller is shown in Figure 4.

**Figure 4.** The structure of proposed controller.

4.3. System Stability Analysis

The transfer function of the DC/DC boost converter can be obtained from Equation (4)

$$G_p(s) = \frac{\Delta d(s)}{\Delta U_o(s)} = \frac{1}{s^2 L R + s L + D^2 R}$$  \hspace{1cm} (35)

The bode diagram of $G_p(s)$ is shown in Figure 5.

**Figure 5.** Bode diagram of $G_p(s)$.

As can be seen in Figure 5, the phase margin of $G_p(s)$ is -16.3 deg and the amplitude margin is -33.6 dB. According to the stability criterion of closed-loop control system, the system is unstable.

Figure 6 shows the control structure for one converter with the implementation of the LADRC method.

![Control Structure](image-url)
As can be seen in Figure 5, the phase margin of $G_2(s)$ is $16.3$ deg and the amplitude margin is $33.6$ dB. According to the stability criterion of closed-loop control system, the system is unstable.

Figure 6 shows the control structure for one converter with the implementation of the LADRC method.

$$H_1(s) = \frac{s^2 + \beta_{11}s + \beta_{12}}{k_1s^2 + (k_1\beta_{11} + \beta_{12})s + \beta_{11}\beta_{12}}$$ (36)

$$G_{c1}(s) = \frac{1}{b_1} \frac{k_1s^2 + (k_1\beta_{11} + \beta_{12})s + \beta_{11}\beta_{12}}{s^2 + \beta_{11}s}$$ (37)

$$H_2(s) = \frac{s^2 + \beta_{21}s + \beta_{22}}{k_2s^2 + (k_2\beta_{21} + \beta_{22})s + k_2\beta_{22}}$$ (38)

$$G_{c2}(s) = \frac{1}{b_2} \frac{k_2s^2 + (k_2\beta_{21} + \beta_{22})s + k_2\beta_{22}}{s^2 + \beta_{21}s}$$ (39)

The $G_{c1}(s)$ and $G_{c2}(s)$ transfer functions are obtained by the DC/DC boost circuit small signal model. The transfer function of the controlled quantity $\Delta d$ to the output voltage $\Delta U_o$ is

$$G_{p1}(s) = \frac{\Delta U_o(s)}{\Delta d(s)} = \frac{-sLRI_L + DRI_0}{s^2L + sL + D^2R}$$ (40)

The transfer function of the controlled quantity $\Delta d(t)$ to the output current $\Delta I_L$ is

$$G_{p2}(s) = \frac{\Delta I_L(s)}{\Delta d(s)} = \frac{sU_0RC + DLI_0 + U_0}{s^2LCR + sL + D^2R}$$ (41)

From Figure 6, the transfer function of the inner loop current loop can be obtained as follows:

$$G_1(s) = \frac{G_{c2}(s)H_2(s)}{1 + G_{c2}(s)G_{p2}(s)}$$ (42)

The system open loop transfer function is

$$G_0(s) = \frac{H_1(s)G_{c1}(s)H_2(s)G_{c2}(s)G_{p2}(s)G_{p3}(s)}{1 + G_{c2}(s)G_{p2}(s)}$$ (43)
To verify the effectiveness of the proposed strategy, simulation tests were designed in
Matlab/Simulink. Under the premise that PI cascade control and LADRC cascade control have
no overshoot, the classical dual-loop PI controller was compared with the proposed controller to
demonstrate the superiority of the proposed method. The circuit parameters and controller
parameters in the simulation are shown in Table 1. To verify the stability of the system under different
cases, three cases were designed, as shown in Table 2. For clarity, we will describe the variables and
acronyms in Table A1 of the Appendix.

Table 1. Simulation parameters.

| Parameters | Description | Value   |
|------------|-------------|---------|
| $U_{ref}$ | Reference value of output voltage | 24 V    |
| $L$       | inductance value | 1 mH    |
| $C$       | capacitance value | 920 $\mu$F |
| $f_{sw}$  | switching frequency | 10 KHz  |
| $a_1, a_2, b_1$ | LADRC parameters of current control loop | 165, 270, 543.5 |
Table 1. Simulation parameters.

| Parameters   | Description                    | Value     |
|--------------|--------------------------------|-----------|
| $U_{oref}$   | Reference value of output voltage | 24 V      |
| $L$          | Inductance value                | 1 mH      |
| $C$          | Capacitance value               | 920 µF    |
| $f_{sw}$     | Switching frequency             | 10 kHz    |
| $\omega_{c1}, \omega_{o1}, b_1$ | LADRC parameters of current loop | 165, 270, 543.5 |
| $\omega_{c2}, \omega_{o2}, b_2$ | LADRC parameters of voltage control loop | 1600, 8800, 24,000 |
| $k_{p1}, k_{i1}$ | PI parameters of voltage control loop | 0.3, 7   |
| $k_{p2}, k_{i2}$ | PI parameters of current control loop | 0.25, 30 |

