ROBUST CONTROL FOR DC-DC BUCK CONVERTER UNDER PARAMETRIC UNCERTAINTIES

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Abstract— DC-DC Buck Converters are widely used in applications demanding the supply of a constant load voltage. However, the dynamic behavior of the buck converter may change due to uncertainties such as load and input voltage variations, as well as variations in the components of the buck converter itself. Because of these variations and the nonlinear behavior due to switching, makes the controller design presents some challenges on obtain the desired performance. In order to guarantee stability of the system and to preserve its dynamic performance under parametric uncertainties, in this paper a robust control technique, based on parametric uncertainties, is studied. The controller is designed by robust pole-placement technique based on a desired performance in closed-loop, specified by a family of characteristic polynomials. The design procedure is formulated as a set of linear constraints solved via linear programming methods. A classical controller, based on pole-placement technique, is used for performance comparison. For performance assessment, several tests were carried out in Matlab/Simulink environment. By calculating the ISE (integral square error) performance index, the obtained results show that the proposed controller obtain robust performance.

Keywords— buck converter, dc-dc converter, robust control, parametric uncertain, linear programing.

Resumo— Conversor CC-CC do tipo Buck são largamente utilizados em aplicações demandando a regulação da tensão na carga. No entanto, seu comportamento dinâmico pode sofrer variações devido à incertezas provocadas por variações de: tensão de entrada, carga e dos componentes do conversor. Considerando estas incertezas e o comportamento não-linear, devido ao chaveamento do conversor, o projeto do controlador apresenta alguns desafios para obter o desempenho desejado. Com o objetivo de garantir a estabilidade robusta e preservar o desempenho dinâmico, é proposto neste trabalho, a investigação de uma estratégia de controle robusta, baseada em incertezas paramétricas. O controlador é projetado por uma técnica robusta de alocação de polos baseada em um desempenho desejado em malha fechada, especificado por uma família de polinômios característicos. O procedimento de projeto é formulado como um conjunto de restrições lineares resolvidas através de métodos de programação linear. Um controlador clássico, baseado na técnica de posicionamento de pólos, é usado para comparação de desempenho. Testes computacionais, em ambiente Matlab/Simulink, foram realizados para avaliação de desempenho da metodologia proposta. Os cálculos do índice de desempenho ISE (erro quadrado integral) mostram que o controlador proposto apresenta desempenho com melhor desempenho robusto.

Palavras-chave— conversor buck, conversores CC-CC, incertezas paramétricas, programação linear.

1 Introduction

Nowadays, DC-DC converters are increasingly used in industrial applications due to their simplicity in structure, high power efficiency, low cost and high reliability (Qian *et al*, 2010), (Zhang *et al*, 2015). Some modern industries, whose processes demand high dynamic performance, have applied different types of converters for applications such as in variable speed DC motor drivers (Bhaumik *et al*, 2016), renewable energy systems (Hassanalieragh *et al*, 2016), (Xu *et al*, 2017), (Kumar *et al*, 2017), transportation systems (Chang & Liaw, 2011), (Ghiasi *et al*, 2017), hybrid energy storage system (Xiong *et al*, 2013), (Xu *et al*, 2017) and communications systems (Xiong *et al*, 2011). The converters are controlled by switching through Pulse Width-Modulation (PWM) to transfer the energy from a power source to a load. Because of switching, the converter converters have some inherent nonlinear behaviors (Mohan *et al*, 2002), (Salimi & Zakipour, 2015). Therefore, it is a challenging task to ensure the stability and higher efficiency of such converters (Salimi & Zakipour, 2015). However, the non-linear behavior, due to switching operation, has been often neglected while designing the control system for the converter (Zhang *et al*, 2015).

One important converter topology is the DC-DC buck converter, where the required output voltage is lower than the source voltage. DC-DC buck converters are typical dynamical nonlinear systems due to the inclusion of diodes and their variable structure characteristics, and their control problems are well acknowledged as a challenging issue (Middlebrook & Cuk, 1976), (Perry *et al*, 2017), (Guo *et al*, 2009). The main reasons are: load variations, power source variations, inevitable parameter uncertainties and exogenous disturbances. All these uncertainties could lead to instability and performance degradation.

The controller design is usually based on a linear approximation of nonlinear dynamics of the converter. Standard linear controllers, such PID controllers for instance, are tuned in order to regulate the output voltage of converters (Forsyth, 1998), (Middlebrook & Cuk, 1976). However, such conventional controllers may experience a sensible performance deterioration under varying operating conditions (Middlebrook & Cuk, 1976). In order to assure robustness against parameter uncertainties, linear controllers must be designed by using robust control theory. Therefore, it is advisable to design controller to cope with a pre-specified range of parameter uncertainties, load variations, or a wide variation of operating points. In addition, the performance of the DC-DC converters is also affected by external disturbance, which may cause instability that usually appear due to the measurement noises (Salimi *et al*, 2011). Therefore, the controller design process must ensure the performance robustness.

