Robust Control Methodologies For dc/dc PWM Converters Under Wide Changes in Operating Conditions

(Invited Paper)

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abstract- In this paper, a comparative study on the subject of robust control of dc/dc PWM converters is presented. Considering a wide range of possible changes for the converter's operating conditions, robust control of dc/dc PWM converters using some state of the art robust controllers i.e., $\mathbf{H}_\infty$, μ , and fuzzy controllers is studied. The system under study is a CUK converter as a non-linear, variable structure, and non-minimum phase plant with complex and potentially chaotic behavior. The results confirm successful performance of the $\mathbf{H}_\infty$ and μ controllers in providing wonderful robustness to even wide changes in the operating point. The results also prove that in compare with the $\mathbf{H}_\infty$, the μ controller can by far provide superior results. As will be shown, while the results are quit interesting, the ability of such linear controllers is restricted to the situations where a linear model for the under study system is considered. They may fall down to control the exact physical system, especially where the large signal behavior of the converter is studied. To overcome the aforementioned issues, a simple robust fuzzy controller accompanied with a non-linear / time varying feed-forward controller is proposed. The results clearly prove the relative superiority of fuzzy controller design framework, which lead to a non-linear controller, to overcome the stability issues of the complex dc/dc converters.

Key-words: dc/dc Converter, Instability, Chaos, Robust Control, Fuzzy Controller, $\mathbf{H}_\infty$ Controller, μ Controller, State Space Averaging, Cuk Converter.

Nomenclature:

V_{ref}:	Reference voltage of converter
X:	Converter's State vector
V:	Input voltage
D:	Duty cycle
Y:	Output voltage
X_0:	State vector at operating point
V_s:	Nominal input voltage
D_0:	Duty cycle at operating point
V_0:	Output voltage at operating point
z:	Deviation of state vector
v:	Deviation of input voltage
d:	Deviation of duty cycle
y:	Deviation of output voltage
S(s), T(s), R(s):	Sensitivity, complementary sensitivity , and additive robustness functions
G(s):	Transfer function of the plant
K(s):	Transfer function of the controller
W_1 , W_2, W_3 :	Weighting functions corresponding to S(s), R(s), and T(s) in $\mathbf{H}_\infty$ design
W_I , W_S, W_T:	Weighting functions of uncertainty, S(s), and T(s) respectively in μ design
K_I , K_P :	Integral and proportional gains of PI controller
Z	Zero
NL:	Negative Large
NM:	Negative Medium
PM:	Positive Medium
PL:	Positive Large
x:	Input signal of fuzzy controller
x':	Derivative of input signal of controller
LHP:	Left Half Plan
LTI	Linear Time Invariant

1 INTRODUCTION

So far, dc/dc pulse width modulated (PWM) power converters have had wide applications in various electrical systems such as switching power supplies, UPSs, and dc machine drives. The topic of robust control of this family of converters has been quite attractive to the researchers in the recent two decades [1]-[10],[12]-[19]. From control point of view, operation of dc/dc converters can be regarded as a tracking problem, in which the output quantity should follow the reference command with good transient behavior and low steady state error. Most of these systems are inherently time varying (Variable Structure), uncertain [20], [21], and non-linear with some complex behavior [22]-[25]. State space averaging [26], the well-known method for modeling wide range of dc/dc converters, provides only an approximate dynamical LTI model for the system. There are various sources may cause uncertainties in such LTI models [20], [21]. Some uncertainties arise by the modeling approach used namely state space averaging / linearizing, which provide an approximate LTI model valid only for low frequencies [26]. In these cases, the calculated LTI model usually depends on the operating point of the converter. On the other hand, any change in the reference command, load parameters, or input dc supply may change the operating point of the system. This operating point change, in turn, alters some parameters of the corresponding LTI model. Thus, where a dc/dc converter is in use, due to possibly wide changes in the input, output, or reference quantities, we should expect rather a wide change in the converter's model and its performance as well. This signifies the subject of robust control of dc/dc converters. It also explains how we need to use robust controllers for overcoming uncertainty issues of the dc/dc converters. In addition, in some cases, the closed loop dc/dc power converter, which is usually non-linear and variable structure, may exhibit a very complex and chaotic behavior [22]-[25]. Such complex behavior along with existence of various major sources of uncertainty makes the controller design task so difficult. So far, application results of several advanced linear as well as non-linear controllers to dc/dc converter field have been reported in the literature [1]-[10],[12]-[19]. Some attractive control methodologies used are $\mathbf{H}_\infty$ [1]-[3], μ [4]-[6], fuzzy logic based [7]-[10], sliding mode [12]-[14], LQG/LTR [15,16], Kharitanov theory based [17], Lyapanuv theory based [18], and QFT [19]. Amongst them, some recent articles represent the latest advances in the field. For example, reference [1] addresses a successful application of $\mathbf{H}_\infty$ theory to control of non-minimum phase boost and buck-boost converters. In [10] robust control of a bad behavior Cuk converter using a fuzzy controller has been discussed. Also, [5] presents a generalized approach for μ synthesis of switching regulators. Within the PWM converters investigated, the Cuk converter can be regarded as the worst behavior topology in compare with other topologies such as buck, boost, and buck-boost. It is of higher degree, non-minimum phase, highly non-linear, and susceptible to become chaotic [22]-[25]. As an important point, most of the articles in the literature on the robust control of dc/dc converters subject have considered only rather small changes for the input voltage of the converter. For example, [4] considers a maximum of 10 % change in the input voltage.

