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A Study on the On-line System Identification and PID Tuning of a Buck Converter

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***Abstract*—In this paper we study the on-line system identification process and the proportional-integral-derivative (PID) tuning of a buck converter. The system identification process was performed using a recursive least squares algorithm. The estimation error and parameter error were generated to demonstrate that the system was converging to its true parameters. The estimation error shows an absolute value of approximately 1×10^{-5} in less that 10ms. All the parameters were effectively converging in less that $100\mu s$. Once the system was properly identified, an off-line PID controller was designed to further implement it on the adaptive loop. Three different techniques were used to satisfy the requirements of the buck converter: phase and gain margin, pole-zero cancellation and frequency loop shaping. Phase and gain margin still prevails as the easiest method to design controllers. Pole-zero cancellation is based on pole-placement and is fairly easy to implement in order to obtain the gains of a PID controller. However, although these controllers can be easily designed, they do not provide the best response compared to the Frequency Loop Shaping (FLS) technique in terms of frequency and time responses.**

***Keywords*—system identification, buck converter, PID controller, frequency loop shaping.**

I. Introduction

Buck converters, which are also known as power converters or DC-DC converters, are electronic devices that change a voltage from one level to another one at a high frequency. The LM27402 is a synchronous DC-DC converter whose switching frequency can vary in a range that goes from 200 kHz to 1.2 MHz [23]. It incorporates an input feed-forward voltage that enables it to maintain stability for the entire input voltage range. Some applications of the LM27402 buck converter go from telecommunications, data-communications and networking to distributed power architectures. Additionally, they can be used for any general buck converter purposes which may include Field Programmable Gate Arrays (FPGA) and Application Specific Integrated Circuit (ASIC). However, due to factors like aging, degradation or failures, the DC-DC converters require a system identification process to track and diagnose their parameters.

Identifying the parameters of the system plays an essential role to design a proportional-integral-derivative (PID) controller that can compensate for failures in the system. This does not only represent a big advantage for monitoring purposes, but also allows the implementation of adaptive controllers [13], [24]. Therefore, buck converters may become more efficient and their lifetime may increase dramatically.

In the recent years we have seen a significant progress in the identification of buck converters [3]. Some previous work involves the use of the cross-correlation technique which is a non-parametric system identification method [16] that allows the digital control of the system [18], [17]. Similarly, a circular cross-correlation technique has been used to obtain the transfer function of a power converter [19]. In this paper, a maximum-length pseudo random binary sequence (m.l.b.s) was used to excite the system. Their use has become popular because it is easy to generate the excitation by using shift registers and an appropriate feedback [14]. Additionally, it has nice properties in the means of periodicity and frequency attributes [22]. The uncertainty of the system is computed by using a fuzzy density approximation. Yet, the signal-to-noise (SNR) ratio plays an important role in the circular correlation technique [12].

Other approaches have also been used to perform a system identification of the power converter such as the black-box technique [6]. In that approach, the authors aimed to obtain a small-signal linear model in discrete time that describes the system as a time-invariant structure. Additionally, the impulse response data has offered an alternative to perform system identification of discrete systems that does not require the numerator to be of a lower degree than the denominator [21].

This paper describes the on-line system identification of the buck converter using a least-square algorithm. It also provides the results from parameter and estimation errors as a measure to determine that the system is converging to its true values. Additionally, it makes a comparison of three different controllers that achieve the design specification of 60 degrees of phase margin and 1.19×10^6 of cutoff frequency.

II. Open-Loop Plant

Modeling a plant requires a procedure that can be broken down as follows:

- First-principles model: First-principles allows us to obtain a preliminary mathematical description of the structure of the system. Having this approximation lets us determine the required excitation to accurately identify the system.
- System excitation: After obtaining the first-principle model, the input signal can be designed so that the interested frequencies are properly identified. Thus, we may be interested in identifying about one decade of the expected gain crossover frequency.

- Parameter estimation: Although there are several methods available for parametric system identification, we have used a least-square parameter estimation.
- Uncertainty estimation: The uncertainty estimation provides a measure of how acceptable the system will be and how suitable the model is for controller design purposes. This information is relevant from the point of view of robust control, so that we can determine if a model unfalsifies the identified plant [15].