Recently, several advanced control techniques have been investigated for DC-DC converter system, which provides powerful tools in system modeling and robust controller design. These control techniques for DC-DC converter systems can be found in the literature, such as robust parametric control (Bhattacharyya *et al*, 1995), adaptive control (Tan *et al*, 2006), sliding mode voltage control (SMVC) (Labbe *et al*, 2014), model predictive control (MPC) (Kim *et al*, 2014) and multivariable robust control (Medeiros *et al*, 2018), to name a few.

In research on dynamic systems with parametric uncertainties, the techniques that deal with this problem have been studied extensively over the last 40 years (Bhattacharyya, 1992), (Bhattacharyya *et al*, 1995). In this context, control strategies, which aim to implement adaptive, predictive and fuzzy control algorithms, have been widely studied for the resolution of control problems of systems with parametric uncertainties. However, adaptive and fuzzy strategies, being able to offer efficient and satisfactory results, can make the implementation and operation of the process more complex (Barra Junior *et al*, 2005).

Another way to deal with parametric uncertainties in systems to be controlled, it is the robust pole-placement technique. In this technique, the robust controller designed must assign the closed-loop poles to a specific region of the complex plane, S, versus the parametric uncertainties related to the mathematical modeling of the system. In Lordelo & Ferrreira (2002), uncertain systems are represented by transfer functions whose coefficients belong to real intervals and the robust pole-placement is developed in order to guarantee robustness of poles in closed-loop in a specified region through the roots of a characteristic polynomial interval. Therefore, parametric uncertainties of a mathematical model are analyzed in controller design through interval analysis concepts.

In this paper, the design of a robust controller by pole-placement in the interval domain is presented. Robust pole-placement is based on a specified by a family of characteristic polynomials. Robust poles of the closed-loop system are obtained by linear programming (Bhattacharyya *et al*, 1995), (Bhattacharyya, 1992), (Bhattacharyya *et al*, 1995).

Theory analysis shows that the proposed controller maintain the stability and performance of systems against possible variations in their operating conditions and load disturbances.

A classical controller, based on pole-placement technique through the Diophantine equation, is used for performance comparison. The simulations have been carried out in MATLAB/SIMULINK.

The rest of the paper is organized as follows. In Section II, system modeling and problem statement are discussed. In Section III, the design procedure of the proposed controller is presented based on the problem formulation in Section II. Section IV is aimed to present all simulation results to justify the robustness of the proposed controller. Finally, the conclusions are presented in Section V.

2 Dynamics of a Buck Converter System

A schematic diagram of buck converter is shown in Figure 1, which comprises an dc voltage source V_i, a PWM gate drive controlled switch d, a diode D_1, a filter inductor L, a filter capacitor C, a load resistance R_{Load} and f_s is a switching frequency. The model also includes the parasitic element, the inductor resistance r_L where the uncertain values are given in Table 1.

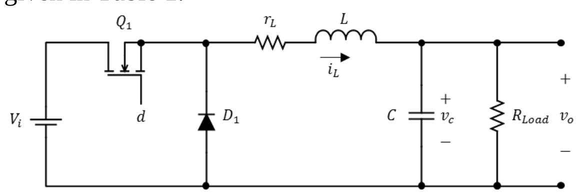

Figure 1. Buck converter topology

Table 1. Uncertain values of the buck converter.

Parameter	*Value*	*Parameter*	*Value*
V_i	$15V \pm 15\%$	V_o	$5V$
r_L	$0.05\Omega \pm 15\%$	R_{Load}	$4\Omega \pm 50\%$
L	$2mH \pm 15\%$	C	$2000uF \pm 15\%$
f_s	$5kHz$		

By referring to the Kirchhoff's voltage law and Kirchhoff's current law, the dynamic model of buck converter in continuous conduction mode (CCM) can be written as follows:

$$\begin{cases} L\dfrac{di_L}{dt} = d \cdot V_i - v_c - r_L \cdot i_L \\ C\dfrac{dv_c}{dt} = i_L - \dfrac{v_c}{R_{Load}} \end{cases} \tag{1}$$

Where is i_L the average inductor current, v_c is the average capacitor output voltage, and the duty cycle $d \in [0,1]$ represent the control signal, which is taken as the conduction PWM signal.