This paper presents a useful comparative study about control of the Cuk converter with $\mathbf{H}_\infty$, μ, and fuzzy controllers, where significant variations in the converter's operating point may occur. The paper also considers some important issues regarding the Cuk converter such as its chaotic behavior. Such feature can seriously doubt ability of any linear robust controller in controlling such complex systems. The results obtained show that $\mathbf{H}_\infty$ [27] and μ [28,29] controllers can provide robust performance/stability for a very wide range of input voltage while the better robustness can be gained by μ controllers. Both Linear controllers are designed based on the averaged and linearized model of the converter [26]. Simulation results also clearly explore some complex and chaotic behavior of the converter at large signal operation. To overcome the instability issues, using a fuzzy logic based controller is suggested. The paper also proves successful performance of the controller in chaos rejection and providing good robustness to significant changes in the load and/or input dc supply. In our studies, we mostly consider the model's variations caused by load and dc voltage changes. They are the most important sources of uncertainty that significantly affect the converter's operation. The other sources of uncertainty such as changes in the reference signal have quite similar effects. Also, due to relatively low effects of high frequency stray dynamics, they are ignored in this study.

The structure of this paper is as follows. In section 2, the system under study with its dynamical model is introduced. Section 3 gives a brief overview of the controller design issues needed for designing linear robust controllers. In sections 4 and 5, the results achieved from application of the $\mathbf{H}_\infty$ and μ controllers are presented and discussed. Large signal and chaotic behavior of the converter are addressed in section 6. Section 7 presents application results of the fuzzy controller. Finally, section 8 concludes the paper.

2 CUK CONVERTER UNDER STUDY

Fig. 1 shows the circuit diagram of the study system, which is the same dc/dc PWM CUK converter as studied in [15] and [16]. The converter's nominal input and output voltages are as $V_s = 25$ v and $V_o = -30$ v respectively. Eq. (1) indicates the relation between input, output, and duty cycle at steady state. According to (1), the nominal value of the duty cycle is calculated as $D_0 = 0.5455$.

$$\frac{V_o}{V_s} = \frac{-D_0}{1-D_0} \Rightarrow D_0 = \frac{-V_o}{-V_o + V_s} \qquad (1)$$

Fig. 2 shows the frequency response of the converter's model obtained from the state space averaging and linearizing technique [26]. The control input "d " and the output signal "y" are deviations around the nominal values of the duty cycle and the output voltage respectively. Transfer function of the converter's model is given by (2).

$$G(s) = \frac{y(s)}{d(s)} = k\frac{(s-z_1)(s-z_1^*)}{(s-p_1)(s-p_1^*)(s-p_2)(s-p_2^*)} \qquad (2)$$

Where * denotes the complex conjugate, and $k=1.219\times10^9$, z_1=65.7+j518.2, p_1=-5.8+j354.77, and p_2=-454.9+j4739.1

Based on the above information, the system has the following features :

i) It has one pair of complex zeros with positive real parts

ii) It has one pair of stable but low-damped and low-frequency poles. and

iii) It has one pair of medium-damped but high frequency poles.

Also, Fig. 3 shows the step response of the converter's model. As seen, there are two different oscillations. One is high frequency and high-damped, and the other is low frequency and low-damped. Each of the addressed oscillations clearly corresponds one of the complex pole-pairs of the system. Any increase in R or V_s will increase the oscillation frequency of the low-damped dynamics.

3 FREQUENCY-DOMAIN REQUIREMENTS

Fig. 4 shows the block-diagram of a general SISO feedback control system. According to Fig. 4, we can define the following well-known transfer functions.

$$T(s)= \frac{Y(s)}{R(s)} = \frac{K(s)G(s)}{1+K(s)G(s)} \qquad (3)$$

$$S(s)= \frac{Y(s)}{D(s)} = \frac{E(s)}{R(s)} = \frac{1}{1+K(s)G(s)} \qquad (4)$$

$$R(s)= \frac{U(s)}{D(s)} = \frac{K(s)}{1+K(s)G(s)} \qquad (5)$$

Also, (3) and (5) imply the following important relation between T(s) and S(s):

$$T(s)+S(s)=1 \qquad (6)$$

S(s), T(s), and R(s) are so called sensitivity, complementary sensitivity, and additive robustness functions respectively. T(s) is the transfer function between the reference and the output of system. It features a key role in tracking performance of the closed loop system as well as its robustness to high frequency uncertainties of the G(s). S(s) represents transfer function between the reference signal "r" and the error signal "e" (see Fig. 4). It also determines the disturbance rejection capability of the closed loop system and its sensitivity. That is S(s) by itself carries very important information on both performance and robustness of the closed loop system. Also, R(s) is the same transfer function between the control signal "u" at the input of the plant and the reference signal "r". (2)

In brief, for any linear robust controller design, the following issues should be considered:

-To gain good tracking ability, T(s) must feature high bandwidth with minimum overshoot.

