SIMPLIFIED APPROACHES FOR CONTROLLING DC-DC POWER CONVERTERS

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Abstract:

This paper represents the design procedures of different compensation schemes for voltage mode controlled (VMC) dc–dc switching converters. Proportional integral derivative (PID) controllers, Fuzzy logic controllers (FLC), parallel combination of PID and FLC, and FLC tuned by PI controller have been investigated. MATLAB software is used to depict the buck converter performance with each compensator type when it is electrically simulated, and analytically modeled using its equivalent transfer function (TF). The comparative study Results emphasize that FLC tuned by PI controller is superior to the other control strategies because of fast transient response, minimum steady state error and good disturbance rejection under various variations of the operating conditions. Hence, it achieves the most tightly output voltage regulation.

Keywords: MATLAB, VMC, PID, FLC, Buck converter.

1. INTRODUCTION

Design and implementation of a control system require the use of efficient techniques that provide simple and practical solutions in order to fulfill the performance requirements despite the system disturbances and uncertainties [Eker and Torun (2006)]. The occurrence of nonlinear phenomena in DC–DC power converters makes their analysis and control difficult [Guesmi *et al.* (2008)]. Classical linear techniques have stability limitations around the operating points [Eker and Torun (2006), Guesmi *et al.* (2008), Khaligh and Emadi (2008)]. Hence digital and nonlinear stabilizing control methods must be applied to ensure large-signal stability [Khaligh and Emadi (2008)].

Fuzzy control has also been applied to control dc–dc converters because of its simplicity, ease of design and ease of implementation [Gao *et al.* (2008), Guo *et al.* (2009), Liu *et al.* (2009), Samosir and Yatim (2010), Bouchafaa *et al*. (2011), Cheng (2011), Dereli *et al*. (2011), Messai (2011)]. Fuzzy controllers are well suited to nonlinear time-variant systems and do not need an exact mathematical model for the system being controlled. They are usually designed based on expert knowledge of the converters [Guo *et al.* (2011)].

In this study, the design procedures of linear PID controller, non-linear FLC, Parallel combination of PID and FLC, and FLC tuned by PI controllers are introduced. The buck regulator topology is selected to illustrate the effect of each controller type on the converter performance, when it is electrically simulated, and analytically modeled using its TF. The proposed controllers design procedures can be generally applied to any dc-dc converter topology for stability enhancement, and output voltage regulation over a wide range of operating conditions.

Results discuss the effect of the on-line changes of the supply voltage, reference voltage and loading conditions on the output voltage regulation. The reference voltage is reduced from 8V to 5V at 5mSec. Then the supply voltage is changed from 12V to 20V at 10mSec, and returned to 12V at 15mSec. The load resistance is changed from 1Ω to 3Ω at 20mSec. The simulation results are quite encouraging and satisfactory.

It worth to mention that, electrical modeling is more recommended than the conventional analytical modeling for the following advantages:

1- Faster to display the system performance within shorter simulation time.
2- Simulation results almost indicate the real system behavior.
3- Accurately evaluate the system performance under different on-line sudden changes of the input supply voltage and the reference voltage.
4- The effect of the on-line variations in the supply voltage, the reference voltage and the loading conditions on the system performance is clearly detected.
5- Simply study the effect of overloading and light loading conditions for different loads type, such as; a simple resistive loads, or inductive resistive loads representing a DC motor. This can be quickly achieved without extra calculations of the system
6- Virtual electrical measuring and monitoring devices to simplify the system analysis procedures of each electrical element.

It is depicted that the use of variable step solver for simulating the converter electrically; by its analogue electrical equivalent circuit; requires a stiff solver, such as ode23tb (stiff/TR-BDF2) or ode23t (Mod. Stiff/Trapezoidal). But when using the analytical converter model using its TF, any simpler solver could be used, such as ode 45 (Dormand-Prince). But the fixed step; discrete solver could be used for simulation of both analytical and electrical converter models.

For the linear controller design, the converter mathematical model must be evaluated. The design of the PI controller poles and zeros are based on the converter frequency response (bode plot).

The fuzzy logic controller determines the operating condition from the measured values and selects the appropriate control actions using the rule base created from the expert knowledge [Sambariya *et al.* (2009)]. The objective of this article is not so much the development of a new method for a dc/dc converter control, but rather than the test of feasibility of an original multiple model control principle; to improve the performances by a progressive mixture of two very simple controllers [Leu (2010)].