Having said that, we can start describing the buck converter transfer function in eq. 1:

$$T_u(s) = \frac{H}{V_m(s)} P(s) \tag{1}$$

where H is known as the feedback factor and equals to 0.333, V_m is the Pulse Width Modulation (PWM) gain and is equivalent to $3.3V$ and $P(s)$ is the open loop transfer function of power stage given by eq. 2.

$$P(s) = P_o \frac{\frac{2\pi f_o^2}{f_{esr}} s + (2\pi f_o)^2}{s^2 + \frac{2\pi f_o}{Q} s + (2\pi f_o)^2} \tag{2}$$

where P_o stands for the minimum gain that can be used or the average between minimum and maximum input value, Q is the quality factor and f_o is the resonance frequency which can be obtained from eq. 3.

$$f_o = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

The values for inductor ($L = 9\mu H$) and capacitor ($C = 400nF$) correspond to the TI 62675 power converter.

Once all the parameters have been specified in eq. 1, the open loop plant is given by eq. 4.

$$T_u(s) = \frac{9820s + 1.403 \times 10^{11}}{s^2 + 1.419 \times 10^5 s + 2.778 \times 10^{11}} \tag{4}$$

However, to simplify computations during the system identification process and controller design, the plant has been scaled down by a factor of 10^6. Then, after a new variable $s' = s/10^6$ is defined, the resulting transfer function for the buck converter is given by eq. 5:

$$T_u(s') = \frac{0.00982s' + 0.1403}{s'^2 + 0.1419s' + 0.2778} \tag{5}$$

A Bode plot was generated for the original and scaled plant. Fig. 1 and Fig. 2 show the frequency response of both systems. The original plant depicts a resonance peak at a value which is below of $6.22 \times 10^5 rad/s$. Their response look similar where the only difference lies on the frequency values. Therefore, the Bode plot of the scaled plant now is depicted in a scale that spans in rad/μs.

A Pseudo Random Binary Sequence (PRBS) was generated and introduced to the simulation model for system identification purposes [27]. A Fast Fourier Transform (FFT) plot of

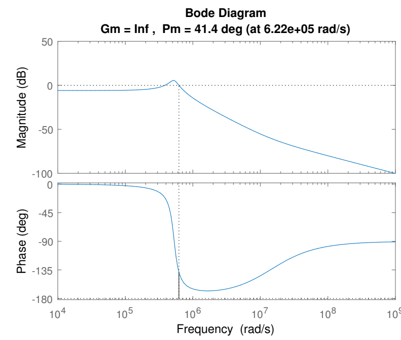

Fig. 1. Uncompensated Original Plant

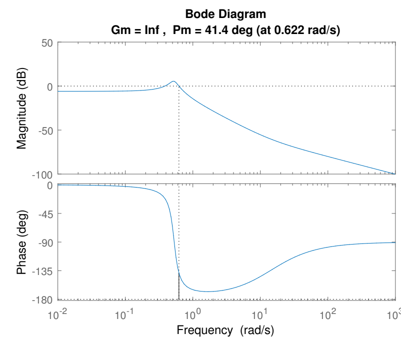

Fig. 2. Uncompensated Scaled Plant

the PRBS signal allowed us to determine if the signal had enough strength in the frequencies of interest. The bandwidth of the scaled system is 0.8084 rad/s which corresponds to an approximately value of 0.12868 Hz. The excitation of the generated PRBS signal should have sufficient energy around the desired closed-loop bandwidth. Additionally, the signal should contain characteristics such as having a good signal to noise ratio while being roughly linear about the chosen operating point [25].

A recursive least-square algorithm was used to identify the system of the scaled plant. The Simulink model shown in Fig. 3 executes an on-line system identification for the nominal plant of the buck converter. All the simulation parameters have been scaled down by a factor of 10^6 to simplify computations. The parameters of the system were initialized with the values shown in table I.

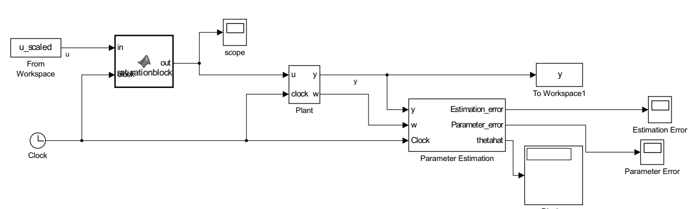

Fig. 3. Simulink Block of the Online System Identification for the Buck Converter. It performs a recursive-least square algorithm to obtain the true parameters of the plant.

