Avrupa Bilim ve Teknoloji Dergisi
Özel Sayı 37, S. 108-112, Haziran 2022
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Araştırma Makalesi

www.ejosat.com ISSN:2148-2683

European Journal of Science and Technology
Special Issue 37, pp. 108-112, June 2022
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Research Article

An Alternative Approach of Disturbance Rejection Control Methodology to DC-DC Boost Converter

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(5th International Symposium on Innovative Approaches in Smart Technologies – 28-29 May 2022)

(**DOI:** 10.31590/ejosat.1136558)

ATIF/REFERENCE: Eker, D. & Özbek, N.S. & Çelik, Ö. (2022). An Alternative Approach of Disturbance Rejection Control Methodology to DC-DC Boost Converter. *European Journal of Science and Technology*, (37), 108-112.

Abstract

This study presents an active disturbance rejection control (ADRC) technique for a boost converter system which is represented with a second - order transfer function. Then, linear active disturbance rejection control (LADRC) technique, wherein a linear extended state observer (LESO) is constructed to estimate both the total disturbance and the system state at the same time, has been applied to the converter. In this context, a pole placement design reduces the number of tuning parameters of LADRC to two to lessen the difficulty of parameter adjustment. The control scheme increases the tracking capability. A numerical example is provided to highlight the effectiveness of the control strategy. The tracking performance and step response are observed via several simulation studies using MATLAB/Simulink tool. It is demonstrated that the algorithm used in study is alternative way of tuning duty cycle of the boost converter instead of PID control technique. The performance of the controller is evaluated with a number of performance metrics. The tabulated results validate the controller's efficacy.

Keywords: Active Disturbance Rejection Control (ADRC), Power Converters, Renewable Energy, Extended State Observer

Yükseltici DA-DA Dönüştürücü için Bozucu Bastırma Kontrolü Metoduna Alternatif Bir Yaklaşım

Öz

Bu çalışma, ikinci derece transfer fonksiyonu ile ifade edilmiş yükseltici konvertör sistemi için aktif bozucu bastırma kontrolü (ABBK) tekniğini ortaya koymaktadır. Daha sonra hem toplam bozulmayı hem de sistem değişkenlerini aynı anda tahmin etmek için tasarlanmış lineer genişletilmiş durum gözleyicisini bünyesinde barındıran doğrusal aktif bozucu bastırma kontrol (DABBK) tekniği dönüştürücüye uygulanmıştır. Bu bağlamda, bir kutup yerleştirme tasarımı, DABBK'nın parametre ayarlama zorluğunu azaltmak için ayar parametrelerinin sayısını ikiye indirmektedir. Kontrol şeması izleme kabiliyetini arttırmaktadır. Kontrol strajesinin etkinliğini vurgulamak için sayısal bir örnek verilmiştir. İzleme performansı ve basamak tepkisi MATLAB/Simulink programı kullanılarak simülasyonla gözlemlenmiştir. Çalışmada kullanılan algoritmanın PID kontrol tekniği yerine yükseltici dönüştürücü görev çevrim oranı

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ayarlanmasının alternatif yolu olduğu gösterilmiştir. Kontrolcünün performansı bir takım performans indisleri ile değerlendirilmiştir. Tablo haline getirilmiş sonuçlar, kontrolcünün etkinliğini doğrular niteliktedir.

Anahtar Kelimeler: Aktif Bozucu Bastırma Kontrolü (ABBK), Güç Dönüştürücüleri, Yenilenebilir Enerji, Genişletilmiş Durum Gözleyicileri

1. Introduction

DC-DC power converters have been employed in a range of applications including wind energy, solar energy, and energy storage systems. To mention a few, in PV systems, power converters are utilized to convert energy form and increase energy harvesting capacity. On the other hand, they are used for the integration of energy storage systems with smart power grids. Power electronics allow control of power through electronic circuits that includes semiconductor devices with different ratings. It is possible to modify the voltage or current in any energy system by using the power electronics circuits. The main goal of the field of power electronics can be expressed as promoting the performance and stability of circuits that are used in energy systems. In this manner, typical applications of power electronics involve the conversion of DC to AC, AC to DC, AC to AC, and DC to DC. The boost converter is one kind of DC-DC converter that is frequently used to accomplish the conversion of DC voltage to a regulated level of DC voltage. Various control strategies have been applied to boost converters such as robust adaptive sliding mode control (Oucheriah & Guo, 2013) and adaptive backstepping sliding mode control (Wu & Lu, 2019).