-To reach low steady state error, T(0) should be kept as close as unity.

-To reduce the system's sensitivity to the external disturbances and uncertainties, it is necessary to minimize the |S(jw)| throughout the pass band of the |T(jw)|.

- A very small |S(jw)| in the closed loop bandwidth may rigorously endanger the stability, specially where the plant is non-minimum phase.
-To have appropriate robust stability, we need to limit the bandwidth of |T(jw)|, avoiding destabilizing effect of the high frequency un-modeled dynamics.
-Any attempt to expand the closed loop bandwidth beyond the plant's bandwidth will dramatically boost the |R(jw)| at some frequencies beyond the G(s) bandwidth. That may cause an inadequate control signal (duty cycle) can invalidate the linear model taken.
-Any attempt to increase the system's bandwidth without considering the RHP zeros also may cause overshoots in the |S(jw)| which in turn may cause instability.

4 DESIGN OF $\mathbf{H}_\infty$ CONTROLLER

In this paper, due to lack of space we will not present any details on the structure and design methodology of the robust controllers under study. For more information , some references such as [1]-[5], [28]-[31], and [7]-[10] are suggested. In this section, results obtained from application of the robust $\mathbf{H}_\infty$ controller to the CUK converter under study are presented. In an optimal design, generally we are concerned with the problems of weighted mixed-sensitivity optimization [31], that deals with minimizing the $\mathbf{H}_\infty$ norm of the following matrix .

$$\left\| \begin{matrix} SW_1 \\ RW_2 \\ TW_3 \end{matrix} \right\|_\infty \tag{7}$$

Weighting functions W_1, W_2 and W_3 have key roles in shaping the S, R, and T functions. In a sub-optimal design based on the four-block approach [32], S, R, and T functions follow the inverse of W_1, W_2, and W_3 respectively as follow:

$$|S(jw)| \le W_1^{-1}(jw) \tag{8}$$

$$|R(jw)| \le W_2^{-1}(jw) \tag{9}$$

$$|T(jw)| \le W_3^{-1}(jw) \tag{10}$$

Among the introduced weighting functions, W_1 has a major impact on bandwidth and robust performance of the system, whereas W_3 mostly affects the high frequency robustness of the system via reducing |T(jw)| at high frequencies. As mentioned before, the variations of the source voltage V_s is a well-known source of parameter variation in most of converters. As V_s changes, the control loop retunes the level of D to keep the output regulated. W_1 and W_3 are generally selected through trial and error to reach a desirable tracking performance, disturbance rejection, and robustness to the V_s variations. Equations (11) and (12) denote the weighting functions selected for this design. In this design we do not consider any explicit restrictions on the R(jw), because a good selection of W_1 and W_3 can often guarantee having a good R(jw) too.

$$W_3^{-1} = 1.3\frac{1+s/3000}{1+s/500} \tag{11}$$

$$W_1^{-1} = 0.02\frac{1+s}{1+s/11000} \tag{12}$$

In this design, the nominal input voltage is considered to be 30 volts. By that assumption, the control system can more adequately keep stable for wider range of input voltage. Fig. 5 shows the frequency response of the resulting T(s), S(s), and R(s) obtained by means of MATLAB Robust Control Toolbox [32]. Fig. 6 shows the step response of the controlled system at its real nominal operation that is where V_s is equal to 25. It also, shows the system response at different values of V_s that is 15v and 30v. The results confirm the system satisfactory response, disturbance rejection, and robustness. Simulation results showed that the system is stable over the wide range of the input voltage mentioned, whereas may become unstable otherwise. Because the converter is non-minimum phase, any further increase in bandwidth of the system may increase the peak of the | S(jw)|. Such peaks can be very dangerous to the system's robustness and stability. According to the authors' experience, designing a $\mathbf{H}_\infty$ controller can ensure the stability of the system over a wider range of the source voltage is quite difficult.