The estimation error and parameter error provide a reliable measure that determines if the system is converging to its true parameters. The estimation error is calculated in eq. 6.

TABLE I. INITIAL VALUES FOR THE ON-LINE SYSTEM IDENTIFICATION OF THE BUCK CONVERTER

Designator	Parameter	Value
$\theta 1$	Parameter 1	8.5×10^{-3}
$\theta 2$	Parameter 2	0.4
$\theta 3$	Parameter 3	0.5
$\theta 4$	Parameter 4	0.5

$$Estimation \quad error = \hat{y} - y \tag{6}$$

where $\hat{y}$ is the estimated output of the system and y is the true output. Additionally, the parameter error is computed by eq. 7.

$$Parameter \quad error = \theta_* - \hat{\theta} \tag{7}$$

where θ_* is the true parameter and $\hat{\theta}$ is the estimated parameter.

III. CONTROLLER DESIGN

Regardless of the significant progress in controller design, proportional-integral-derivative (PID) controllers is until now the most typical controller structure used in many everyday applications. An extensive literature is available on their properties as well as thier tunning process [1], [2], [20], [8]. PID controllers offer an attractive integral action that eliminates set-point errors and disturbance offsets. Additionally, their phase lead is capable of adjusting crossover properties such as phase-margin. Consequently, the closed-loop damping is also improved. At the same time, their implementation is simple which allows a straightforward application including discretization [11], [4], and ad-hoc, but very important, modifications for anti-windup and parameter scheduling. Additionally, a lot of studies have been conducted to consider quantization levels for discrete controllers [7], [9], [10], [5].

The type 3 controller shown in Fig. 4 is a comparator with a PID structure whose transfer function corresponds to a system that has two zeros and three poles as given in eq. 8.

$$\begin{aligned} C(s) &= \frac{Vout(s)}{V_1(s)} \\ &= -\frac{sR_2C_1 + 1}{sR_1(C_1 + C_2)(1 + sR_2\frac{C_1C_2}{C_1+C_2})} \cdot \frac{sC_3(R_1 + R_3) + 1}{sR_3C_3 + 1} \end{aligned} \tag{8}$$

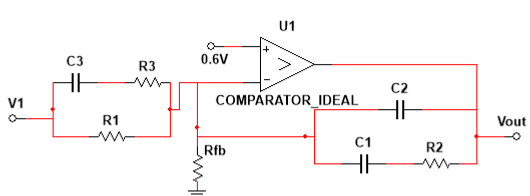

Fig. 4. Type 3 Controller

The main reason to select this controller was its nice frequency response since it can boost the phase up to 180 degrees. A PID was designed using three different techniques: PID+filter using gain and phase margin specifications, PID+filter using the zero-pole cancellation technique and frequency loop shaping (FLS).

IV. RESULTS AND DISCUSSION

Based on the results obtained in the estimation error plot in Fig. 5, we can point out that the estimated values of the plants are converging since the error is decreasing. After running the simulation for about 10000 μs, the estimated error is below 0.1. A similar behavior happens when the parameter error is analyzed in Fig. 6. Each parameter was initialized at a value which was different from the true value. But when the on-line system identification was performed, the parameters converged in 100 μs, approximately. These two metrics allow us to determine that the system was converging to the true parameters.

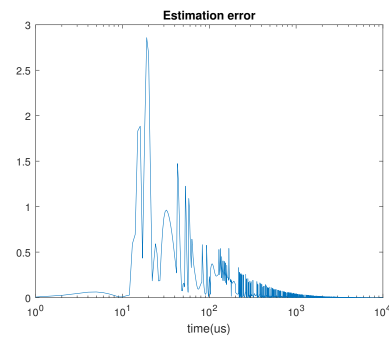

Fig. 5. Estimation Error

After performing the on-line system identification for the buck converter, three different techniques were used to design a PID controller: PID+filter using gain and phase margin specifications, pole-zero cancellation, and a PID+filter using the Frequency Loop Shaping technique. All the controllers met the design specifications of 60 degrees of phase margin and 1.19×10^6 of cutoff frequency. The results are shown in Fig. 7.

