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Active Disturbance Rejection Control Method with Its Application to DC/DC Converter

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Abstract: This paper investigates the control of DC-DC converter with the help of Active Disturbance Rejection Control (ADRC). The DC-DC converter is an important power electronic equipment used for voltage regulation, but its performance is often influenced by external disturbances. Traditional control approaches, such as PID, are inadequate in handling such disturbances in real-time. To address this challenge, an ADRC-based control approach is applied. The ADRC control approach, particularly through the use of Extended State Observer (ESO), is configured to address and reject disturbances, ensuring accurate output voltage control. In this paper, DC-DC buck converter and boost converter are both applied with ADRC control approach, to analyze the more general situation.

Keywords: ADRC, DC-DC converter, extended state observer.

1. Introduction

The DC-DC converter is one of the most commonly used power electronic circuits, with the purpose of changing DC voltage to lower or higher levels with high efficiency. The converter consists of main components including a controlled switch, an inductor, a capacitor, and a load resistor, all of which influence the stability and performance of the output voltage [1]. However, practical applications of DC-DC converters often face significant challenges due to disturbances such as supply voltage instability, changes in the load resistance, and other external uncertainties [2].

Traditional PID controllers struggle to regulate DC-DC converters due to their limited ability to handle non-linearities and external disturbances.[3], [4]. Active Disturbance Rejection Control (ADRC) offers a prospective implementation strategy for such challenges [5], as it is specifically designed to address the presence of unknown disturbances in dynamic systems [6]. Through the use of Extended State Observer (ESO), ADRC estimates the total disturbance time by time, providing an efficient way to reject disturbances and enhance disturbance rejection capability and reference following precision [6]–[8]. Unlike traditional methods, ADRC doesn't require precise mathematical models of the disturbances, making it particularly suitable for systems with complex and uncertain behaviors [5].

The ADRC approach is demonstrated through simulation results, which show a better control effectiveness in the converter's performance compared to traditional control strategies [6], [9]–[11]. The ability of ADRC to preserve regulated load terminal potential under the presence of disturbances such as input voltage variations and load changes underscores its potential for real-world applications in power regulation systems [8], [9], [12]. Reconfigurable intelligent surface (RIS)-based wavefront manipulation [14] and orbital angular momentum (OAM) transmission [15], with their rapid response and anti-interference characteristics, offering new perspectives for DC-DC converters with the help of ADRC approach.

This paper presents a systematic approach to applying ADRC to the DC-DC converters. The dynamic model of the converters is derived at the beginning of each part. The ADRC controller is then applied in converters with mathematic method to optimize the performance of converters, with particular emphasis on minimizing the output voltage tracking error. Through the use of an ESO, the controller effectively compensates for the disturbances, resulting in improved voltage regulation.

2. ADRC on DC-DC buck Converter

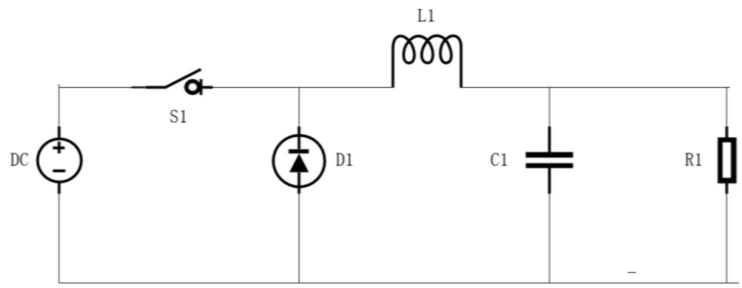

Figure 1: DC-DC buck converter.

Figure 1 shows the DC-DC buck converter with PWM which is made up of a direct current supply V_i, an active switching element S1 driven by PWM, a diode to regulate unidirectional current D1, an energy storage inductor L1, a filter capacitor C1 and an electrical resistance R1. The dynamic model is given as follows

$$\begin{cases} \frac{dv_o(t)}{dt} = \frac{1}{C} i_{in}(t) - \frac{1}{CR} v_o(t), \\ \frac{di_{in}(t)}{dt} = \frac{1}{L} \mu(t) V_i - \frac{1}{L} v_o(t), \end{cases} \tag{1}$$

where V_o refers to the potential difference across capacitor C1, which represents the system's output voltage. i_{in} stands for the mean input current. C represents the capacitance of C1. R stands for the load impedance of the dynamic model. L represents the magnetic storage capacity of L1,and $\mu(t) \in [0, 1]$ denotes the control signal. V_i donates to an input voltage. Find the derivative of the first equation and then subtract the two equations, we have

$$\frac{d^2 v_o(t)}{dt^2} = -\frac{1}{CR} \frac{dv_o(t)}{dt} - \frac{1}{CL} v_o(t) + \frac{V_i}{CL} \mu(t) \tag{2}$$

We define the expected output voltage as $v_r(t) = V_r$, and the error of output voltage as $e(t) = v_o(t) - v_r(t)$.