5 DESIGN OF μ CONTROLLER

It is known in the literature that $\mathbf{H}_\infty$ controllers are very conservative [28], [29]. When we intend to design a $\mathbf{H}_\infty$ controller, it is usually difficult to make a good trade-off between the desired performance and robustness. In contrast, the μ controller design framework provides more flexibility with respect to both performance and robustness. And consequently, the resulting system is expected to be less conservative and more robust as well. That is because in μ controller design framework, it is possible to consider and incorporate a model for the uncertainties explicitly. Such model of uncertainty can be made with the help of the existing information on the plant under control and its parameter variations. As a simple way, it can be performed through considering some changes in some system's parameters such as operating point, and then calculating the worst possible model for the uncertainties. Here, there are weighting functions called W_T, W_s, and W_I selected based on the performance and robustness requirements. In this section a summary of results obtained from designing a μ controllers are summarized. Here, to simplify the design, only the unstructured uncertainties are considered. That is because the structured uncertainties caused by changes in the electronic elements, have not so sever impact as those arias by the changes in the input supply and/or load impedance. Furthermore, that assumption significantly reduces the design complexity, which is of significant importance.

5.1 Design of the Controller

In this design, the weighting functions W_T, W_s, and W_I corresponding to the transfer function, sensitivity function, and uncertainty model respectively, are selected as follow:

$$W_T = 2.5\frac{s+200}{s+100000} \tag{13}$$

$$W_S = 1/6\frac{s+300}{s+0.5} \tag{14}$$

$$W_I = 100\frac{s+20}{s+50} \tag{15}$$

D-K iterative approach [29] using MATLAB Mu-Synthesis Toolbox [33] is implemented to design the controller. The resulting step response of the system is shown in Fig. 7. As seen, the system presents a slow response but stable for a very wide range of the source voltage changes, namely from 5 to 100 volts. The results clearly prove the superiority of μ controllers over $\mathbf{H}_\infty$ controllers. In contrast, μ controller normally has higher degree in compare with any other linear controllers. However, the controller can easily be reduced by means of one of the known model reduction techniques [5].

6 LARGE SIGNAL BEHAVIOR

Most of the controller design techniques for dc/dc converters rely on the approximate LTI models. Such models are useful only where the large signal behavior of the converter is not considered. At large signal conditions, such as start-up scenarios, the LTI model loses its validation. In such situations, the converter may even exhibit complex behavior such as chaos [22]-[25]. Moreover, at large signal condition, there is a possibility of operation in discontinuous conduction mode that may significantly invalidate the assumed model for the converter. In this section, we explore that important concept with the help of two case studies. Fig. 8 shows the start-up response of the open loop CUK converter under study along with its time-response with the μ controller presented in section 5. As Fig. 8 explores, the open loop system has a poor transient response, as it contains a high over-shoot and some unfavorable oscillations as well. Fig. 8 also reveals that the controlled system is unstable and chaotic while the exact model of the converter is used. Unfortunately, in general, when a linear controller exhibits such a complex behavior, there is no clear and straightforward design methodology to overcome the problem. Fig. 9 shows the block diagram of the under study system with a conventional PI controller, which is the most common control scheme for control of dc/dc converters in practice. Simulation studies show the unstable and chaotic behavior of the system where the exact mathematical model of the converter is considered. As a new example, Fig. 10 shows the start-up response of the closed loop system with the following parameters for the PI controller: $K_I = 20$ K_p=1. This figure also shows the state trajectory of two state variables of the system (Voltage of capacitors V_{c_1} and V_{c2}) to highlight the complexity of the system behavior. The results clearly reveal the weaknesses of the linear controllers to overcome complex behavior of PWM dc/dc converters. In this concern, non-linear controllers such as the fuzzy controllers may be a better choice

7 DESIGN OF FUZZY CONTROLLER

As mentioned before, for the applications where the under control system is non-linear and may become chaotic, a non-linear controller in general, and a fuzzy controller in particular looks to be a better choice. Articles [7]-[10] are suitable references on the applications of fuzzy controller to dc/dc converters. Reference [10] addresses a successful design of a fuzzy controller for a CUK converter. The converter studied in [10] is similar to the one considered in this paper but here we consider a worse behavior CUK converter. Also, here we consider the cases where the reference command is constant whilst there are sufficient variations in both the load resistance and the input dc supply. Such cases are more likely to occur in practice. Fig. 11 shows the structure of the fuzzy controlled system while Fig. 12 indicates block the diagram of the fuzzy controller. The control system consists a fuzzy PD controller, a conventional PI controller to guarantee zero steady state error, and a non-linear/ time varying feed-forward controller to reduce the impact of the input dc voltage V_s variations. The fuzzy logic based controller receives the signal (x) and its derivative (x') from the output of the PI controller. It then tunes the converter's duty cycle around its nominal point to regulate the output voltage. To gain the desired response, the following parts of the controller need tuning.

-PI controller parameters K_I and K_p

-Input membership functions of x and x'.

-Output membership functions.

-Rule base parameters.

-Non-linear feed forward controller.