From the feedback control point of view, numerous types of PID controllers are dominantly used in order to stabilize the output voltages and to provide the need of tracking performance; but for the converters that have dynamic system functionality, the PID controllers do not have the ability to maintain the same efficiency. Active Disturbance Rejection Control (ADRC) is one of the recently utilized control techniques which could overcome the drawbacks of conventional controllers. The application of ADRC to DC-DC converters is still remained a gap to be filled.

Apart from the various control techniques, ADRC can be considered as an efficient technique that is used in several sectors of industry and research. It was first proposed by J. Han (Han, 2009). The main motivation is to demonstrate the fact that PID control is not satisfactory for the new demands of industry and an alternative control technique could be used instead of PID. The reason behind raised motivation is the capability of ADRC regarding dealing with a wide range of uncertainties and disturbances (Herbst, 2013). Although it was first proposed as a nonlinear control technique, it is such an effective method that can overcome the drawbacks of PID. The effectiveness of ADRC has been investigated in several engineering applications by conducting experimental and simulation studies. Some ADRC applications have been carried out in various fields such as diesel engines (Criens et al., 2015), flywheel energy storage systems (Chang et al., 2015), photovoltaic systems (Zhou et al., 2021), DC microgrid systems (Liu et al., 2021), and gas turbine systems (Shi et al., 2020).

Besides the aforementioned studies, improved version of ADRC algorithm is applied to the DC bus voltage of the wind power grid-connected inverter system which contains nonlinearities and susceptibility to the grid-side voltage changes in (Yuan et al., 2022). The traditional Linear Active Disturbance Rejection (LADRC) and improved version of that algorithm mentioned in the study are compared in terms of disturbance rejection performance. In terms of renewable energy field likewise the wind energy concept mentioned above, DC-DC buck converters are widely used to reduce the voltage. In (Abdelmalek et al., 2020) DC-DC buck converter control problem is adressed because the voltage trajectory tracking and Maximum Power Point (MPP) applications are the concerns to be clarified. With proposed technique which includes sliding mode controller, nonlinear state observer for current estimation; different test scenarios on state estimation, trajectory tracking and active disturbance rejection performances are compared with PI control technique. Whereas the comparison of PI and ADRC are the topics of some papers, the combination of them for inverter-based arc supression coils are used particularly in resonant grounded distribution power systems in (Barzegar-Kalashani, M., & Mahmud, M. A., 2022). The fault currents and faulty phase voltages are compansated and disturbance rejection performance of the hybrid controller performs better than individually designed ADRC and PI controllers. Another combination of ADRC with Fuzzy control technique is applied to the interior permanent magnet synchronous motor to find a solution of speed control issue in (Feng et al., 2022). The speed fluctuations in Fuzzy-LADRC is observed less than that in LADRC technique.

The idea of ADRC is to treat all uncertainties and disturbances as a generalized disturbances and to estimate them by Extended State Observer (ESO) (Eker & Özbek, 2021). Then, the control scheme utilizes the uncertainties and disturbances as feedback to reduce undesired signals. Although the ADRC algorithm is easy to implement with modern digital computers, the designer is expected to deal with a set of parameters. To overcome this issue a new approach is proposed namely Linear Active Disturbance Rejection Control (LADRC), wherein a linear ESO and state feedback are used.

This paper is organized as follow. In Section 2, the studied model is given for the individual parameters as a transfer function. Then, in Section 3, LADRC algorithm is applied to the boost converter model and obtained results are addressed. In Section 4, the functionality of the controller is discussed and comments are given.

2. Model of the Boost Converter

A DC-DC boost converter circuit, as illustrated in Fig.1, is a power electronic circuit that employs a switching mechanism to transfer one voltage level to another voltage level. Because of its potential impact on the power capacity, control of DC-DC power converters is an issue that attracts attention in industrial applications.