In the following task, an optimized ADRC algorithm is applied to let $e(t) \rightarrow 0$ as $t \rightarrow \infty$, which can reduce uncertainties such as input voltage variations, load resistance changes, and other external disturbances.

The formula (2) can be rewritten as

$$\ddot{v}_o(t) = f\big(v_o(t), \dot{v}_o(t), \mu(t)\big) + b_0 \mu(t) \tag{3}$$

where L_0, C_0 and V_{i0} represents the nominal values of L, C and V_i, $f\big(v_o(t), \dot{v}_o(t), \mu(t)\big) = a_1 v_o + a_2 \dot{v}_o + (b - b_0)\mu$ represents the uncertainties, with

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$$a_1 = -\frac{1}{CL},\ a_2 = -\frac{1}{CR}, b_0 = \frac{V_{i0}}{C_0 L_0}, b = \frac{V_i}{CL} \tag{4}$$

According to ADRC control approach, an ESO for the dynamic system shown above is described as [6]

$$\begin{cases} \hat{v}_o = z_1, \hat{\dot{v}}_o = z_2, \hat{f} = z_3, \\ \dot{z}_1 = z_2 - \beta_1(z_1 - v_o), \\ \dot{z}_2 = z_3 + b_0\mu - \beta_2(z_1 - v_o), \\ \dot{z}_3 = -\beta_3(z_1 - v_o), \end{cases} \tag{5}$$

where β_1, β_2, β_3 represent the gains of the observer, $\hat{v}_o$, $\hat{\dot{v}}_o$ and $\hat{f}$ represents the estimates of v_o, $\dot{v}_o$ and f. A full-order generalized proportional integral observer for the converter system can be formulated similarly by[13]

$$\begin{cases} \hat{v}_o = z_1, \hat{\dot{v}}_o = z_2, \hat{f} = z_3, \hat{\dot{f}} = z_4, \\ \dot{z}_1 = z_2 - \beta_1(z_1 - v_o), \\ \dot{z}_2 = z_3 + b_0\mu - \beta_2(z_1 - v_o), \\ \dot{z}_3 = z_4 - \beta_3(z_1 - v_o), \\ \dot{z}_4 = -\beta_4(z_1 - v_o), \end{cases} \tag{6}$$

where β_1, β_2, β_3, β_4 represent the gains of the observer, $\hat{v}_o$, $\hat{\dot{v}}_o$, $\hat{f}$ and $\hat{\dot{f}}$ are estimates of v_o, $\dot{v}_o$, f and $\dot{f}$. Based on the above two observers, the system model with ADRC laws applied can be designed as

$$\mu(t) = -\frac{1}{b_0}\left[k_1\left(v_o(t) - v_r(t)\right) + k_2\hat{\dot{v}}_o(t) + \hat{f}(t)\right] \tag{7}$$

Feedback control gains can be designed by changing k_1 and k_2.

3. ADRC on DC-DC boost Converter

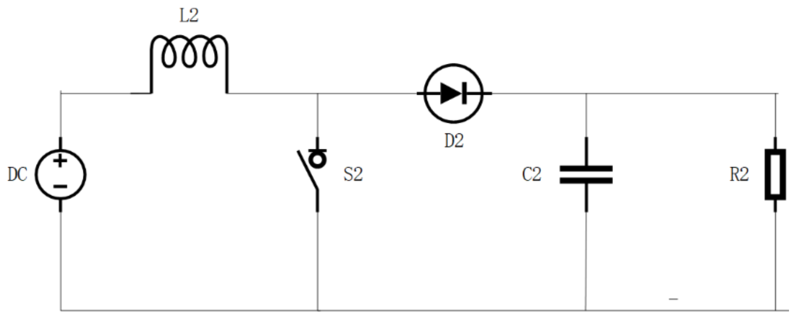

Figure 2: DC-DC boost converter.