7.1 Fuzzy Controller Design

According to the literature, whenever we are concerned with a control design problem such as fuzzy controller, in which there are a large number of parameters to be designed, achieving an optimal controller without hiring an automatic approach such as Genetic Algorithms (GA) is quite difficult. On the other hand, using GAs while very useful, can be time-consuming [11]. Two save time, the engineering trial and error based approach is employed here. Based on the available conceptual information and after some meaningful trail and error, the rule base is formed as shown in *Table 1*. After each change in the rule-base, the system response is examined. Then, the rule base is updated accordingly. As for the input and output membership functions, they are selected and tuned via engineering trail and error. Fig. 13 shows the final input and output membership functions.

7.2 Feed Forward Controller Design

To improve the transient response of the system, a feed-forward controller is added to set the nominal value of D_0 at input of the modulator. As addressed earlier, D_0 significantly depends on the source voltage V_s as well as the desired output voltage V_{ref}. It should be recognized that incorporating effect of V_s in the rule base in not practical. That is because it makes the rule base three-dimensional and so difficult to handle. Thus, as it is not a suitable task, we reduce the V_s effect by means of a feed-forward controller. Authors' experience shows that a time-varying controller, which smoothly sets the value of D_0 to its final value, can improve the start-up response significantly. Equation (16) shows the mechanism applied to the feed forward controller where D_o (k) is the nominal duty cycle at k^{th} switching period.

$$D_0(k+1) = \begin{cases} D_0(0) + \frac{k}{200} * (\frac{-V_{ref}}{-V_{ref}+V_s}) & if\ D_0(k+1) \le (\frac{-V_{ref}}{-V_{ref}+V_s}) \\ (\frac{-V_{ref}}{-V_{ref}+V_s}) & if\ D_0(k+1) \ge (\frac{-V_{ref}}{-V_{ref}+V_s}) \end{cases} \quad (16)$$

Once a sufficient change in the V_s and /or V_{ref}, recognized, the counter k in (16) is reset to zero, and D_o (0) is also set to the value calculated in the pervious iteration. Hence, the feed-forward controller acts based on (16) to reach the final value of D_o . Equation (16) also explains that the final value of D_o (k) is equal to $(\frac{-V_{ref}}{-V_{ref}+V_s})$, which is the same value required at steady state. It also describes that how the controller controls the rate of changes in D_o to prevent poor transient response. To reach a good transient response, taking about 200 cycles for settling down the D_o (as appear in (16)) can be a good choice. In this design, the rate of changes in D_o from D_o (0) to D_o (∞)is limited to $\frac{k}{200}$. A higher value for that limited may result in an inadequate transient response in terms of over shoot. On the contrary, a low rate-limit may lead to a slow transient response. In this scenario, D_o (0) is set to zero once is started up .

In this design, value of the PI controller parameters are as K_I=1 and K_p=100. Figs. 14 shows the start-up response of the fuzzy controlled system for the nominal V_s and R (load resistance) values. Fig. 15 summarized the responses of the system for some other values of the R and V_s.. The results prove the satisfactory performance and inherent robustness of the fuzzy controlled system. The results show the superiority of the fuzzy controllers over linear ones to control complex and non-linear dc/dc converters at start-up scenario. It should be mentioned that designing a controller with faster response and/or lower overshoot is certainly possible but needs more trial and error. Also, the control system without the aforementioned feed forward controller is stable with satisfactory response.

8 CONCLUSION

In this paper a comparative study on the subject of robust control of dc/dc converters in both small and large signal conditions were performed. The system under study was a CUK converter as a non-linear and variable structure plant with complex and chaotic behavior. Comparative study of three important types of robust controllers that is $\mathbf{H}_\infty$, μ, and fuzzy controllers showed excellent robust stability and robust performance of $\mathbf{H}_\infty$ and μ controllers when the small signal response of the converter is considered. Amongst the controllers investigated, the μ controller can by far provide more robustness. It was shown that the studied system could become unstable and chaotic at large signal conditions where the aforementioned robust but linear controllers are used. To overcome the instability and chaos issues, a robust fuzzy logic based controller accompanied with a non-linear and time-varying feed forward controller was proposed. It was shown that it could provide excellent response as well as good robust performance at start-up. The results obtained prove the superiority of the fuzzy controller in compare with linear robust controllers to control non-linear converters. As a notable conclusion of the paper, it seems that the linear robust controller design methodologies still need significant enhancement to be able to overcome the robustness and stability problems of the nonlinear and chaotic power converters.

APPENDIX

Nominal parameters of the Cuk converter under study are as follow.