Due to the non-linearity introduced by static switching, the analysis can be divided into two different operation intervals for each period in CCM. Figure 2 shows the state operation of the buck converter in CCM.

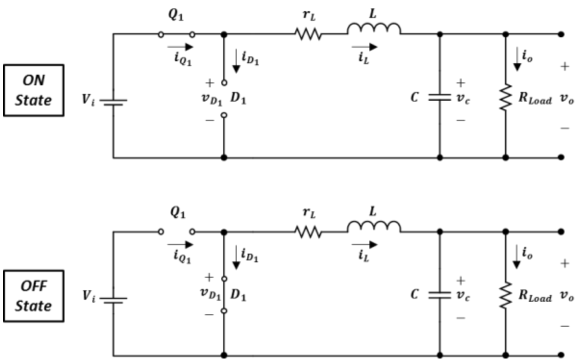

Figure 2. Buck power stage states in CCM

The dynamic behavior for on and off state is defined by equations (2) and (3).

$$On \rightarrow \begin{cases} L\dfrac{di_L}{dt} = V_i - v_c - r_L \cdot i_L \\ C\dfrac{dv_c}{dt} = i_L - \dfrac{v_c}{R_{Load}} \end{cases} \tag{2}$$

$$Off \rightarrow \begin{cases} L\dfrac{di_L}{dt} = -v_c - r_L \cdot i_L \\ C\dfrac{dv_c}{dt} = i_L - \dfrac{v_c}{R_{Load}} \end{cases} \tag{3}$$

If the buck converter operated at fixed switching frequency, the average state-space model can be described from Equation (1) and can be calculated the transfer function of the system.

$$\frac{V_c(s)}{D(s)} = \frac{\dfrac{V_i}{L \cdot C}}{s^2 + \left(\dfrac{1}{R_{Load} \cdot C} + \dfrac{r_L}{L}\right)s + \left(\dfrac{1}{L \cdot C} + \dfrac{r_L}{R_{Load} \cdot L \cdot C}\right)} \tag{4}$$

3 Control Design

Voltage mode control (VMC) is a general method used to solve the output voltage tracking problem of buck converter. First, a classical PID is presented by pole-placement from the solution of a Diophantine equation. Then, in order to deal with the parametric uncertainties, a robust control by robust pole-placement is proposed. Average model of buck converter with voltage mode control is presented in Figure 3.

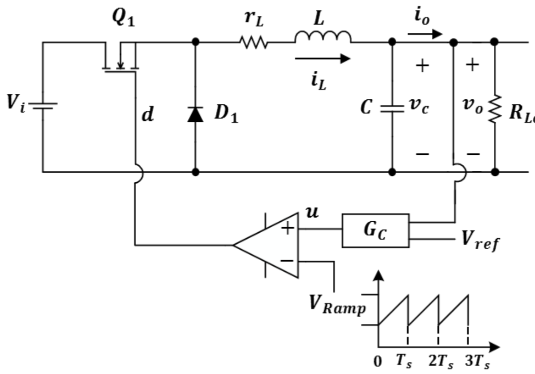

Figure 3. Voltage Model Control of buck converter.

where G_c is the PID controller.

3.1 Classical Pole-Placement Methodology

Pole-placement methodology from the solution of equation Diophantine is used to design the classical PID controller. The average model in (4) is used to design the controller under a fixed operation condition.

Considering the transfer function of the open-loop system $G(s)$ of dynamic order n and the controller transfer function $C(s)$ of dynamic order r, represented in (9) and (10), the solution of the Diophantine equation (11) summarizes the pole-placement problem.

$$G(s) = \frac{n(s)}{d(s)} = \frac{n_n s^n + n_{n-1}s^{n-1} + \cdots + n_o}{d_n s^n + d_{n-1}s^{n-1} + \cdots + d_o} \tag{9}$$

$$C(s) = \frac{n_c(s)}{d_c(s)} = \frac{a_r s^r + a_{r-1}s^{r-1} + \cdots + a_o}{b_n s^r + b_{r-1}s^{r-1} + \cdots + b_o} \tag{10}$$

$$d(s)d_c(s) + n(s)n_c(s) = d_F(s) \tag{11}$$

$$\delta(s) = \delta_{n+r}s^{n+r} + \delta_{n+r-1}s^{n+r-1} + \cdots + \delta_o \tag{12}$$

where $d_F(s)$ is the closed-loop characteristic polynomial and $\delta(s)$ is the desired poles of closed-loop system.

