SELF-TUNING ADAPTIVE CONTROLLER APPLIED TO THE BOOST CONVERTER VOLTAGE CONTROL

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Abstract – **This paper presents the design and simulation tests of fixed and adaptive pole placement control techniques to the Boost converter voltage control. Due to the converter non-minimum phase characteristics, no zeros cancellation was considered in the design procedures. An indirect self-tuning (STR) adaptive controller with online plant estimation and controller design was evaluated. A recursive least-squares method was used to identify the plant model in real time. Simulations results with a nonlinear model are presented and discussed. It can be noticed that for abrupt changes in the plant dynamics or operational condition, the STR adaptive control works better, rejecting disturbances and following the reference signal. In the other hand, the system with the fixed controller, after some specific load resistance change, cannot reject disturbances, leading the system to an oscillatory response.**

Keywords **– Boost Converter Control, Pole Placement, Recursive Least-squares Method, Self-Tuning Regulator.**

I. INTRODUCTION

The Boost topology is a DC-DC step-up converter widely used in electrical engineering applications. The safe operation meeting stability and performance specifications for the output current and voltage is achieved by using control systems that allow a wide range of operational conditions. Changes in the converter conditions, such as load resistance or input voltage, can modify significantly the converter dynamics [1] [2]. In addition, due to the natural nonlinearities of the physical system, the operational condition also changes with the duty cycle or reference signal variations.

Among the control techniques that handle uncertainties and operational condition variations, the adaptive control strategies stand out for reach the closed loop stability and performance for a wide range of operational conditions which are often harder to achieve with a fixed parameters control technique [2].

In [2], experimental results of self-tuning regulator (STR) adaptive controller were evaluated on a buck-boost converter. The adaptation capability of the proposed controller was assessed throughout reference tracking tests for different values of load resistance. In [3] and [4], simulation and experimental results of robust controllers were also evaluated on a Boost converter. The design performance was investigated throughout regulation tests with the application of disturbances in the values of load resistance and input voltage. An adaptive control strategy for a DC-DC boost stage PV converter is proposed in [5], which enables the use of a small input capacitor preserving at the same time the performance of the original system with a large capacitor.

In this work is investigated the application of the indirect STR adaptive technique to the Boost converter output voltage control. The performance of the proposed controller was assessed not only from reference tracking but also with regulation tests, for different values of load and input voltage. In this STR control strategy, the plant parameters are estimated in real time throughout the Recursive Least Squares (RLS) algorithm and after that, the controller parameters are calculated by using the pole placement method [3]. Therefore, the adaptive control law can cope with changes in the plant dynamics. For comparisons reason, a fixed parameter controller was also tuned and evaluated.

II. SYSTEM MODELING

The Boost converter topology considered in this work is illustrated in Fig. 1. For control ends, the model was approximated by an AC equivalent circuit model, as proposed in [1]. This strategy allows obtaining an average model of the Boost converter, which does not consider switching effects in the inductor current and in the capacitor output voltage. In addition, the converter is analyzed only at the continuous conduction mode.

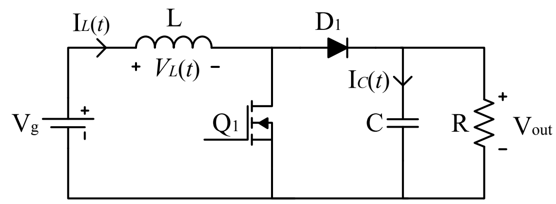

Fig. 1. Boost Converter Topology.

Using the linear model approximation [1], the converter transfer function, that relates changes in the output voltage and in duty cycle, is obtained as:

$$G_{vd}(s) = \frac{\hat{V}_0}{\hat{d}} = \frac{V_{out}}{D'} \frac{\left[1 - s\left(\frac{LI_L}{D'V_{out}}\right)\right]}{\left(\left(\frac{CL}{D'^2}\right)s^2 + \left(\frac{L}{RD'^2}\right)s + 1\right)} \qquad (1)$$

where V is the output voltage DC component, I_L is the inductor current DC component, D is the duty cycle and D' = 1 - D considering the specific operating condition of R = 12 ohms, L = 221 uH, C = 77.1 uC, V_{out} = 19 V, I_L = 2.51 A, and D = 0.37.