$R = 30\,\Omega$, $f_s = 10\,kHz$, $L_1 = 1.9\ mH$, $L_2 = 0.96\ mH$, $C_1 = 850\,\mu F$, $C_2 = 47\,\mu F$

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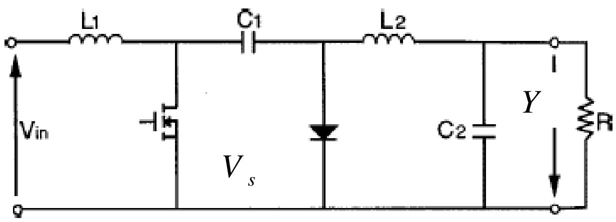


Fig. 1 : CUK converter circuit under study

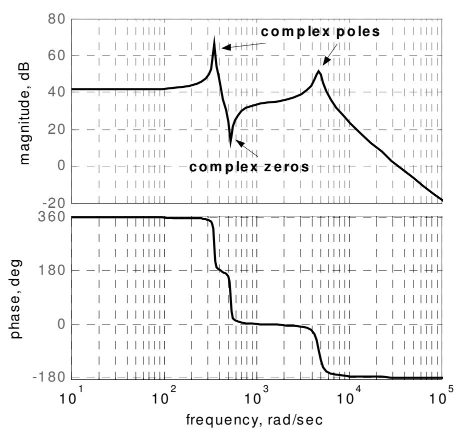


Fig. 2 : Frequency response of the converter (LTI model).

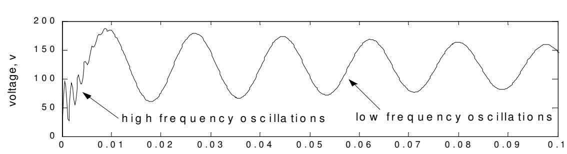


Figure 3 : Step response of the open loop Cuk converter

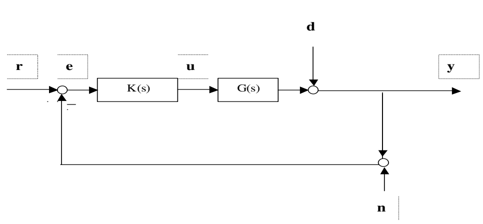


Figure 4: Block diagram of a typical feed back system

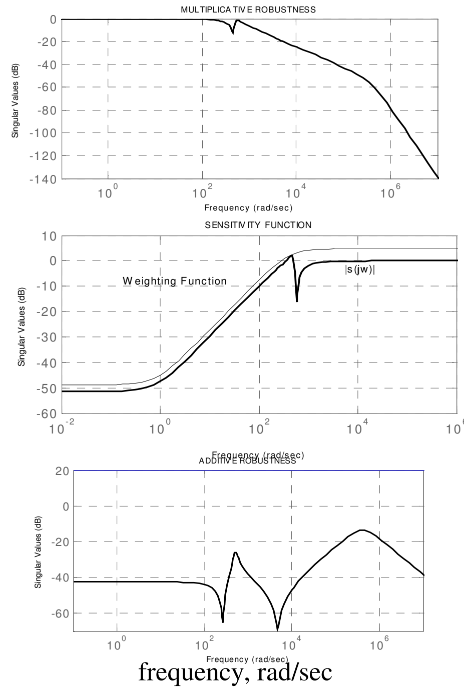


Fig. 5 : Frequency response of the $\mathbf{H}_\infty$ controlled system. Up to down: T(s) , S(s) , R(s)

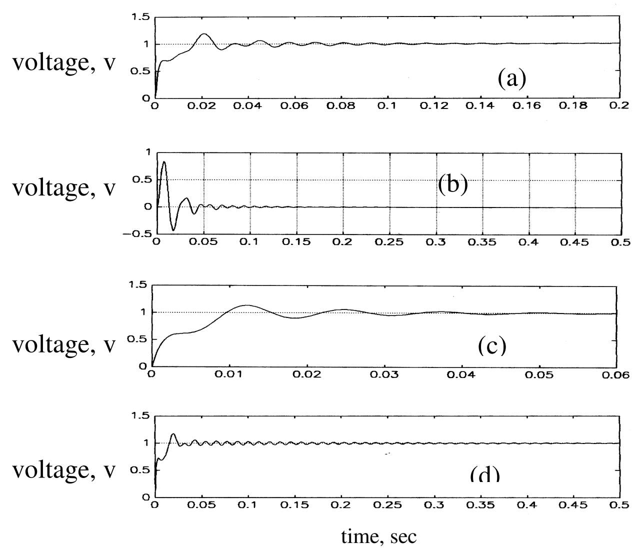


Fig. 6 : Step response of the $\mathbf{H}_\infty$ controlled system. a) Vs=25, b)signal applied to the disturbance input(Vs=25), c) Vs=15) and d) Vs=30.