However, it is necessary to transform Equation (11) into a system of linear algebraic equations. Thus, equation (11) is rewritten as the following linear equation,

$$Mx = P \tag{13}$$

where M is the Sylvester matrix associated with the polynomial coefficients of the plant expressed by Equation (4), P is the vector associated with the desired polynomial coefficients in closed-loop, and x is the vector associated with the coefficients of the controller.

$$P=\begin{bmatrix}\delta_{n+r} & \delta_{n+r-1} & \cdots & \delta_o\end{bmatrix} \qquad (14)$$

$$x=\begin{bmatrix}a_0 & a_1 & \cdots & a_r & b_0 & b_1 & \cdots & b_r\end{bmatrix} \qquad (15)$$

It is known in the literature that when $r=n-1$ the above equations admit a solution for the controller coefficients. Therefore when $r=n-1$, there always exist a pole-placement controller [8].

The elements of M depend only on the coefficients of the numerator and denominator of $G(s)$.

$$M=\begin{bmatrix} n_n & & & & d_n & & & \\ n_{n-1} & n_n & & & d_{n-1} & d_n & & \\ \vdots & n_{n-1} & \ddots & & \vdots & d_{n-1} & \ddots & \\ \vdots & \vdots & \ddots & n_n & \vdots & \vdots & \ddots & d_n \\ n_o & \vdots & & n_{n-1} & d_o & \vdots & & d_{n-1} \\ & n_o & & \vdots & & d_o & & \vdots \\ & & \ddots & \vdots & & & \ddots & \vdots \\ & & & n_o & & & & d_o \end{bmatrix} \qquad (16)$$

The desired specifications for the closed-loop voltage control for the buck converter are set to: Settling time $t_{set}=100ms$ and overshoot $SP=5\%$.

3.2 Robust Control Technique

Considering the case where the plant, defined in (9), is subject to parameter uncertainty, the transfer function plant become an interval transfer function as follows:

$$G(s)=\frac{n(s)}{d(s)}=\frac{\sum_{i=0}^{n} n_i s^i}{\sum_{i=0}^{n} d_i s^i} \qquad (17)$$
$$n_i^- \le n_i \le n_i^+,\, d_i^- \le d_i \le d_i^+,\, \forall i$$

The characteristic polynomial family of the closed-loop system is determined by equation (11).

In order to guarantee the robustness of the closed-loop system against uncertainties, it is considered that the parameters of the desired polynomial, described by equation (12), assume values such that their coefficients belong to an interval, as shows in equation (18), delimiting a desired region for the robust pole-placement. Thus, the desired polynomial in closed-loop corresponds to an interval polynomial family, which includes the desired nominal polynomial.

$$\delta(s)=\delta_{n+r}s^{n+r}+\delta_{n+r-1}s^{n+r-1}+\cdots+\delta_o \qquad (18)$$
$$\delta_i^- \le \delta_i \le \delta_i^+,\, \forall i$$

To satisfy the stability and performance conditions, it is necessary and sufficient to satisfy the condition shown in equation (19).

$$\delta(s)=d_F(s) \qquad (19)$$

According to Keel & Bhattacharyya (1997) and Equation (19), for the robust controller design is formulated a linear inequalities set, which restricted the plant and desired polynomial coefficients in the defined intervals, as shown in Eq. (20). Thus, the closed-loop system has its poles within the roots space of interval-desired polynomial, ensuring the robust stability (Lordelo and Ferreira, 2002).

$$\begin{bmatrix}\delta_{n+r}^- \\ \delta_{n+r-1}^- \\ \vdots \\ \delta_o^-\end{bmatrix} \le \begin{bmatrix} n_n a_r + d_n b_r \\ n_n a_{r-1}+n_{n-1}a_r+d_n b_{r-1}+d_{n-1}b_r \\ \vdots \\ n_o a_o + d_o b_o\end{bmatrix} \le \begin{bmatrix}\delta_{n+r}^+ \\ \delta_{n+r-1}^+ \\ \vdots \\ \delta_o^+\end{bmatrix} \qquad (20)$$

The robust controller coefficients are calculated by using the linear programming technique as shown below,

$$\min_{A_c x \le b} = f(x) \qquad (21)$$

where,

$$A_c=\begin{bmatrix}A \\ -A\end{bmatrix}, b=\begin{bmatrix}b_{\max} \\ b_{\min}\end{bmatrix} \qquad (22)$$

where $f(x)$ is an arbitrary linear function in x, x is the vector with the parameter of the controller to be optimized, $b_{\min}$ and $b_{\max}$ are, respectively, the inequalities relative to lower and higher limits of the closed-loop system. The matrix A corresponds to open-loop plant coefficients.

