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Novel Control Technique for DC-DC Buck Converters with Parametric Uncertainties

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***Abstract*— In this paper, a novel control technique i.e., Single-loop Adaptive Control (SA) for DC-DC buck converters is proposed. Initially, the nominal system of the DC-DC buck converter without considering the parametric uncertainties is built to develop the SA. Adaptive and back stepping control approaches are used to build the proposed technique. The proposed control strategy is analyzed for load variations and also for change in reference voltages. The advantages and disadvantages of the proposed control strategy are compared, analyzed and a conclusion is drawn.**

***Index Terms*— Adaptive, back stepping approach, Parametric uncertainties, Single-loop Adaptive Control (SA)**

I. INTRODUCTION

DC-DC converters are widely used for power conversion applications such as, electrical equipment used in medical systems, Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV), power supply and portable recharging systems. As there are numerous applications, the requirements for output voltage vary from application to application [1] – [3]. Also, the requirement for converters differs as well, so as to achieve faster dynamic response or to decrease the ripples in the output voltage, while some require a stable output voltage even in the presence of load variations and parametric uncertainties. Thus, the focus of the industries and scholars has been to design a converter which satisfies the requirements of all the applications.

Typically, the control structure presented is single loop control structure. The other type of control structure is double loop control structure [4]. The advantages of single loop control structure over double loop control structure is its simple implementation; also that current measurement is not required and hence, single loop control is also known as direct output control or voltage mode control. Whereas, a double loop control structure has two loops i.e., voltage regulation loop and current tracking loop and this control is known as indirect output control. It has strong anti-interference ability as it allows internal loop to control disturbances before affecting primary control objective [5]. Though double loop control can improve the system dynamic performance and tighter control, it is way more complex compared to single loop control as it needs to measure current also [6]. Based on single and double loop control structures, several control techniques have been proposed during the course of time [10] - [15]. To control buck converters, some linear control techniques were designed based on the linear modelling [16]. But, it is known that, the traditional linear controllers have worse dynamic performance compared to nonlinear controllers [17]. Some of the linear control techniques applied to the DC-DC buck converters are Traditional Sliding Mode Control (SMC), Second order sliding mode control for output voltage regulation [7] – [9], [13]. Double loop control structure SOSM controllers are designed containing voltage regulation loop and current tracking loop [22]. They are well known for their good tracking performance and Disturbance rejection ability against parametric uncertainties and external disturbances [13]. Adaptive control techniques [5], [20], [21] and fuzzy controllers are some of the other suitable techniques. In one of the adaptive control techniques, adaptive finite time control algorithm, voltage regulation time has been enhanced by using two finite time convergent observers to estimate unknown input voltage and load variations [23]. Though these non-linear control techniques improve the performance of the converter, most of them assume nominal values of filter inductor and output capacitor same as their actual values which effects the control performance of converter system as parameter uncertainties exist in practice. Though the control strategies such as SOSM and intelligent control algorithms show high performance, they are not highly recommended for being highly non-linear, complicated and having many control parameters making them difficult to analyze, design and implement. Few works have evaluated the performance difference between the both type of control structures through experiments too. Thus, the main contribution of this paper is to design control strategy, model of the system with and without considering parametric uncertainties in order to design the proposed Single loop adaptive control technique. The objective is to regulate output voltage to its desired reference voltage in presence of unknown disturbances and parametric uncertainties. By focusing on this objective a simple yet novel control technique i.e., Single Loop Adaptive Control Strategy has been designed based on the adaptive and back-stepping control approaches.

II. STATE SPACE REPRESENTATION OF DC-DC BUCK CONVERTER MODEL

The parameters of the DC-DC buck converter as shown in Figure. 1 are: v_{in}, the input voltage, L is the filter inductor, C is the output capacitor and R is the equivalent load considering the unknown disturbance.

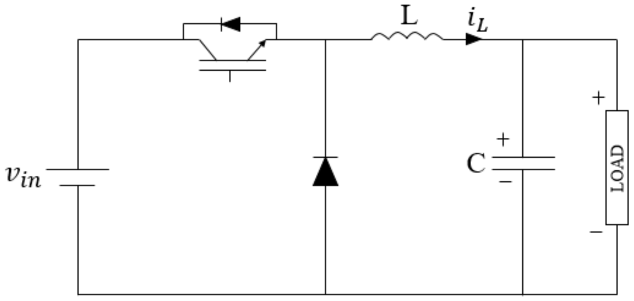

Figure. 1. DC-DC BUCK CONVERTER

When the switch is ON, by applying KVL we get,

$$v_{in} = L\frac{di}{dt} + v_c \tag{1}$$

When the switch is OFF, by applying KCL,

$$i_L = i_c + i_o \tag{2}$$

Where, $i_c = C\frac{dv_c}{dt}$ and $i_o = \frac{v_o}{R}$

By considering output voltage $(V_C)a\ x_1$, current through inductor (I_L) as x_2, control input as u_{av}, the averaged model of the DC-DC buck converter in continuous conduction mode (CCM) can be expressed as follows:

$$\dot{x}_1 = \frac{x_2}{C} - \frac{x_1}{RC} \tag{3}$$

$$\dot{x}_2 = -\frac{x_1}{L} + \frac{v_{in}}{L}u_{av} \tag{4}$$

It is to be observed that for the sake of simplicity, Discontinuous Conduction Mode (DCM) is not considered. The above system (3) - (4) is the nominal system for the converter without considering the parametric uncertainties of the filter inductor and output capacitor. Considering the fact that some practical applications do not know the accurate values of inductor and capacitor, the actual values of inductor and capacitor are defined as follows:

$$\bar{L} = L + \Delta L, \bar{C} = C + \Delta C \tag{5}$$

Where, L and C are nominal values and ΔL and ΔC are parametric uncertainties (unknown values) of filter inductor and output capacitor respectively.

Thus the DC-DC buck converter with uncertainties can be written as,

$$\dot{x}_1 = \frac{x_2}{\bar{C}} - \frac{x_1}{R\bar{C}} \tag{6}$$

$$\dot{x}_2 = -\frac{x_1}{\bar{L}} - \frac{v_{in}}{\bar{L}}u_{av} \tag{7}$$

By the dynamics of the converter, (6) and (7) can be rewritten as:

$$\dot{x}_1 = \frac{x_2}{C} + d_1 \tag{8}$$

$$\dot{x}_2 = -\frac{x_1}{L} + \frac{v_{in}}{L}u_{av} + d_2 \tag{9}$$

Where, $d_1 = -\frac{\Delta C x_2}{C(C+\Delta C)} - \frac{x_1}{R(C+\Delta C)}$ and $d_2 = -\frac{\Delta L x_1}{L(L+\Delta L)} - \frac{\Delta L v_{in} u_{av}}{L(L+\Delta L)}$

The State Space Representation of the converter can further be expressed in the form of,

$$\dot{x} = Ax + Bu_{av} + d$$

$$\text{i.e., } \begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & \frac{1}{C}\\ -\frac{1}{L} & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}0\\ \frac{v_{in}}{L}\end{bmatrix}u_{av} + \begin{bmatrix}d_1\\ d_2\end{bmatrix} \tag{10}$$

Where, $= [x_1\ x_2]^T$, $A = \begin{bmatrix}0 & \frac{1}{C}\\ -\frac{1}{C} & 0\end{bmatrix}$, $B = \begin{bmatrix}0\\ \frac{V_{in}}{L}\end{bmatrix}$, $d = \begin{bmatrix}d_1\\ d_2\end{bmatrix}$

As the objective is to regulate the output voltage to its desired reference voltage even if unknown disturbances and parametric uncertainties are present, based on the above dynamic model, Single-Loop Adaptive Control strategy will be designed to achieve the control objective. Before proceeding, the following lemma is presented.

Lemma 1: [25] If $\mathbf{F} \in \mathbb{R}^{n\times n}$ is the Hurwitz matrix, then there exists a positive scalar $\in$, such that $\|e^{Ft}\| \leq \in e^{\frac{\lambda max}{2}t}$ where , where $\lambda_{\max}$ is the largest eigenvalue of **F**.

III. STATE SPACE REPRESENTATION OF SINGLE LOOP ADAPTIVE CONTROL STRATEGY FOR NOMINAL SYSTEM

Based on the nominal system (3) - (4), the Single Loop Adaptive Control strategy is designed to achieve the control objectives. The error in obtaining desired output voltage, $z_1 = x_1 - x_1^*$

Where, x_1^* = desired output voltage

Where, x_1^* = desired output voltage

From equations (3) and (4), $\dot{z}_1 = \frac{x_2}{C} - \theta x_1 - x_1^*$

Where, $\theta = \frac{1}{RC}$ (Unknown parameter)

For load variation, let us assume that equivalent load R is known and changes in steps. By defining $\bar{\theta} = \hat{\theta} - \theta$

Lyapunov function can be constructed, $v_{s11} = \frac{1}{2}z_1^2 + \frac{1}{2\eta}\tilde{\theta}^2$

Where $\hat{\theta}$ = adaptive law to be designed.