The sensitivity and complementary sensitivity responses describe the frequency response of the compensated loop. A good sensitivity response seeks to attenuate the gain at lower frequencies to have a good command following characteristic and disturbance attenuation at the plant output. The sensitivity plot shown in Fig. 8 illustrates the responses corresponding to the different controllers. It depicts a “slump” characteristic at around $5 \times 10^5 rad/sec$ due to the resonance peak of the open-loop plant.

Furthermore, an appropriate complementary sensitivity re-

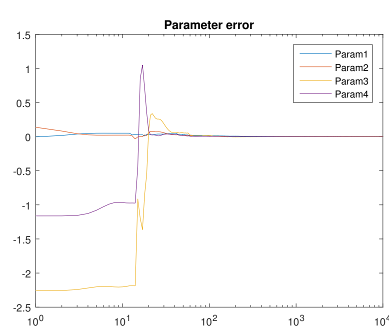

Fig. 6. Parameter Error

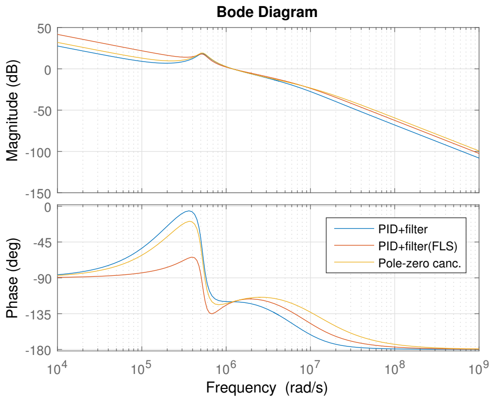

Fig. 7. Compensated Plant

sponse should depict a small gain at higher frequencies for noise attenuation. Fig. 9 shows that the complementary sensitivity plot is similar for all the controllers tested in the compensated loop.

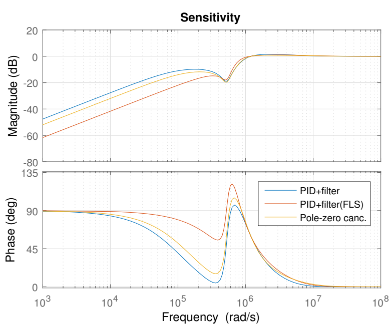

Fig. 8. Comparison of sensitivity

In general, having good responses for sensitivity and complementary sensitivity allows the system to have desired stability robustness properties. However, our analysis in controller design is not limited to look at frequencies response of the compensated loop. Characteristics such as the step response and disturbance rejection allows us to determine how the system behaves in a closed-loop fashion.

The step response shown in Fig. 10 depicts how fast the system is stabilizing with each controller design. It is clear to notice that by using a PID+filter controller, the system takes more time to reach stabilization. Additionally, it does not have any overshoot but it does not reach the unit step input until around 60 us. We can also observe that the response goes down which can make the system to oscillate between two different states prior stabilization. This might not be an ideal scenario for electronic systems because the DC-DC converter could be remaining at a low digital value when it is supposed to be high.

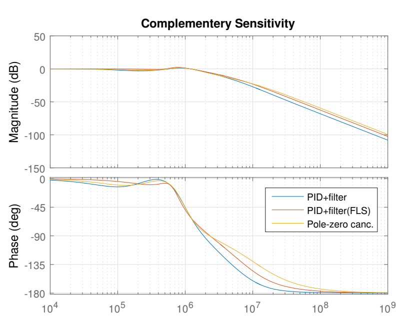

Fig. 9. Comparison of complementary sensitivity

When the pole-zero cancellation controller was used, the step response was faster compared to the PID+filter technique. It also stabilizes faster with the implementation of this controller. In addition, it reaches the unit input, but then goes down below 80 percent which can probably make the system to oscillate between two different states as it happened with the use of a PID+filter controller. It certainly provides a better response compared to the previous controller, but it can still be improved.