3.3 Robust Control Design by linear programming

According to the uncertainties of the plant defined in Table 1, the transfer function in (4) become an interval transfer function as shown belong,

$$G(s)=\frac{V_c(s)}{D(s)}=\frac{n_o}{s^2+d_1 s+d_o}$$
$$n_o^- \le n_o \le n_o^+ \qquad (23)$$
$$d_1^- \le d_1 \le d_1^+,\, d_o^- \le d_o \le d_o^+$$

The values of the desired interval polynomial in closed-loop are obtained by varying the performance established for the classical controller as follows,

$$t_{set}=100ms \pm 25\%$$
$$SP=5\% \pm 25\% \qquad (24)$$

According to equation (24), the interval values of damping coefficients and natural frequency are $\xi_d=[0.52,0.86]$ and $\omega_n=[43.47,72.45]$, respectively. The adoption of interval values theses parameters allow increase the damping of dominant oscillatory mode.

The controller structure and the closed-loop desired polynomial are shown in equations (25) and (26), respectively.

$$C(s)=\frac{K_d s^2+K_p s+K_i}{s(s+\alpha)}=\frac{a_2 s^2+a_1 s+a_o}{b_2 s^2+b_1} \qquad (25)$$

$$
\begin{gathered}
\delta(s) = \delta_4 s^4 + \delta_3 s^3 + \delta_2 s^2 + \delta_1 s + \delta_o \\
\delta_i^- \le \delta_i \le \delta_i^+ , i = 0,1,2,3,4 \\
\delta(s) = \left(s^2 + 2\xi\omega_n s + \omega_n^2\right)\left(s+a\right)\left(s+b\right) \\
\xi^- \le \xi \le \xi^+ , \omega_n{}^- \le \omega_n \le \omega_n{}^+
\end{gathered}
\tag{26}
$$

where a and b are non-dominant poles of the systems, therefore their characteristic do not influence in the system behavior. The location of these non-dominant poles is at the discretion of designer.

$$
\begin{aligned}
\delta_4 &= 1 \\
\delta_3 &= \left[203.75, 339.58\right] \\
\delta_2 &= \left[2.04, 3.41\right] \cdot 10^5 \\
\delta_1 &= \left[1.57, 2.62\right] \cdot 10^5 \\
\delta_o &= \left[4.41, 10.68\right] \cdot 10^8
\end{aligned}
\tag{27}
$$

By using the robust control technique in (21) and (22), the robust controller is tuned. The classical and robust controller are shown in (28) and (29), respectively.

$$
C(s)_{Classical} = \frac{0.0008959s^2 + 0.1717s + 227.9}{s\left(s{+}80\right)} \tag{28}
$$

$$
C(s)_{Robust} = \frac{0.0007338s^2 + 0.0543s + 225.6}{s\left(s{+}81.72\right)} \tag{29}
$$

4 Simulation Results

The performance of the robust controller, defined in (29), is evaluated and compared with classical controller, defined in (28), by using MATLAB/SIMULINK. The simulation parameters of buck converter is presented in Table 1.

These controllers must guarantee robustness and maintain performance against disturbances caused by the parametric uncertainties. For this reason, the performance of each controller is analyzed with the following disturbances. First, the load, R_{Load}, of the converter is varied within the range established in Table 1.Then the performance is analyzed with variations in the dc input voltage V_i. Finally, it is simulated for changes in operating voltage V_o.

The results for the first case is shown in Figure 5. Figure 4 shows the load variation over time.

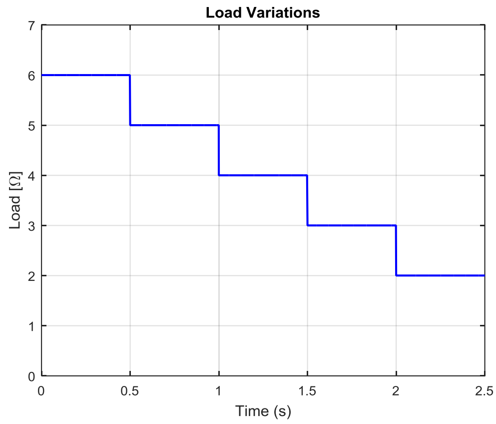

Figure 4. Load variation over time.

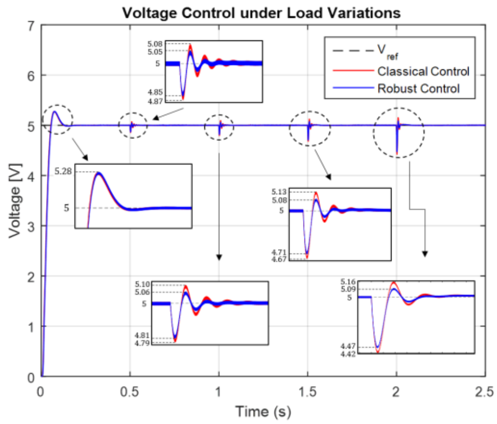

Figure 5. Voltage control under load variations.