By differentiating above equation,

$$\dot{v_{s11}} = z_1\left(\frac{x_2}{C} - \theta x_1 - \dot{x_1^*}\right) + \frac{1}{\eta}\tilde{\theta}\dot{\tilde{\theta}}$$

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From above equation, one can design as follows: virtual control $\boldsymbol{\alpha_1} = -\boldsymbol{k_{s11}z_1} + \dot{\boldsymbol{x}}_1 + \widehat{\boldsymbol{\theta}}\boldsymbol{x_1}$;

error variable $\boldsymbol{z_2} = \frac{\boldsymbol{x_2}}{\boldsymbol{C}} - \boldsymbol{\alpha_1}$ and adaptive law $\dot{\widehat{\boldsymbol{\theta}}} = -\boldsymbol{\eta z_1 x_1}$; where, k_{s11} & η are two scalars.

By substituting the value of x_2, $\dot{\boldsymbol{z}}_2 = -\frac{\boldsymbol{x_1}}{\boldsymbol{LC}} + \frac{\boldsymbol{V_{in}}}{\boldsymbol{LC}}\boldsymbol{u_{av}} - \dot{\boldsymbol{\alpha}}_1$

Lyapunov function v_{s12} for error system, $\boldsymbol{z} = [\boldsymbol{z_1}, \boldsymbol{z_2}]^T$ *is*

$$\boldsymbol{v_{s12}} = \boldsymbol{v_{s11}} + \frac{1}{2}\boldsymbol{z_2^2}$$

$$\dot{\boldsymbol{v}}_{s12} = -\boldsymbol{k_{s11}z_1^2} + \boldsymbol{z_1z_2} + \boldsymbol{z_2\dot{z}_2}$$

$$= -\boldsymbol{k_{s11}z_1^2} + \boldsymbol{z_2}\left(\boldsymbol{z_1} - \frac{\boldsymbol{x_1}}{\boldsymbol{LC}} + \frac{\boldsymbol{v_{in}}}{\boldsymbol{LC}}\boldsymbol{u_{av}} - \boldsymbol{\alpha_1}\right)$$

The control u_{av} such that $\dot{\boldsymbol{v}}_{s12} < 0$, $\boldsymbol{u_{av}} = \frac{\boldsymbol{LC}}{\boldsymbol{v_{in}}}\left(-\boldsymbol{z_1} + \frac{\boldsymbol{x_1}}{\boldsymbol{LC}} + \boldsymbol{\alpha_1} - \boldsymbol{k_{s12}z_2}\right)$

$\dot{\boldsymbol{v}}_{s12} = -\boldsymbol{k_{s11}z_1^2} - \boldsymbol{k_{s12}z_2^2} \leq \boldsymbol{0}$ **i.e.,** the error system $(\boldsymbol{z_1}, \boldsymbol{z_2}) \rightarrow \boldsymbol{0}$ i.e., the controller can regulate the output voltage to its desired reference.

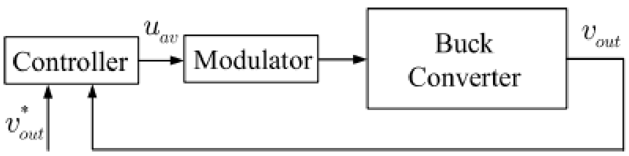

Figure. 2. Block diagram of Single-Loop Adaptive Control Strategy

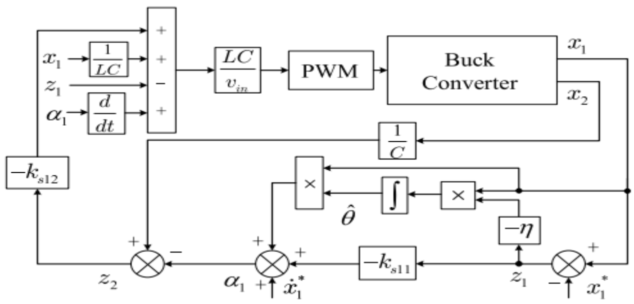

Figure. 3. Control Structure of SA control strategy

I. NOMINAL PARAMETERS OF THE BUCK CONVERTER

Description	Parameter	Nominal Value	Units
Switching frequency	f_{sw}	15	KHz
Inductor	L	38.7×10^{-3}	H
Capacitor	C	8.33×10^{-4}	F
Load Resistance	R	20→10	Ω
Input Voltage	V_{in}	340	V
Reference Voltage	x_1^*	72→55	V

II. CONTROL PARAMETERS OF THE PROPOSED CONTROL STRATEGY

CONTROL PARAMETER	VALUE
η	1200
K_{s11}	150
K_{s12}	200

IV. SIMULATION RESULTS

In this section, the results obtained for the proposed strategy to control the output of DC-DC buck converters are analyzed. The nominal parameters of the buck converter and the control parameters of the proposed control strategies are presented in I and II, respectively. The control objective is to regulate the output voltage and the results are given for two cases: load resistance and reference voltage variations.