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The transfer function described in equation (1) was discretized, considering a sample time (T_s) of 0.0001 s, resulting in the following nominal model:

$$G_{vdz}(z) = \frac{0.3533z + 6.177}{z^2 - 1.681z + 0.8976}. \quad (2)$$

This model was used to calculate the initial parameters of the controller.

III. INDIRECT SELF-TUNING REGULATOR

The self-tuning regulator strategy (STR) has the online parameters estimation as the main part of this control technique, as shown in Fig. 2. If the plant parameters are modified, they are estimated for this new operational condition, and, after that, the controller parameters are also recalculated. Due to this fact, is expected that the controller adapt to the new operational condition. This adaptive control scheme is called Indirect STR. The plant parameters estimation is based in the Recursive Least Squares (RLS) method, which processes input and output data for the estimation to be done.

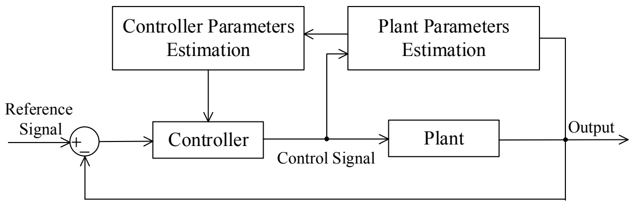

Fig. 2. Indirect STR scheme.

A. The pole placement method

The discrete controller used in the STR adaptive method has a RST topology as showed in [6]. This controller is composed by three polynomials, R_c, S and T, adjusted to achieve a desired reference tracking and regulation performance. The resultant output to reference closed-loop transfer function is defined as:

$$G_{mf}(z) = \frac{BT}{AR_c + BS}, \quad (3)$$

where B and A are the polynomials with the zeros and poles of the discrete plant model (ARX model). The pole placement method is based on the solution of equation (4), where the right side is the closed loop characteristic polynomial and the left term is a discrete polynomial specified according to the desired response.

$$AR_c + BS = A_c. \quad (4)$$

The polynomial A_c is calculated according to a reference filter G_{ref} = B_m/A_m with damping factor and natural frequency previously determined. The equation (4) is known as Diophantine equation, and its solution gives us the coefficients of R_c and S, and another condition is needed to find T. For solution purposes, the polynomials B and R_c can be written as $B = B^+B^-$ and $R_c = R'_cB^+$, where B^- is the polynomial with the unstable or not well damped zeros and B^+, with the stable and so well damped zeros. For the Boost converter control, its zero cannot be canceled because it is unstable. Therefore, $B^+ = 1$, and the Diofantine equation becomes:

$$AR'_c + B^-S = A_0A_m \quad (5)$$

And *T* can be found as:

$$T(z) = \beta A_0, \quad (6)$$

where A_0 is known as observer polynomial and $\beta = A_m(1)/B_m(1)$ according to [6].

By solving equations (5) and (6), the controller coefficients are found and the closed loop system can be made and tested.

B. Boost Converter RLS System Identification

The Recursive Least Squares Method [6] [7] was used in this work to perform the online estimation of the Boost ARX model. The main goal of this method is to minimize the error between the measured and the estimated converter output voltage. Therefore, one needs to find the minimum of equation 7:

$$V(\theta, t) = \frac{1}{2}\sum_{i=1}^{t} \lambda^{t-1}\left(y(i) - \varphi^T(i)\theta\right)^2, \quad (7)$$

where y is the vector that contains the observed variables, $\varphi^T(i)$, the regression variables, θ, the parameters of the model to be determined and λ is known as the forgetting factor, which $0 < \lambda \leq 1$. In this work, λ was chosen to be equal to 0.88.