The ISE index can be observed in Figure 6. The ISE of robust controller is lower in all the entire variation range.

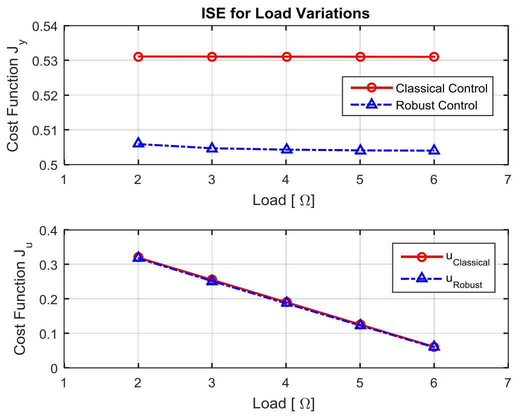

Figure 6. The cost function ISE when the system submitted a parametric variation in load using a classical and robust controller.

Figure 5 presents the simulated output behavior by using a classical and robust control. Note that both controller have succeeded in correcting the variation. However, the robust controller reduces the amplitude of oscillations, allowing a shorter settling time.

Figure 8 shows the close-loop response of the system for input voltage variations as shown in Figure 7.

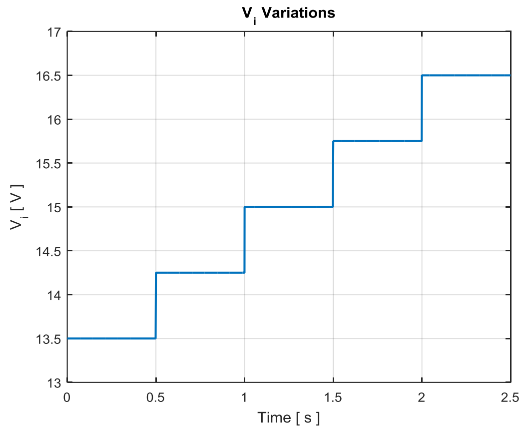

Figure 7. V_i variation over time.

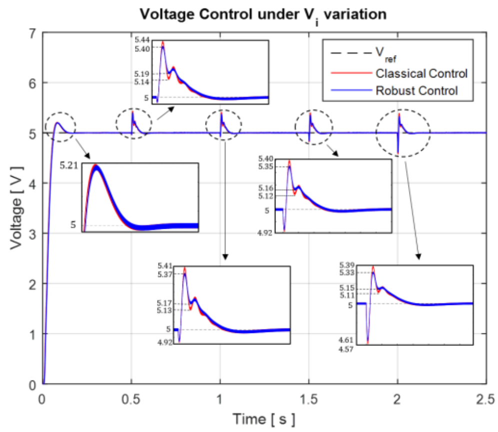

Figure 8. Voltage control under input voltage variations.

It can be observed in Figure 8 that both controllers can compensate for the input voltage variation, but the robust controller more effectively compensates the oscillations. Figure 9 shows the comparison of ISE performance index of classical and robust controller. This index evaluates the impact of voltage variation on the controller performance. Therefore, the robust controller shows the best performance under input voltage variations.

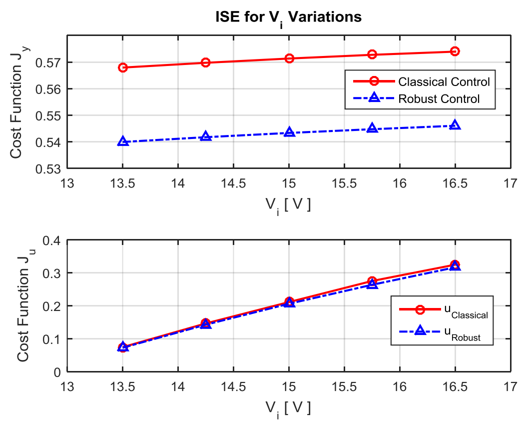

Figure 9. The cost function ISE when the system submitted a parametric variation in input voltage using a classical and robust controller.

Figure 10 shows the closed-loop dynamic under variations in operating voltage. Note that the performance of controllers is almost the same under variations in the operation voltage. The operation voltage vary in a range of $[4,6]V$.

Figure 11 shows the cost function ISE when the system is subjected to a variation of the output voltage. The comparison of the ISE index for variations of operation condition.