Figure 2 shows the DC-DC buck converter with PWM which is made up of a direct current supply V_i, an active switching element S2 driven by PWM, a diode to regulate unidirectional current D2, an energy storage inductor L2, a filter capacitor C2 and an electrical resistance R2. The dynamic model is given as

$$\begin{cases} \frac{dv_o(t)}{dt} = \frac{1}{C}[1-\mu(t)]i_{in}(t) - \frac{1}{CR}v_o(t), \\ \frac{di_{in}(t)}{dt} = \frac{1}{L}V_i - \frac{1}{L}[1-\mu(t)]v_o(t), \end{cases} \tag{8}$$

where V_o refers to the potential difference across capacitor C2, which represents the system's output voltage. C denotes the capacitance of C2. $\mu(t) \in [0, 1]$ stands for the control signal. i_{in} stands for the mean input current. R stands for the load impedance of the dynamic model. L represents the magnetic storage capacity of L2 and V_i donates to an input voltage. Subsequently, this paper will introduce the two cases of ADRC controlling current and voltage in two separate parts.

1) The current controller is designed as follows:

$$\frac{di_{in}(t)}{dt} = \frac{1}{L}V_i - \frac{1}{L}[1-\mu(t)]v_o \tag{9}$$

We define the expected output current as $i_r(t) = I_r$, and the error of output voltage as $e(t) = i_{in}(t) - i_r(t)$, and the formula (2) can be rewritten as

$$\dot{i}_{in}(t) = f\big(i_{in}(t), \mu(t)\big) + b_0\mu(t) \tag{10}$$

where L_0, C_0 and V_{i0} represents the nominal values of L, C and V_i, $f\big(i_{in}(t), \mu(t)\big) = \frac{1}{L}V_i - \frac{1}{L}v_o$ represents the uncertainties, with $b_0 = \frac{1}{L_0}$.

According to traditional ADRCs, an ESO for the dynamic system shown above is designed as

$$\begin{cases} \hat{i}_{in} = z_1, \hat{f} = z_2, \\ \dot{z}_1 = z_2 + b_0\mu - \beta_1(z_1 - i_{in}), \\ \dot{z}_2 = -\beta_2(z_1 - i_{in}), \end{cases} \tag{11}$$

where β_1, β_2, β_3 represent the gains of the observer, $\hat{i}_{in}$ and $\hat{f}$ are estimates of i_{in} and f. Based on the above observer, the system model with ADRC laws applied can be designed as

$$\mu(t) = -\frac{1}{b_0}\left[k_1\big(i_{in}(t) - i_r(t)\big) + \hat{f}(t)\right] \tag{12}$$

Feedback control gains can be designed by changing k_1.

2) The voltage controller is described as:

$$\frac{dv_o(t)}{dt} = \frac{1}{C}[1-\mu]i_{in}(t) - \frac{1}{CR}v_o(t) \tag{13}$$

The expected output voltage is defined as $v_r(t) = V_r$. The error of output voltage is defined as $e(t) = i_{in}(t) - i_r(t)$, and the formula (2) can be rewritten as

$$\dot{v}_o(t) = f\big(v_o(t), i_{in}(t)\big) + b_0 i_{in}(t) \tag{14}$$

where L_0, C_0 and V_{i0} represent the nominal values of L, C and V_i, $f(v_o(t), i_{in}(t)) = -\frac{1}{CR}v_o(t)$ represents the uncertainties which have been mentioned above, with $b_0 = \frac{1}{C}[1-\mu]$.

According to traditional ADRCs, an ESO for the dynamic system shown above is designed as

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$$\begin{cases} \hat{v}_o = z_1, \hat{f} = z_2, \\ \dot{z}_1 = z_2 - \beta_1 (z_1 - v_o), \\ \dot{z}_2 = z_3 + b_0 i_{in} - \beta_2 (z_1 - v_o), \end{cases} \tag{15}$$

where β_1, β_2, β_3 represent the gains of the observer, $\hat{v}_o$ and $\hat{f}$ stand for estimations of v_o and f. Based on the above observer, the system model with ADRC laws applied can be designed as

$$\mu(t) = -\frac{1}{b_0}\left[k_2\left(v_o(t) - v_r(t)\right) + \hat{f}(t)\right] \tag{16}$$

Feedback control gains can be designed by changing k_2.

4. Conclusion

This paper has explored the application of ADRC to improve the performance of DC-DC converters, which are essential components in power electronics. The dynamic modeling of both buck and boost converters has been conducted to provide a comprehensive understanding of their behavior under varying conditions. By employing an ESO, the ADRC control approach dynamically estimates and compensates for disturbances, enabling precise output voltage regulation without measuring precise data of the circuits. The findings of this study underscore the potential of ADRC as a robust and efficient control approach for DC-DC converter applications. Its ability to operate effectively in the presence of uncertainties makes it an invaluable tool for modern power systems requiring precise and reliable voltage regulation. Future work could involve the implementation of ADRC in hardware systems and further optimization to enhance its real-time performance.

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