The forgetting factor changes how the classical RLS works, introducing a way of giving different weights to different samples, which most likely gives the actual sample more importance in the estimation. In this work, that factor substituted the algorithm of resetting the covariance matrix. The forgetting factor needed to be used due the frequent estimated parameters changes.

The estimation algorithm is performed and updated by the recursive algorithm as the following:

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)\left(y(t) - \varphi^T(t)\hat{\theta}(t-1)\right), \quad (8)$$

$$K(t) = P(t-1)\varphi(t)\left(\lambda + \varphi^T(t)P(t-1)\varphi(t)\right), \quad (9)$$

$$P(t) = \left(I - K(t)\varphi^T(t)\right)\frac{P(t-1)}{\lambda}. \quad (10)$$

IV. DESIGN OF A FIXED CONTROLLER

In this work, in order to evaluate the adaptation capability, a fixed parameter was also designed. This controller was tuned throughout the pole placement technique, described in section III, by using the discretized model, described in equation (2).

The RST parameters were calculated and the controller polynomials were found as ($T_s = 0.0001$ s):

$$R_c(z) = (z^2 + 1{,}048z + 0.906)(z - 1), \tag{11}$$

$$S(z) = 0{,}1131z^2 - 0{,}2334z + 0{,}1316, \tag{12}$$

$$T(z) = 0{,}0114z^2. \tag{13}$$

For both of controllers, fixed and adaptive, the desired characteristic polynomial A_m was chose to be the same:

$$A_m(z) = z^3 - 1{,}633z^2 + 0{,}7139z - 0{,}006977. \tag{14}$$

This polynomial A_m was chosen in order to ensure that the model reference filter works as a second order filter with natural frequency (ω_n) of 3000 rad/s and damping factor (ξ) of 0.6, leading the desired closed-loop system to have a settling time of 2.2 ms and overshoot of 10%, approximately. It can be noticed that A_m is a third order polynomial due to a Diophantine equation solution requirement [6].

V. SIMULATION RESULTS

In order to evaluate both of the controllers, fixed and adaptive, simulation experiments were done, as shown in Fig. 3 to 6. During these simulation tests were considered the operating conditions as R = 12 ohms, V_{in} = 12 V, and V_{out} = 19 V, with disturbances applied to specific parameters. In order to reproduce the natural noise of a real converter, a white noise signal was summed to the voltage output signal of the simulation model. This noise signal was set with spectral power of 1.10^{-6} and the sample time equal to T_s.

For the first simulation, the load resistance was changed to 7 ohms at 0.07 s, the input voltage was reduced to 10 V at 0.08 s and brought back to 12 V at 0.085 s, represented in Fig. 3 and Fig.4. It can be noticed that both of controllers regulated the output on the reference value, rejecting the disturbances.

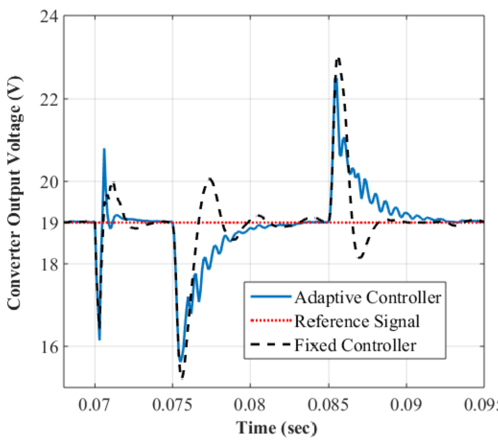

Fig. 3. Disturbance Analysis – Load Resistance 7 ohms.

Despite of the peaks in the control signal, shown in Fig. 4, is can be notice that the respective control efforts did not saturate.

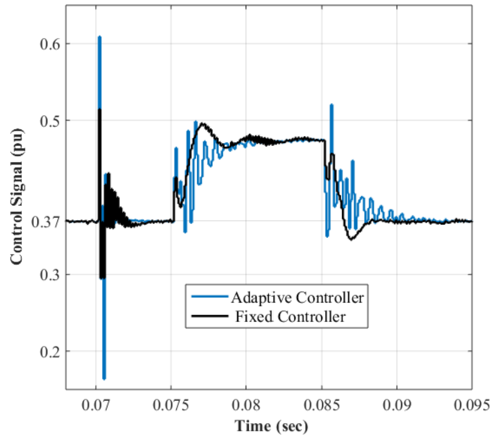

Fig. 4. Disturbance Analysis – Control Signal.