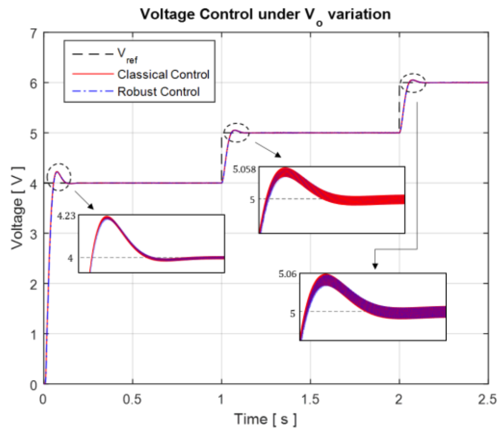

Figure 10. Voltage control under operation condition variations.

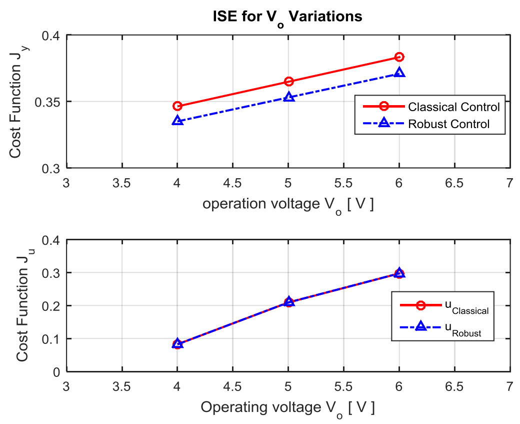

Figure 11. The cost function ISE when the system submitted a variation in output voltage using a classical and robust controller.

5 Conclusion

This paper proposed to use a robust control technique integrated to linear programming technique for the design of a fix order robust controller by robust pole-placement, in order to guarantee the stability of the system and maintain the desired performance against parametric uncertainties.

The results show that both controller ensured the robust stability of the system. Both controllers present a good performance under variations of the operating conditions of the system. However, the index performance comparison show that the robust controller more effectively compensates for disturbances.

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References

Barra Junior, W.; Barreiros, J. A. L; Costa Júnior, C. T.; and Ferreira, A. M. D (2005). Controle Fuzzy Aplicado à Melhoria da Estabilidade Dinâmica em Sistemas Elétricos de Potência. Revista Controle & Automação. Vol.16, No.2. pp. 173-186.

Bhattacharyya, S. P (1992). Recent Results in Robust Parametric Stability and Control. IEEE International Symposium on Circuits and Systems.

Bhattacharyya, S. P.; Chapellat, H.; Keel, L. H (1995). Robust Control: The Parametric Approach, Prentice Hall, Upper Saddle River, NJ.

Bhattacharyya, S. P., Chapellat, H. and Keel, L. H (1995). Robust Control: The Parametric Approach, Vol.1.

Bhaumik, A.; Srivastava, S.; Kumar, Y.; Islam, M (2016). Performance studies of a separately excited DC motor speed control fed by a buck converter using optimized PIλDμ controller. International Conference on Circuit, Power and Computing Technologies (ICCPCT), Nagercoil, India, 18–19 March 2016; pp. 1–6.

Chang, H. C. and Liaw, C. M (2011). An Integrated Driving/Charging Switched Reluctance Motor Drive Using Three-Phase Power Module. IEEE Trans. Ind. Electron., Vol. 58, No. 5, pp. 1763–1775.

Forsyth, A. J (1998). Modeling and Control of DC-DC Converters. Power Engineering Journal, Vol. 12, No. 5, pp. 229-236.

Guo, L., Hung, J. Y., and Nelms, R. M (2009). Evaluation of DSP-Based PID and Fuzzy Controllers for DC-DC Converters. IEEE Trans. Ind. Electron., Vol. 56, No. 6, pp. 2237–2248.

Ghiasi, M. I., Golkar, M. A. and Hajizadeh, A (2017). Lyapunov BasedDistributed Fuzzy-Sliding Mode Control for Building Integrated-DC Microgrid With Plug-In Electric Vehicle. IEEE Access, Vol. 5, pp. 7746–7752.

Hassanalieragh, M., Soyata, T., Nadeau, A. and Sharma, G (2016). UR-SolarCap: An Open Source Intelligent Auto-Wakeup Solar Energy Harvesting System for Supercapacitor-Based Energy Buffering. IEEE Access, Vol. 4, pp. 542–557.

Keel, L. H., and Bhattacharyya, S. P., 1997. A linear programming Approach To Controller Design, IEEE Transactions on Automatic Control, California USA.