Table 2. Different cases.

| Case | Input Voltage | Load     |
|------|---------------|----------|
| 1    | 12 V→10 V     | 50 Ω      |
| 2    | 12 V→8 V      | 50 Ω      |
| 3    | 12 V          | 50 Ω→25 Ω|

Case 1: The converter input voltage was changed to examine the stabilization performance. At the beginning, the output voltage was regulated at 24 V with a 50 Ω resistance load. At 0.6 s, the input voltage of the converter was reduced from 12 V to 10 V. The voltage response is shown in Figure 8; the converter is controlled by LADRC cascade, the output voltage drops from 24 V at 23.6 V and reaches the desired value after 0.05 s. In contrast, the converter is controlled by PI cascade, the output voltage drops from 24 V to 23.3 V, and it takes 0.25 s to reach the desired value. The converter controlled by the proposed method can respond immediately and achieve the desired effect. At the same time, a longer response time and a large voltage deviation can be observed under the PI controller. The current response is shown in Figure 9; by further observing the change of the inductor current, both the LADRC control and the PI control can quickly reach the desired value, but the current shock of the PI control is larger than proposed method.

![Figure 8. Output voltage responses in Case 1.](image1)

![Figure 9. Inductance current responses in Case 1.](image2)

![Figure 10. Output voltage responses in Case 2.](image3)

![Figure 11. Inductance current responses in Case 2.](image4)
Case 2: To further validate the proposed control method, the changes of the input voltage were doubled. The basic setting was identical with the Case 1. Firstly, the output voltage was regulated at 24 V, and a 50 Ω resistance was connected to the DC bus. At 0.6 s, the input voltage of the converter was reduced from 12 V to 8 V. The output voltage response is shown in Figure 10; the converter is controlled by LADRC cascade, the output voltage drops from 24 V at 23.2 V and reaches the desired value after 0.07 s. In contrast, the converter is controlled by PI cascade, the output voltage drops from 24 V to 22.6 V, and it takes 0.28 s to reach the desired value. The current response is shown in Figure 11; the verification results are consistent with the results of Case 1.

Case 3: For load changes, the proposed control method was verified by Case 3. Initially, the output voltage was stable at 24 V and a 50 Ω resistance is connected. Then, the resistance decreased to 25 Ω in 0.6 s. The output voltage response is shown in Figure 12. With the load changes, the voltage deviation of PI control is 2.6 V and the recovery process is 0.35 s. The recovery process of the proposed control algorithm is 0.1 s, which is shorter than the recovery process of PI control by 0.25 s. Simulation results show that the proposed control algorithm has good dynamic performance. In addition, the output current response is shown in Figure 13; by observing changes of the inductor...
current, LADRC control can quickly reach the desired value, while PI control takes a long time to reach the desired value.

6. Hardware Experiment

Case 1: The converter input voltage was changed to examine the stabilization performance. At 6 V, the power circuit was regulated to 24 V with a 30-Ω resistance load. A 0.6-V input current was applied to the converter, and the DC/DC boost converter experimental platform was built, as shown in Figure 7. The platform consists of a power circuit, a DC/DC converter, an electronic load, and a computer. During the experiment, the input voltage was set to 0.6 V, and the output voltage was monitored. The stabilization performance was tested at 4 V, 6 V, 8 V, and 10 V. The output current was 0.1 A. With the same load change, the output voltage was regulated at 24 V, and the inductor current was recorded. The control performance of LADRC control was compared with PI control through simulation. The simulation results show that the proposed control algorithm has good dynamic performance. In addition, the output current response is shown in Figure 13; by observing changes of the inductor current, the proposed control method can achieve the desired value, but the current of PI control takes a long time to reach the desired value.

Case 2: To verify the proposed control method, the input voltage of the converter was increased from 6 V to 28 V, and the input current was doubled. At 0.6 V, the input current was applied to the converter, and the output voltage was regulated at 24 V. The output voltage response is shown in Figure 14. By observing the changes of the inductor current, both the LADRC control and the PI control can quickly reach the desired value; however, the PI control has a larger voltage deviation. The proposed control method has good dynamic performance.

Figure 12: Inductance current responses in Case 3.

Figure 13: Output voltage responses in Case 3.