In the second case (see Fig. 5 and Fig. 6) the load resistance was changed to 5.7 ohms at 0.07 s, the input voltage reduced to 10 V at 0.075 s and brought back to 12 V at 0.085 s. Is clear that the system with the adaptive controller presented a better response than when the system operated with the fixed controller. Both of controllers rejected the resistance output disturbance, but as soon as the input voltage disturbance was applied, the fixed controller could not reject it and the system became oscillatory.

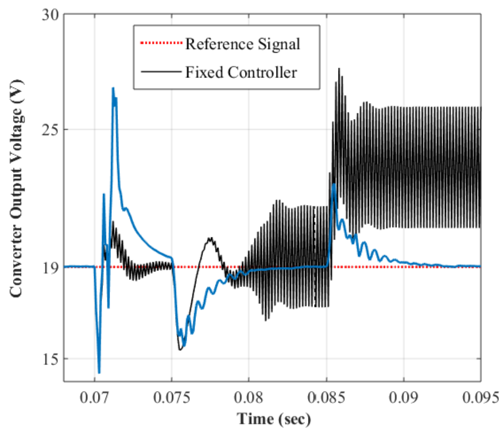

Fig. 5. Disturbance Analysis –Load Resistance 5.7 ohms.

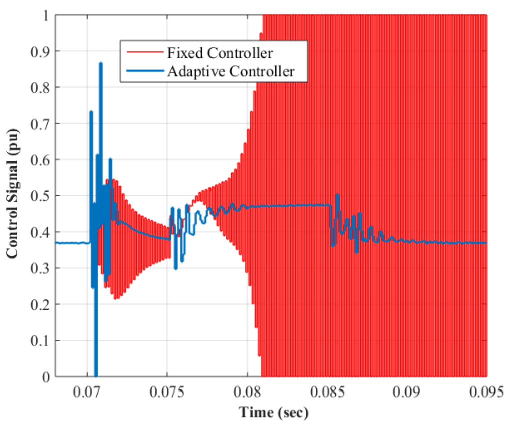

Fig. 6. Disturbance Analysis – Control Signal.

In addition to the simulation results in changing output resistance and input voltage, three more simulations were considered. It this case, it was considered a change in the reference signal with no changes in the other system parameters, represented in Fig. 7 to Fig. 12.

Fig. 7 shows the response of both of controllers, fixed and adaptive, to a change in the reference signal of 1 V. It can be notice that both of the controllers have a good response. Actually, the fixed controller has a better response, almost exactly equal to the reference filter, due to the way the adaptive controller was implemented, with non-linearity characteristics on its parameters update strategy. In Fig. 8, it can be notice that fixed and adaptive controllers' control signal are very close to each other, what, again, does not show a clear better performance of any control strategy.

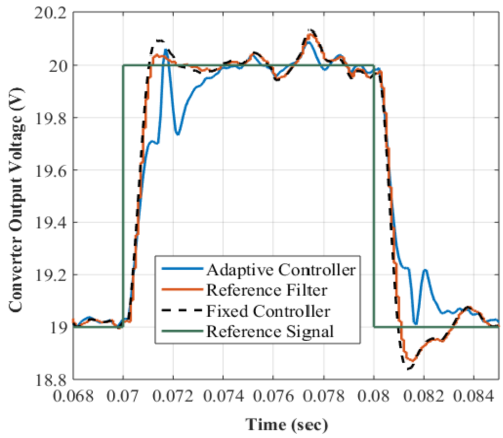

Fig. 7. Change in the Reference Signal – 1 V.