Kim, S., Kim, J., Park, C. and Lee, Y. I (2013). Output-feedback model predictive controller for voltage regulation of a DC/DC converter. IET Control Theory Appl., Vol. 7, No. 16, pp. 1959–1968.

Kumar, D., Zare, F. and Ghosh, A (2017). DC Microgrid Technology: SystemArchitectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects. IEEE Access, Vol. 5, pp. 12230–12256.

Labbe, B., Allard, B. and Lin-Shi, X (2014). Design and Stability Analysis of a Frequency Controlled Sliding-Mode Buck Converter. IEEE Trans. Circuits Syst. I, Reg. Papers, Vol. 61, No. 9, pp. 2761–2770.

Lordelo, A. D. S., Ferreira, P. A. V (2002). Interval Analysis and Design of Robust Pole Assignment Design. Decision and Control, 2002, Proceedings of the 41st IEEE Conference, Las Vegas, USA, 10–13 December 2002; pp. 1–6.

Medeiros, R. L. P.; Barra Junior, W.; Bessa, I. V.; Chaves Flilho, J. E.; Ayres, F. A. C., Neves, C. C (2018). Robust decentralized controller for minimizing coupling effect in single indcutor multiple output DC-DC converter operating in continuous conduction mode. ISA Transactions, Vol. 73, pp. 112-129.

Middlebrook, R. D. and Cuk, S. (1976). A general unified approach to modelling switching-converter power stages. Proc. IEEE Power Electron. Spec. Conf., pp. 18-34.

Mohan, N., Undeland, T. M. and Robbins, W. P (2002). Power Electronics: Converters, Applications, and Design, 3rd Bk&Cdr edition, Wiley.

Perry, A. G., Feng, G. and Liu, Y. F. and Sen, P. C (2007). A Design Method for PI-like Fuzzy Logic Controllers for DC-DC Converter," IEEE Trans. Ind. Electron., Vol. 54, No. 5, pp. 2688–2696.

Qian, Z., Rahman, O. A., Al-Atrash, H. and Bataresh, I (2010). Modeling and control of three-port DC/DC converter interface for satellite applications. IEEE Trans. on Power Electronics, Vol. 25, No. 3, pp. 637-649.

Salimi, M., Soltani, J. and Markadeh, G. A (2011). A novel method on adaptive backstepping control of buck choppers. Proc. of the 2nd Power Electronics, Drive Systems and Technologies Conf., pp.562-567, 16-17 February 2011.

Salimi, M., and Zakipour, A (2015). Direct voltage regulation of DC-DC buck converter in a wide range of operation using adaptive input-output linearization. IEEE Transaction, Vol. 10, pp. 85-91.

Tan, S. C., Lai, Y. M., Tse, C. K, and Cheung, M. K. H (2006). Adaptive feedforward and feedback control schemes for sliding mode controlled

power converters. IEEE Trans. Power Electron., Vol. 21, No. 1, pp. 182– 192.
Xu, Q., Zhang, C., Wen, C. and Wang, P (2017). A Novel Composite Nonlinear Controller for Stabilization of Constant Power Load in DC Microgrid. IEEE Trans. Smart Grid, published online, doi:10.1109/TSG.2017.2751755.
Xiong, X., Tse, C. K. and Ruan, X (2013). Bifurcation Analysis of StandalonePhotovoltaic-Battery Hybrid Power System. IEEE Trans. Circuits Syst. I, Reg. Papers, Vol. 60, No. 5, pp. 1354–1365.
Xu, Q., Hu, X., Wang, P., Xiao, J., Tu, P., Wen, C. and Lee, M. Y (2017). A Decentralized Dynamic Power Sharing Strategy for Hybrid Energy Storage System in Autonomous DC Microgrid. IEEE Trans. Ind. Electron., Vol. 64, No. 7, pp. 5930–5941..
Xiong, X., Ruan, X., Xi, H. and Ge, J (2011). Feed-Forwarding the Output Voltage to Improve Efficiency for Envelope-Tracking Power Supply Based on a Switch-Linear Hybrid Scheme. IEEE Trans. Power Electron., Vol. 26, No. 8, pp. 2106–2111.
Zhang, C., Wang, J., Li, S., Wu, B. and Qian, C (2015). Robust control for PWM-based DC-DC buck power converters with uncertainty via sampled-data output feedback. IEEE Trans. on Power Electronics, Vol. 30, No. 1, pp. 504-515.
Zhang, C., Wang, J., Li, S., Wu, B. and Qian, C (2015). Robust Control for PWM-Based DC-DC Buck Power Converters With Uncertainty Via Sampled-Data Output Feedback. IEEE Transactions on Power Electronics, Vol. 30, No. I, pp. 504-515.