Finally, the frequency loop shaping technique allows the system to stabilize much faster than the other two controllers. Although there is an overshoot of about 10 percent, this characteristic can be improved by the implementation of a prefilter in the compensated loop. This controller depicts a better response since in the buck converter we are always trying to stabilize the system the fastest possible.

Furthermore, the disturbance rejection was also evaluated at the plant input. The analysis is done so that we can evaluate if our system is able to reject any disturbance at the input of the plant in the smallest time possible. Based on that description, the FLS controller also provides a better response compared to the other two type of controllers. First, we observe that the PID+filter controller rejects the disturbances in at least $60\mu s$. The pole-zero cancellation controller rejects the disturbances in about $35\mu s$. However, the FLS controller is capable of rejecting disturbances in about $20\mu s$. However, we should also point out that this controller initially oscillates in the disturbance rejection response.

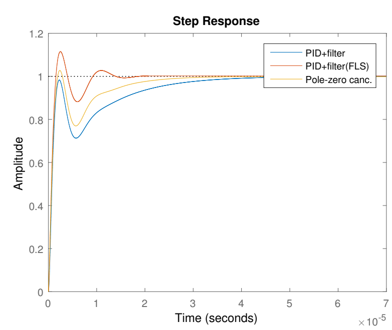

Fig. 10. Step Responses

Although the FLS controller provides better responses, it is important to mention that we could not obtain feasible values for resistors and capacitors consistent with the type 3 controller. Therefore, if we want to continue using that structure, an optimization problem should be addressed to properly acquire practical values for theses elements. Another alternative would be to implement a direct estimation of the

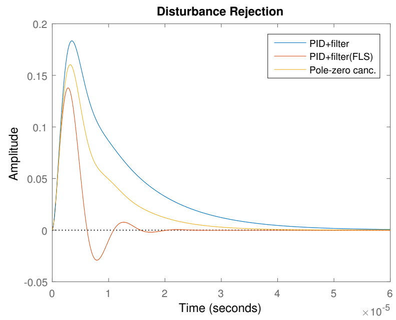

Fig. 11. Comparison of Disturbance Rejection Responses

controller parameters along the lines of [26], but this is left as a subject for future research.

V. Conclusions

We have shown a simulation of the on-line system identification process for the buck converter. We began our analysis by obtaining the nominal plant transfer function of the buck converter. This allowed us to determine the PRBS signal required to properly identify the system.

The system identification process was performed using a recursive least squares algorithm. The plant was scaled down by a factor of 10^6 to simplify computations in the Simulink model. The estimation error and parameter error were generated to demonstrate that the system was converging to its true parameters. The estimation error shows an absolute value of approximately 1×10^{-5} in less that 10ms. The parameter error was initialized to have different values which were off from the true parameters. This allowed us to observe when the regressor was operating on the system and to determine if the plant was converging. All the parameters were finally converging at a value which is less that $100\mu s$.

All the controllers met the parameter specifications required by the system. However, the frequency loop shaping controller provides a better frequency response compared to the other controllers. When the compensated loop was analyzed, we observed that the response given by all controllers is similar at the cutoff frequency. However, the FLS controller provides a higher gain at lower frequencies. Additionally, the step response and disturbance rejection are also better when a FLS controller was implemented. The step response shows that the system stabilizes faster compared to the other controllers. We could also observe a little overshoot when the FLS controller was implemented; however; this feature can be improved by the introduction of a pre-filter in the controlled loop.

References

[1] D. Adams. Real-time Auto Tuning of a Closed Loop Second Order System with Internal Time Delay Using Pseudo Random Binary Sequences. 2013.

[2] T. Astrom, K.J. and Hagglund. *PID Controllers: Theory, Design, and Tuning*. ISA, 2nd edition, 1995.

[3] A. Barkley and E. Santi. Improved online identification of a DC-DC converter and its control loop gain using cross-correlation methods. *IEEE Transactions on Power Electronics*, 24(8):2021–2031, 2009.

[4] C. Phillips and H. Nagle. *Digital Control System Analysis and Design*. Prentice-Hall, Uppeer Saddle River, NJ, 1995.

[5] W.-W. Che. Quantized Dynamic Output Feedback H∞ Control for Discrete-time Systems with Quantizer Ranges Consideration. *Acta Automatica Sinica*, 34(6):652–658, 2009.