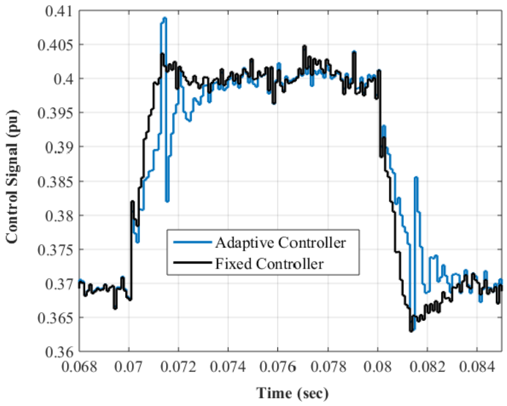

Fig. 8. Change in the Reference Signal – 1 V – Control Signal.

In Fig. 9, it is shown a simulation which the signal reference is changed from 19 V to 24 V, an increase of 5 V. It is noticed that the fixed controller loses performance, leading the output to a more oscillatory response and with a higher setting time than the reference filter. This characteristic can be explained and it is expected to happen due to the fact that the fixed controller parameters are calculated near a specified operational condition, 19 V, in this case. By the other hand, the adaptive controller has a good performance, near to the reference filter response. Fig. 10 shows that also the control signal from the fixed controller oscillates more than the one from the adaptive.

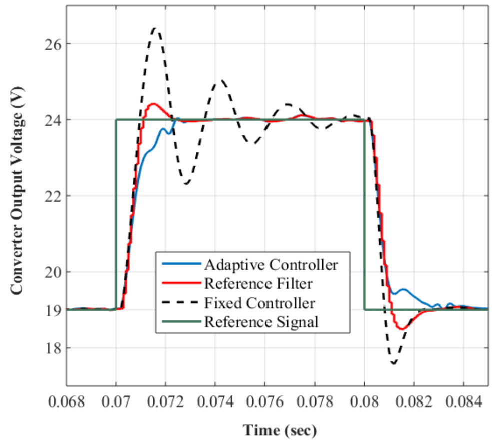

Fig. 9. Change in the Reference Signal – 5 V.

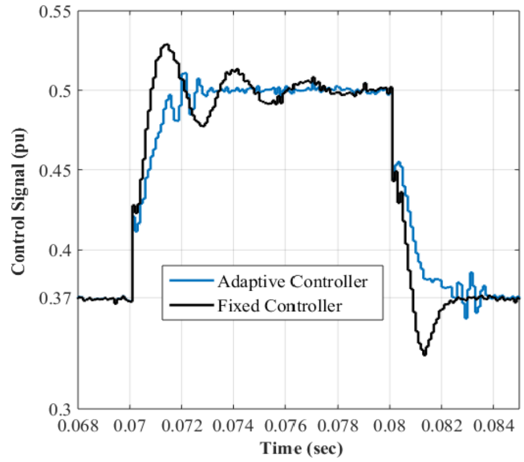

Fig. 10. Change in the Reference Signal – 5 V – Control Signal.

In the simulation represented in Fig. 11, when the reference signal increases from 19 V to 29 V, the fixed controller loses its performance, not meeting overshoot or settling time criterions, leading the output signal to an oscillatory response. The adaptive control systems, however, has the desired performance, quite near to the reference filter response. That way, it is clear that with the adaptive controller, one can reach the specified response also with abrupt changes in the reference signal.

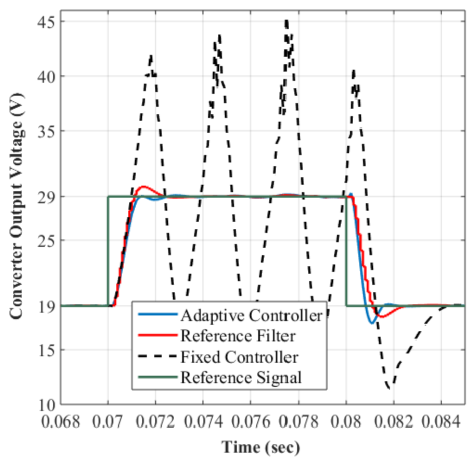

Fig. 11. Change in the Reference Signal - 10V.