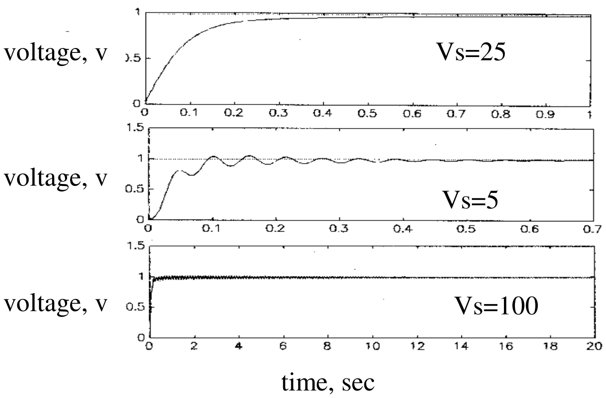


Fig. 7 : Response of the μ controlled system . Up to Down : Step signal applied to the reference(Vs=25, 5, and 100 volts)

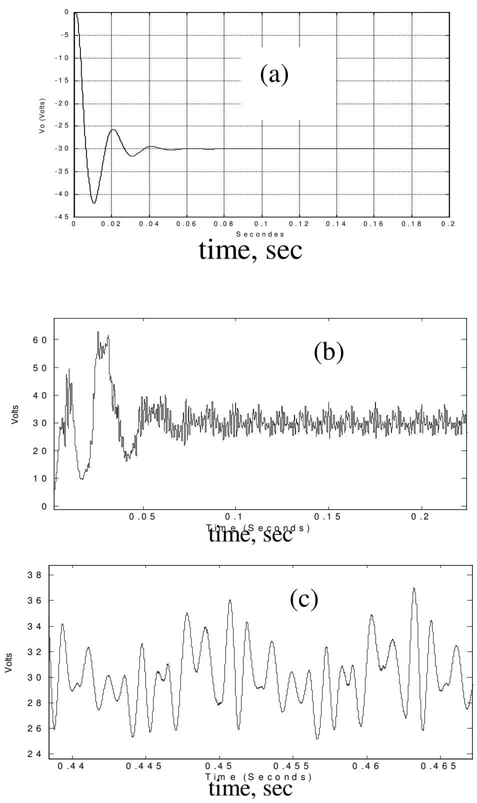


Fig. 8: Start-up response of the system, a) open loop system, b) with μ controller , and c) the enlarged version of (b)

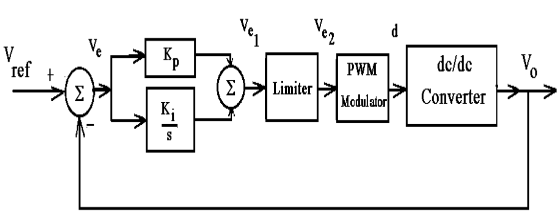


Fig. 9 : Block diagram of the PI controlled system

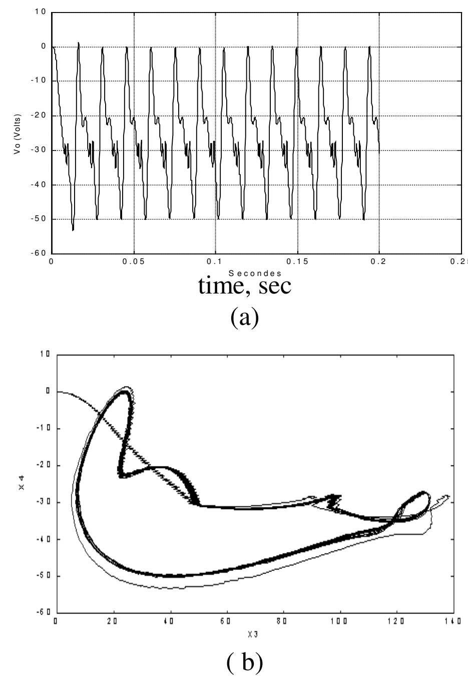


Fig. 10: Response of the system with PI controller., a) Startup response, b) State trajectory V_{c_2} versus V_{c_1}

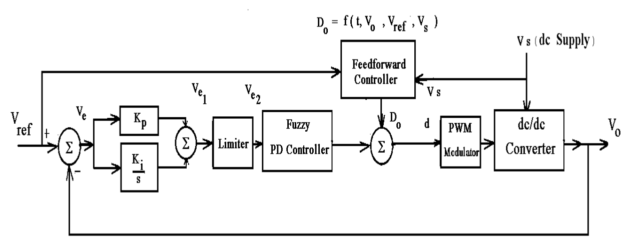


Fig. 11 : Block diagram of the fuzzy logic based control system of the CUK converter

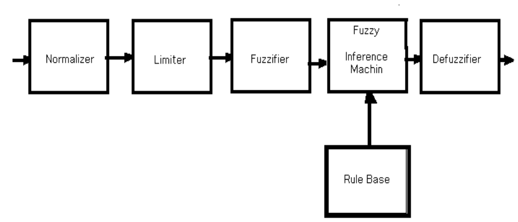
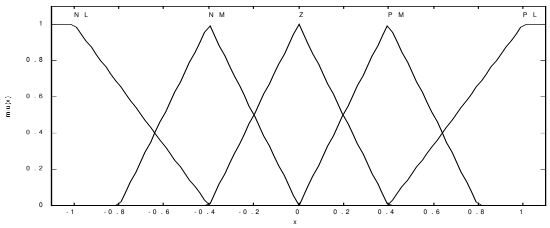
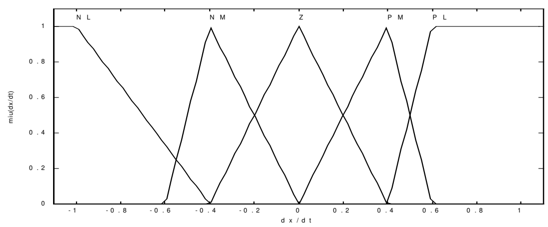