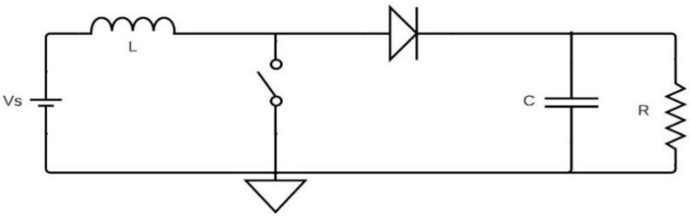


Fig. 1. DC-DC Boost Converter Topology

As in Fig.1. the capacitance, load resistance, and inductance are denoted by C, R, and L, respectively. For modelling of boost converter, firstly the state space equations are extracted to get the transfer function of the system. For the elaborated DC-DC ideal boost converter, the system states are $x_1 = i_L$, $x_2 = V_C$; and D represents the switching state of the DC-DC boost converter, which is a discrete set in the range 0–1. The following state-space representation is used to develop an accurate control scheme.

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\begin{bmatrix}0 & -(1-D)/L\\ (1-D)/C & -1/(R\times C)\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\begin{bmatrix}V_C/L\\ -i_L/C\end{bmatrix}\hat{d}$$
$$[y]=\begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} \qquad (1)$$

By using the system variables, small-signal model is expressed as a transfer function. Based on the converter parameters and state variables, the resulting transfer function is as follows:

$$G(s)=\frac{-60000[s-(1.25\times10^4)]}{s^2+1000s+(1.25\times10^7)} \qquad (2)$$

The parameters of the elaborated boost converter are presented in Table 1.

Table 1. Boost Converter Parameters

Converter Parameters	**Symbol**	**Value**
Input Voltage	V_{in}	15 V
Inductance	L	2 mH
Capacitance	C	10 uF
Resistance	R	100 Ω
Duty Cycle	D	0.5

3. ADRC Design for the Boost Converter

The functionality of the boost converter is to get a higher output voltage level than the input voltage level with the same polarity. According to converter parameters such as input voltage and duty cycle, the second-order model is constructed in the previous section. Through the model; DC gain, damping factor, and time constant of the system can be calculated for utilization in LADRC algorithm.

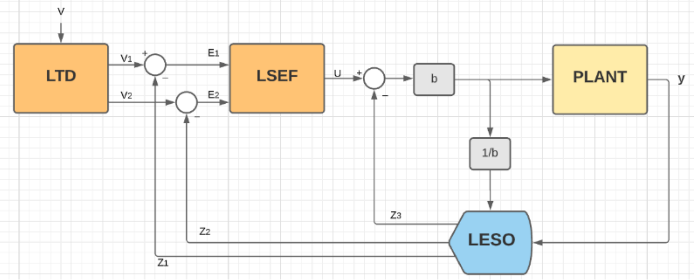


Fig. 2. LADRC topology

According to the transfer function *K, D,* and *T* values can be calculated as *60*, *500*, and *0.002* seconds, respectively. The transfer function has one zero, that is why by evaluating the natural frequency w_n of the transfer function and using with damping ratio ζ value, a second-order transfer function is constructed as the standard form of the second-order system:

$$\frac{w_n}{s^2+2\zeta w_n s+w_n^2} \qquad (3)$$

The system model is rearranged by using the equation (3) as given below:

$$\ddot{y}=b_o u+f \qquad (4)$$

where b_0 is the input parameter, u is the input signal, y is the output signal, and f is the generalized disturbance. It should be noted that f parameter involves the input disturbance, the first derivative part of output signal. The parameter b_0, which improves the control performance of ADRC, can be approximately calculated from K/T^2. However, the tuning of b_0 is generally found by trial and error (Wang, F., Wang, R.-J., & Liu, 2019).