A. Load Resistance Variations:

In this, the aim is to maintain the output voltage constant even during load variations. Thus, the reference voltage is kept constant at 72V and the load resistance is changed from 20Ω to 10 Ω. Through the results obtained, it can be seen that the proposed control strategy can regulate the output voltage to its reference voltage even under load variations. As shown in Figure. 4, the recovery time is 60msec and the voltage ripple is 160mV. Here, the voltage drop is less due to the adaptive law which adapts the unknown parameter, $\theta = \frac{1}{RC}$; Also the recovery time is very less and it has a faster dynamic response.

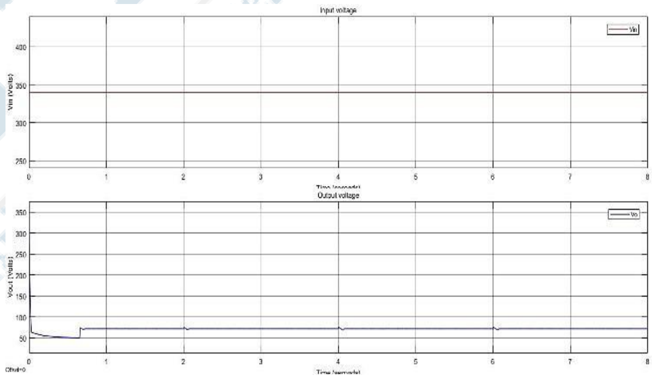

Figure. 4. Simulation result for load resistance variations

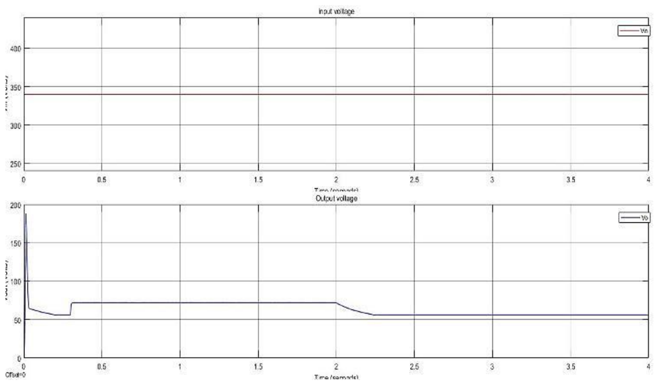

Figure. 5. Simulation result for voltage reference variations

B. Reference Voltage Variations:

Here, the reference voltage is changed from 72V to 55V

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while the load resistance and control parameters are kept constant. As shown in Figure. 5, when the reference voltage is changed, the voltage undershoots and recovers to its new reference voltage. Here, the recovery time is 250msec and ripple voltage is 130mV.

Therefore, the proposed Single Loop Adaptive control strategy can be used for the DC-DC buck converter to achieve the best performance in applications which require fast dynamic responses when the load or reference voltage changes.

V. CONCLUSION

The problems associated with regulation of output voltage in a DC-DC buck converter has been investigated in this paper. Based on the nominal and uncertain systems of the DC-DC buck converter, a novel control strategy, Single loop adaptive control strategy has been proposed. The characteristics and design procedure of the control strategy are discussed and analyzed. The results of the load resistance variation and the reference voltage variation, are provided to further analyze the advantages and disadvantages of the proposed strategy. The SA can ensure that the output voltage has the shortest recovery time whenever the load or the reference voltage changes. On the other hand, how to design an efficient controller for DC-DC buck converters considering the practical inductor and capacitor with parasitic resistances is still an open problem.

REFERENCES

[1] E. Hernández-Márquez et al., “Robust tracking controller for a DC/DC buck-boost converter–inverter–DC motor system,” Energies, vol. 11, no. 10, pp. 2500–2515, 2018.

[2] J. I. Leon, S. Vazquez, and L. G. Franquelo, “Multilevel converters: Control and modulation techniques for their operation and industrial applications,” Proc. IEEE, vol. 105, no. 11, pp. 2066–2081, Nov. 2017.

[3] M. K. Kazimierczuk, Pulse-Width Modulated DC-DC Power Converters. Hoboken, NJ, USA: Wiley, 2015.

[4] S. Bacha, (Advanced Textbooks in Control and Signal Processing). New York, NY, USA: Springer, 2014.