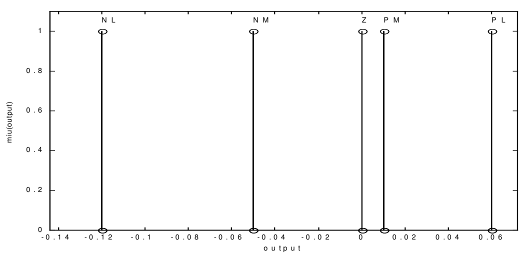
Figure 12: Block diagram of the fuzzy controller



(a)



(b)



(c)

Fig. 13: Fuzzy controller membership functions. a) input x, b) input x', c) output d.

Table1: Rule base of Fuzzy Controller

↓x x'→	NL	NM	Z	PM	PL
NL	**NL**	**NL**	**NL**	**NM**	**NM**
NM	**NL**	**NL**	***<u>NL</u>***	**NM**	**Z**
Z	**NM**	**Z**	**Z**	**Z**	**PM**
PM	**Z**	***<u>Z</u>***	**PM**	**PM**	**PL**
PL	***<u>NL</u>***	***<u>PM</u>***	**PL**	**PL**	**PL**

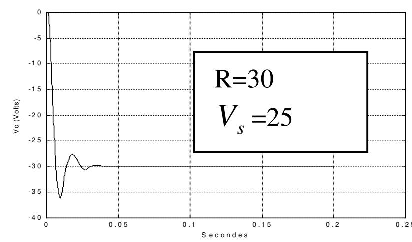


Fig. 14: Large signal response of the fuzzy controlled system at start-up for R=30 and V_s =25 (Nominal Values)

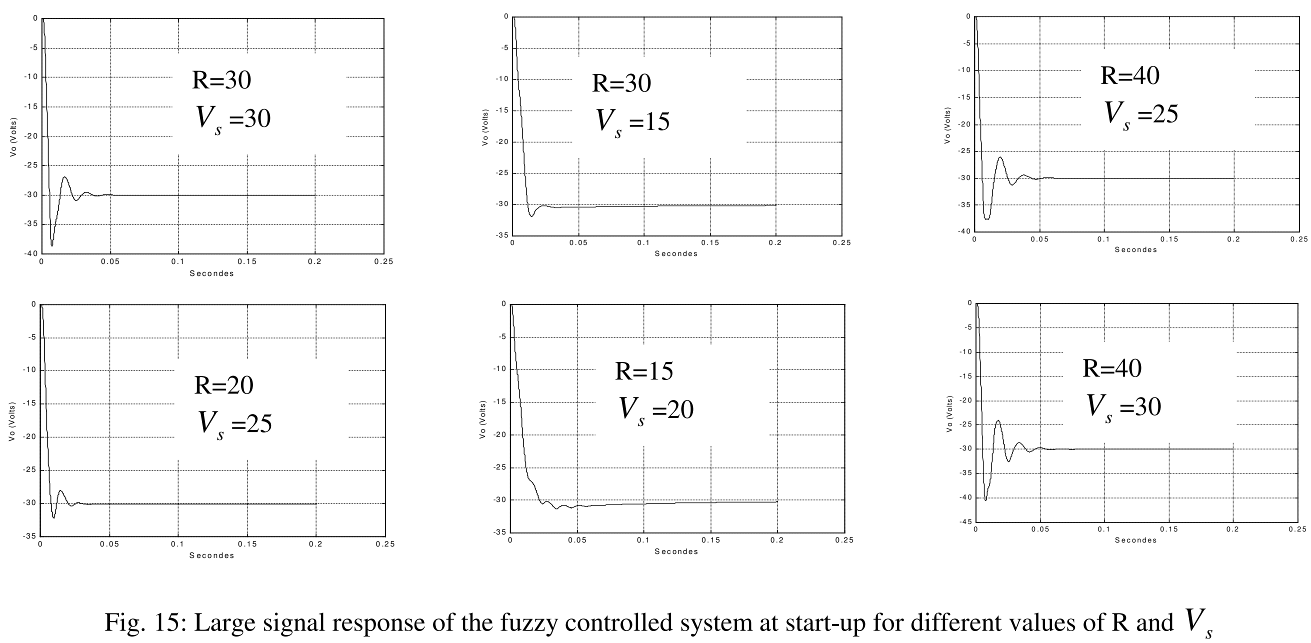


Fig. 15: Large signal response of the fuzzy controlled system at start-up for different values of R and V_s