Fig. 12 shows the both of the controllers control signal and emphasizes the better response of the adaptive control strategy. The control signal of the fixed controller has an oscillatory response while the adaptive controller control signal has a smooth variation.

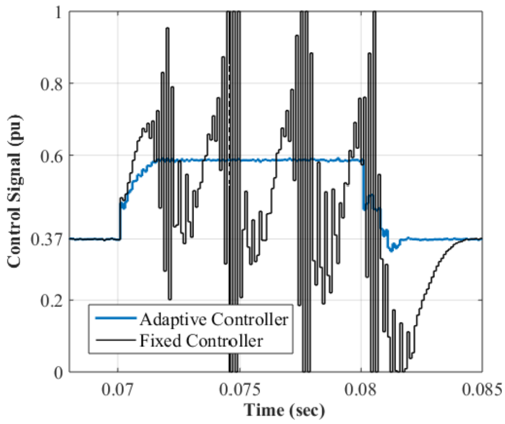

Fig. 12. Change in the Reference Signal - 10V – Control Signal.

Even if there is no need of the converter operational conditions variation, within some time of the converter utilization, some of the converter electronic devices nominal values may change which changes the system dynamics. For example, it is common that the converter the output capacitance decreases with time.

Therefore, to analyze how such a change would impact in the controller performance, one more simulation was done. Fig. 13 shows how both of the controllers work for a output resistance change, from 12 ohms to 7 ohms, in 0.007 s and a output capacitance change, from 77.1 uF to 47.1 uF, in 0.075 s. As one can notice, for a change of 30 uF in the output capacitance, the adaptive controller works as designed, while the fixed controller cannot stabilize the system and, within 0.015 s, approximately, leads the system to an oscillatory response. Fig. 14 shows the control signal for both of the strategies. As expected, for the fixed controller, this signal is stable only before the disturbance in the capacitance. After that, this controller cannot stabilize the system. Again, the adaptive controller works better, emphasizing the importance of this strategy.

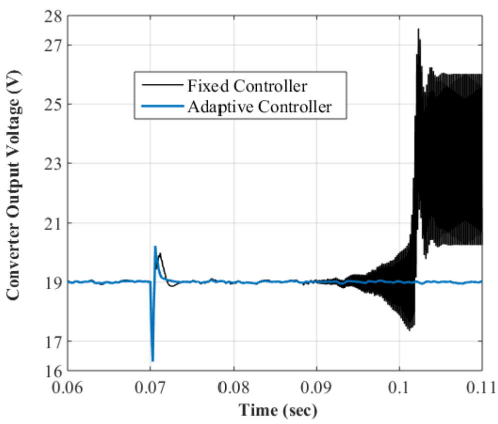

Fig. 13. Change of the capacitance value.

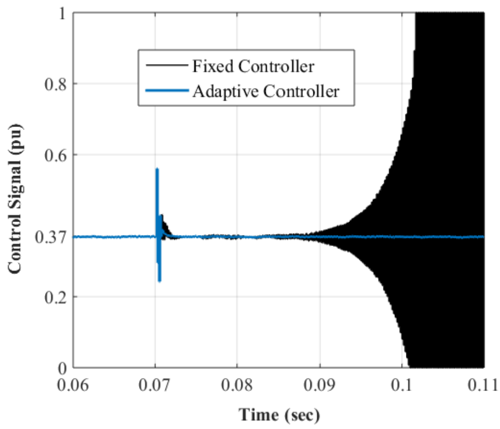

Fig. 14. Change of the capacitance value – Control Signal.

VI. CONCLUSION

This work has represented a comparison between fixed and adaptive control systems applied to the Boost converter output voltage control. For the considered operational conditions and disturbance values, the simulation results showed a better performance of the STR adaptive controller, which presented better disturbances rejection and reference tracking response. No adverse effects were observed in the simulation tests. However, the Boost converter topology must be assembled experimentally to validate the obtained results.

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