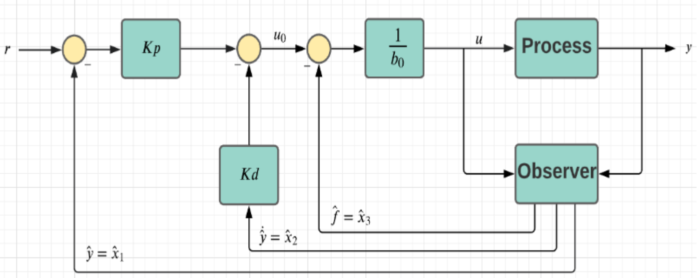


Fig. 3. ADRC topology used in the study

For the simplicity b_0 is considered to be 1 in the present study. In the pursuit of getting good robustness and satisfactory dynamic response simultaneously, the parameter can be selected a small value, then increase slowly until a sufficient control system performance is achieved. There will be three state variables for a second-order system due the augmented generalized disturbance parameter as an extra state, see Fig. 3. The most crucial part for the estimation the state variables is to design the observer as in Fig. 3. For this study Luenberger type of observer is designed. The objective is to design the observer to make the estimation of all system parameters as close as actual state variables. The states are:

$$\begin{aligned}x_1 &= y\\ x_2 &= \dot{y}\\ x_3 &= f\end{aligned} \qquad (5)$$

According to these considerations the state-space representation can be arranged as:

$$\begin{aligned}\dot{x} &= Ax+Bu+B_f\dot{f}\\ y &= Cx\end{aligned} \qquad (6)$$

When the system parameters *A, B, C,* B_f are determined, the observer can be designed according to the following equation:

L can be named as the observer gain and selection of observer parameters depend on the parametrization techniques. Then, PD controller parameters can be evaluated by determining the settling time of the system. The designer should adjust the settling time depend on the design and application of the boost converter.

One practical approach to tune the controller is to choose K_p and K_d as critically damped behaviour. For this simulation, the settling time is selected as *1* second and selection of the closed-loop poles as selected according to 5% rule regarding to:

$$s_{CL} = -\frac{6}{T_{settling}}, K_p = (s_{CL})^2, K_d = -2\times(s_{CL}) \qquad (7)$$

According to the design procedure K_p and K_d are calculated as *36* and *12* respectively, but it is a necessity to define the observer gains and pole locations. According to the bandwidth parametrization method (Gao, 2003), it can be calculated as:

$$s^{ESO} = (3...10)\times s_{CL} \qquad (8)$$

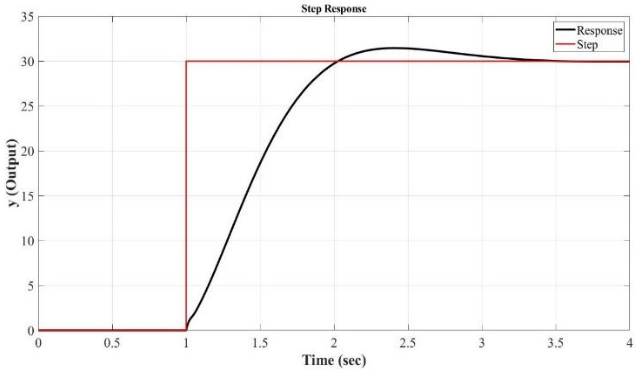
Observer poles should be selected as at least three times faster than closed-loop poles as regards Equation (7). For this simulation, observer poles are selected as five times faster than closed-loop poles. Once the observer pole locations are chosen, the observer gains are computed from the characteristic polynomial of (A-LC) but it can be calculated directly from:

$$l_1 = -3\cdot s^{ESO}, l_2 = 3\cdot(s^{ESO})^2, l_3 = -(s^{ESO})^3 \qquad (9)$$

By using Eq. 9 the gains are calculated and design procedure can be completed. However, the tuning procedure should be adjusted with b_0 value. It should be selected as *1* at the beginning of simulation and increase slowly to get rid of the oscillation at the starting point of transition.

4. Performance Evaluation

The closed loop system was simulated via MATLAB/Simulink platform. Step response graph and tracking graphs of the systemare shown in Fig. 4 (a) and (b), respectively.