Figure 14: Inductance current responses in Case 3.
First, the input voltage of the boost converter was changed to 12 V and the load resistance was changed from 50 Ω to 25 Ω to verify the stability of the system under different loads. To ensure a constant output voltage, the current amplitude rises from 0.8 A to 2 A over a certain period. The experimental results are shown in Figure 17. The output voltage and inductor current controlled by LADRC reach the desired value more quickly than the PI control.

**Figure 14.** DC/DC boost converter experimental platform.

**Figure 15.** (a) LADRC controller: experimental comparison responses with Case 1; and (b) PI controller: experimental comparison responses with Case 1.

**Figure 16.** (a) LADRC controller: experimental comparison responses with Case 1; and (b) PI controller: experimental comparison responses with Case 2.

**Figure 17.** (a) LADRC controller: experimental comparison responses with Case 3; and (b) PI controller: experimental comparison responses with Case 3.

First, the input voltage of the boost converter was changed to examine the stability of the system. The output voltage was controlled at 24 V and a 50 Ω resistive load was connected to the voltage output. As shown in Figure 15, the input voltage of the boost converter drops from 12 V to 10 V. To ensure a constant output voltage, the current amplitude rises from 0.8 A to 1 A in a short time. The recovery time of the output voltage controlled by LADRC is shorter than the recovery time of the PI control. To further verify the stability of the system, the comparison of similar conditions continued, and the input voltage was changed by twice as much. Consistent with the previous results, the LADRC controller can quickly reach the desired value, while PI control takes a long time to bring the output voltage to the desired value faster. Experimental results are shown in Figure 16. The output voltage and inductor current controlled by LADRC reach the desired value more quickly than the PI control.

**Figure 14.** DC/DC boost converter experimental platform.

**Figure 15.** (a) LADRC controller: experimental comparison responses with Case 1; and (b) PI controller: experimental comparison responses with Case 1.

**Figure 16.** (a) LADRC controller: experimental comparison responses with Case 1; and (b) PI controller: experimental comparison responses with Case 2.

**Figure 17.** (a) LADRC controller: experimental comparison responses with Case 3; and (b) PI controller: experimental comparison responses with Case 3.
The authors declare no conflict of interest.

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8. Conclusions

The instability of the output voltage caused by the fluctuation of input voltage and that of loads is solved by designing the LADRC controller. The simulation and experimental results show that the output voltage by using LADRC cascade control reaches the desired value more quickly than the PI control.

Appendix A

Symbol | Description | Definition and Explanation
--- | --- | ---
LSEF | linear state error feedback | Linear active disturbance rejection control
ADRC | active disturbance rejection control | ADRC
ESO | extended state observer | ESO
PWM | pulse width modulation | PWM
L | inductance value | In a short time.
R | resistive load | Resistor.

Electronics 2019, 8, x; doi: FOR PEER REVIEW...
T switching period
\(d\) duty cycle
\(\mu(t)\) pulse function
\(U_d(\infty)\) the steady state values of \(U_d\)
\(I_L(\infty)\) the steady state values of \(I_L\)
\(U_{ref}\) reference value of output voltage
\(I_{Lref}\) reference value of inductor current
\(r\) first-order LADRC input reference
\(u_0\) controlled quantity
\(\omega\) external disturbance of the system
\(G_p\) controlled object
\(y\) system output
\(\hat{y}\) estimated value of system output
\(f\) total disturbance of the system
\(\hat{f}\) estimated value of the total disturbance
\(b_0\) system gain
\(K_p\) gain of LSEF
\(L_o\) gain of LESO
\(\omega_o\) observer’s bandwidth
\(\omega_c\) controller’s bandwidth
\(D\) 1-d
\(G_p(s)\) transfer function of the DC/DC boost converter
\(\Delta U_{ref}\) reference voltage of the voltage loop
\(\Delta I_{ref}\) reference current of the current loop
\(\Delta U_o\) output voltage
\(H_1(s), G_{c1}(s)\) transfer function of LADRC voltage outer loop
\(H_2(s), G_{c2}(s)\) transfer function of LADRC current inner loop
\(G_{p1}(s)\) transfer function of the \(\Delta d\) to \(\Delta U_o\)
\(G_{p2}(s)\) transfer function of the \(\Delta d(t)\) to the \(\Delta I_L\)
\(G_{c1}(s)\) transfer function of the inner loop current loop
\(G_{c2}(s)\) system open loop transfer function
\(\omega_{c1}, \omega_{c1}, b_1\) LADRC parameters of current control loop
\(\omega_{c2}, \omega_{c2}, b_2\) LADRC parameters of voltage control loop
\(k_{p1}, k_{i1}\) PI parameters of voltage control loop
\(k_{p2}, k_{i2}\) PI parameters of current control loop

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