[6] J.-Y. Choi, B. H. Cho, H. F. Vanlandingham, H.-S. Mok, and J.-H. Song. System identification of power converters based on a black-box approach. *IEEE Transactions on Circuits and Systems-I: Fundamental Theory and Applications*, 45(11):1148–1158, 1998.

[7] H. Gao and T. Chen. A new approach to quantized feedback control systems. *Automatica*, 44(2):534–542, 2008.

[8] T. Hägglund and K. J. Å ström. Revisiting The Ziegler-Nichols Tuning Rules For Pi Control. *Asian Journal of Control*, 4(4):364–380, 2002.

[9] T. Hayakawa, H. Ishii, and K. Tsumura. Adaptive quantized control for linear uncertain discrete-time systems. *Automatica*, 45(3):692–700, 2009.

[10] T. Hayakawa, H. Ishii, and K. Tsumura. Adaptive quantized control for nonlinear uncertain systems. *Systems & Control Letters*, 58(9):625–632, 2009.

[11] G. Herjolfsson and a.S. Hauksdottir. Direct computation of optimal discrete-time PID controllers. *Proceedings of the 2004 American Control Conference*, 1(3):46–51, 2004.

[12] D.-K. Hong, C.-H. Park, M.-C. Ju, K.-J. Youn, S.-D. Jun, and J.-W. Cho. SNR estimation in frequency domain using circular correlation. *Electronics Letters*, 38(25):1693–1694, 2002.

[13] K. J. Astrom and B. Wittenmark. *Adaptive Control*. Addison-Wesley, Reading, MA, 1995.

[14] K. R. Godfrey. Introduction to binary signals used in system identification. In *International Conference on Control*, pages 161–166, 1991.

[15] R. Kosut. Uncertainty model unfalsification: a system identification paradigm compatible with robust control design. *Proceedings of 1995 34th IEEE Conference on Decision and Control*, 4(December):3492–3497, 1995.

[16] L. Ljung. *System Identification: Theory for User*. Prentice-Hall, Englewood Cliffs, NJ, 2nd ed. edition, 1999.

[17] B. Miao, R. Zane, and D. Maksimovic. Practical on-line identification of power converter dynamic responses. In *Proc. 20th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC 2005)*, volume 1, pages 57–62.

[18] B. Miao, R. Zane, and D. Maksimović. System identification of power converters with digital control through cross-correlation methods. *IEEE Transactions on Power Electronics*, 20(5):1093–1099, 2005.

[19] T. Roinila, T. Helin, M. Vilkko, T. Suntio, and H. Koivisto. Circular correlation based identification of switching power converter with uncertainty analysis using fuzzy density approach. *Simulation Modelling Practice and Theory*, 17(6):1043–1058, 2009.

[20] T. O. R. S. Scheit. Automatic Tuning of PID Controllers Based on Transfer Function Estimation. *Automatica*, 30(12):1983–1989, 1994.

[21] A. K. Shaw and P. Misra. Time domain identification of proper discrete systems from measured impulse response data. In *International Conference in Acoustics, Speech and Signal Processing, ICASSP-91*, pages 1689–1692, 1991.

[22] T. Soderstrm and P. Stoica. *System Identification*. Prentice-Hall International, Series in Systems and Control Engineering, University Press, Cambridge, 1989.

[23] Texas Instruments. High Performance Synchronous Buck Controller with DCR Current Sensing. Technical Report March, 2013.

[24] K. S. Tsakalis and S. Dash. Adaptive PID Control using Filter-Banks and Frequency Loop Shaping. pages 1340–1347, 2007.

[25] K. S. Tsakalis and S. Dash. Identification for PID Control. In R. Vilanova and A. Visioli, editors, *PID Control in the Third Millennium, Advances in Industrial Control. Lessons Learned and New Approaches*, chapter 10, pages 283–317. Springer, 2012.

[26] K. S. Tsakalis and S. Dash. Approximate H_inf loop shaping in PID parameter adaptation. *International Journal of Adaptive Control and Signal Processing*, 27:136–152, 2013.

[27] R. Zane, B. Miao, and D. Maksimovic. Active System Identification of a DC-DC Converter Using Digital Control. *2nd International Energy Conversion Engineering Conference*, pages 1–8, 2004.