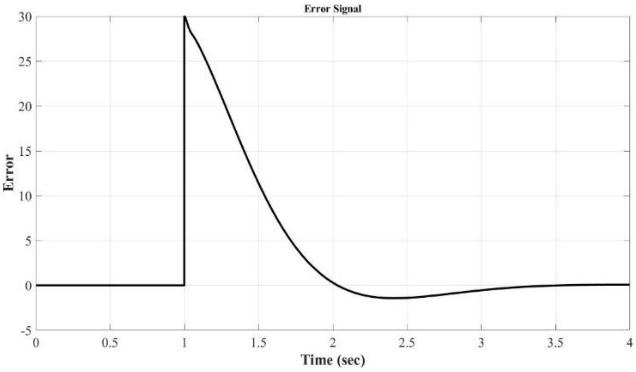


Fig. 4. (a) Step Response Graph and (b) Error Signal Graph

It can be seen that LADRC algorithm operates and regulates the converter regarding the conditions that designer chooses. The reference voltage is set to 30 V. From the Fig. 4 (a), a small amount of overshoot can be observed and the maximum value of the overshoot 31.45 V. The desired settling time is arranged as 1 second while the designing procedure and after tuning, the settling time is monitored as 0.85 second. This demonstrates that performance of controller is satisfactory for the boost converter model used in this paper. From the Fig. 4 (b), the maximum output voltage difference between the reference voltage and the maximum output voltage can be calculated as 1.45V. Thus, the maximum error voltage regarding to reference voltage is 4.83 % which is below the expected percentage error value.

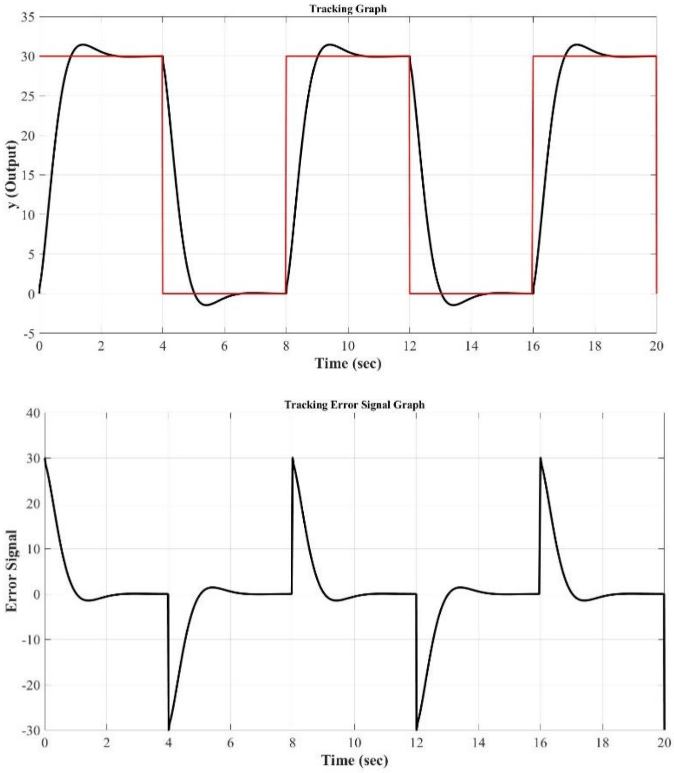


Fig. 5. (a) Tracking Graph and (b) Tracking Error Graph

In the second scenario tracking performance is tested in the presence of square wave input signal. According to the Fig. 5., 50% of the square wave which has an amplitude value of 30 V is applied to the closed loop system for the duration of 20 seconds. The capability of tracking the voltage values indicated as in the graph shows that the tracking performance of the controlled systemis sufficient for the application.

A number of performance metrics namely Integral Absolute Error (IAE), Integral Squared Error (ISE), Integral Time Square Error (ITSE) and Integral Time Absolute Error (ITAE), have been employed for a quantitative performance measurement of the control scheme. In this context, the numerical results of the aforementioned indices are shown in Table 2, wherein the step changes were taken into account in order to get the performance indices.

Table 2. Performance Criterions

Performance Parameter	**Value**
IAE	14.04
ISE	251.89
ITAE	19.80
ITSE	305.9

During the parameter tuning procedure, it is not recommended to increase the b_0 parameter too much because it affects the duration of the settling time.

5. Conclusion

In this paper, a new control technique named as ADRC is applied to a boost converter model. After the transfer function of the system is extracted, the damping factor, time constant, and DC gain of the system are adjusted. PD based LADRC is designed with proportional gain and derivative gain by using the practical approach. Then, the locations of the observer poles are determined to complete the design procedure. Regarding to the results, it can be stated that the LADRC approach is an alternate technique that may be utilized in the place of the PID.

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