[5] S.-C. Tan, Y. M. Lai, M. K. H. Cheung, and C. K. Tse, “On the practical design of a sliding mode voltage controlled buck converter,” IEEE Trans. Power Electron., vol. 20, no. 2, pp. 425–437, Mar. 2005.

[6] K. J. Åström and T. Hägglund, PID Controllers: Theory, Design, and Tuning. Triangle Park, NC, USA: Instrument Society of America Research, 1995.

[7] S. Li, J. Yang, W.-H. Chen, and X. Chen, Disturbance Observer-Based Control: Methods Application. Boca Raton, FL, USA: CRC Press, 2016.

[8] L. Dixon, “Average current mode control of switching power supplies,” in Unitrode Power Supply Design Seminar Handbook. Merrimack, NH, USA: Unitrode Corp., 1990.

[9] M. Corless and G. Leitmann, “Continuous state feedback guaranteeing uniform ultimate boundedness for uncertain dynamic systems,” IEEE Trans. Autom. Control, vol. 26, no. 5, pp. 1139–1144, Oct. 1981.

[10] K. Hyeon Kim, J. Kim, H. Jun Kim, S. Hee Han, and H. Jung Kim, “A megahertz switching DC/DC converter using FeBN thin film inductor,” IEEE Trans. Magn., vol. 38, no. 5, pp. 3162–3164, Sep. 2002.

[11] J. Sha, D. Xu, Y. Chen, J. Xu, and B. W. Williams, “A peak-capacitor current pulse-train-controlled buck converter with fast transient response and a wide load range,” IEEE Trans. Ind. Electron., vol. 63, no. 3, pp. 1528–1538, Mar. 2016.

[12] A. N. Vargas, L. P. Sampaio, L. Acho, L. Zhang, and J. B. R. do Val, “Optimal control of DC-DC buck converter via linear systems with inaccessible Markovian jumping modes,” IEEE Trans. Control Syst. Technol., vol. 24, no. 5, pp. 1820–1827, Sep. 2016.

[13] R. Ling, D. Maksimovic, and R. Leyva, “Second-order sliding-mode controlled synchronous buck DC–DC converter,” IEEE Trans. Power Electron., vol. 31, no. 3, pp. 2539–2549, Mar. 2016.

[14] F. L. Luo and H. Ye, Advanced DC/DC Converters. Boca Raton, FL, USA: CRC Press, 2016

[15] Y. Zhao, W. Qiao, and D. Ha, “A sliding-mode duty-ratio controller for DC/DC buck converters with constant power loads,” IEEE Trans. Ind. Appl., vol. 50, no. 2, pp. 1448–1458, Mar. 2014.

[16] H.-H. Park and G.-H. Cho, “A DC–DC converter for a fully integrated PID compensator with a single capacitor,” IEEE Trans. Circuits Syst. II, Exp. Briefs, vol. 61, no. 8, pp. 629–633, Aug. 2014.

[17] V. S. C. Raviraj and P. C. Sen, “Comparative study of proportional integral, sliding mode, and fuzzy logic controllers for power converters,” IEEE Trans. Ind. Appl., vol. 33, no. 2, pp. 518–524, May 1997.

[18] Y. Huangfu, S. Zhuo, A. K. Rathore, E. Breaz, B. Nahid-Mobarakeh, and F. Gao, “Super-twisting differentiator-based high order sliding mode voltage control design for DC-DC buck converters,” Energies, vol. 9, no. 7, pp. 494–511, 2016.

[19] V. Utkin, “Sliding mode control of DC/DC converters,” J. Franklin Inst., vol. 350, no. 8, pp. 2146–2165, Oct. 2013.

[20] Y. Yin, J. Liu, S. Vazquez, L. Wu, and L. G. Franquelo, “Disturbance observer based second order sliding mode control for DC-DC buck converters,” in Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc., Oct. 2017, pp. 7117–7122.

[21] F. Giri, O. El Maguiri, H. El Fadil, and F. Z. Chaoui, “Nonlinear adaptive output feedback control of series resonant DC–DC converters,” Control Eng. Pract., vol. 19, no. 10, pp. 1238–1251, Oct. 2011.

[22] Y. Cheng, H. Du, C. Yang, Z. Wang, J. Wang, and Y. He, “Fast adaptive finite-time voltage regulation control algorithm for a buck converter system,” IEEE Trans. Circuits Syst. II, Exp. Briefs, vol. 64, no. 9, pp. 1082–1086, Sep. 2017.

[23] C. Elmas, O. Deperlioglu, and H. H. Sayan, “Adaptive fuzzy logic controller for DC–DC converters,” Expert Syst. Appl., vol. 36, no. 2, pp. 1540–1548, 2009.