2. MATHEMATICAL MODELING OF THE SWITCHING CONVERTER:

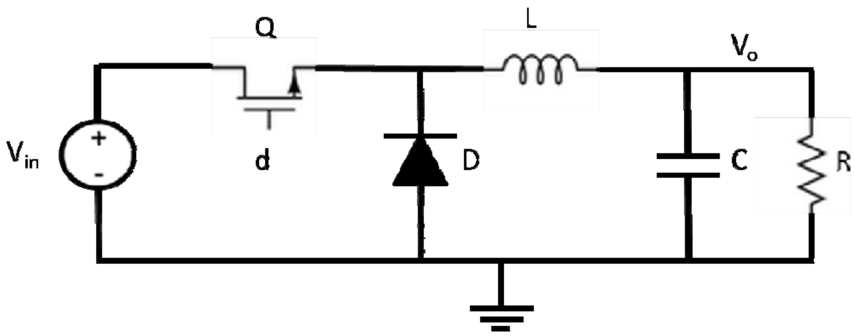


Fig. 1. Buck type dc – dc switching regulator

According to the state space averaged (SSA) model for the buck converter operating in continuous conduction mode (CCM) represented by [Su *et al.* (2002)], the converter transfer functions could be expressed as

$$G_{vd}(s) = \frac{[C_{11}s + (A_{21}C_{12} - A_{22}C_{11})]\ V_g}{L[s^2 - (A_{11} + A_{22})s + (A_{11}A_{22} - A_{21}A_{12})]} \tag{1}$$

$$G_{vg}(s) = \frac{[C_{11}s + (A_{21}C_{12} - A_{22}C_{11})]\ D}{L[s^2 - (A_{11} + A_{22})s + (A_{11}A_{22} - A_{21}A_{12})]} \tag{2}$$

Where: $G_{vd}(s)$: The control – to - output TF & $G_{vg}(s)$: The line – to - output TF.

$$A_{11} = -\frac{1}{L}\left(R_L + \frac{R_o R_C}{R_o + R_C}\right) \tag{3}$$

$$A_{12} = -\frac{1}{L}\frac{R_o}{R_o + R_C} \tag{4}$$

$$A_{21} = \frac{1}{C}\left(\frac{R_o}{R_o + R_C}\right) \tag{5}$$

$$A_{22} = -\frac{1}{C}\left(\frac{1}{R_o + R_C}\right) \tag{6}$$

$$C_{11} = \frac{R_o R_C}{R_o + R_C} \tag{7}$$

$$C_{12} = \frac{R_o}{R_o + R_C} \tag{8}$$

3. CONTROL NETWORK BLOCK DIAGRAM

The basic concept of closed loop control system for power switching regulators is illustrated as shown below:

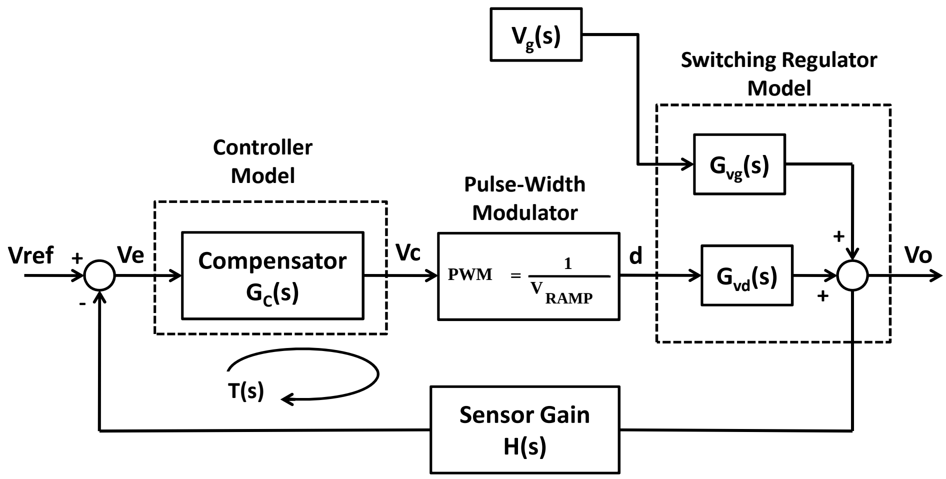


Fig. 2. The compensation network block diagram.

The closed loop output voltage of the switching converter could be written in terms of the loop gain T(s) as:

$$\hat{v}_o(s) = \frac{1}{H(s)}\frac{T(s)}{1+T(s)}\hat{v}_{ref}(s) + \frac{G_{vg}(s)}{1+T(s)}\hat{v}_g(s) \tag{9}$$

Where $\hat{v}_{ref}(s)$ & $\hat{v}_g(s)$ represent the reference and the supply voltage perturbations.

& $$T(s) = H(s)G_c(s)G_{vd}(s)/V_{RAMP} \tag{10}$$

Stability could be determined directly from T(s). If there is exactly one crossover frequency, and if T(s) contains no right half plane (RHP) poles then $\frac{T(s)}{1+T(s)}$ & $\frac{1}{1+T(s)}$ contains no RHP whenever the phase margin φ_m is positive [Su *et al.* (2002)].

4. PROGRAMMING & SIMULATION PROCEDURES

Consider the buck-type switching converter rated at 100 Watt, operating in CCM. Its circuit parameters are represented in table (1).

Table 1. The proposed buck converter parameters.

Variable	Parameter	Value
V_S (V)	Input voltage	12
V_{ref} (V)	Reference output voltage	5
f_S (kHz)	Switching frequency	55
L(μH)	Magnetizing inductance	150
R_L (Ω)	Inductance internal resistance	0.25
C (μF)	Output filter capacitance	200
R_C (Ω)	Capacitance ESR	0.25
R_O (Ω)	Load resistance	1

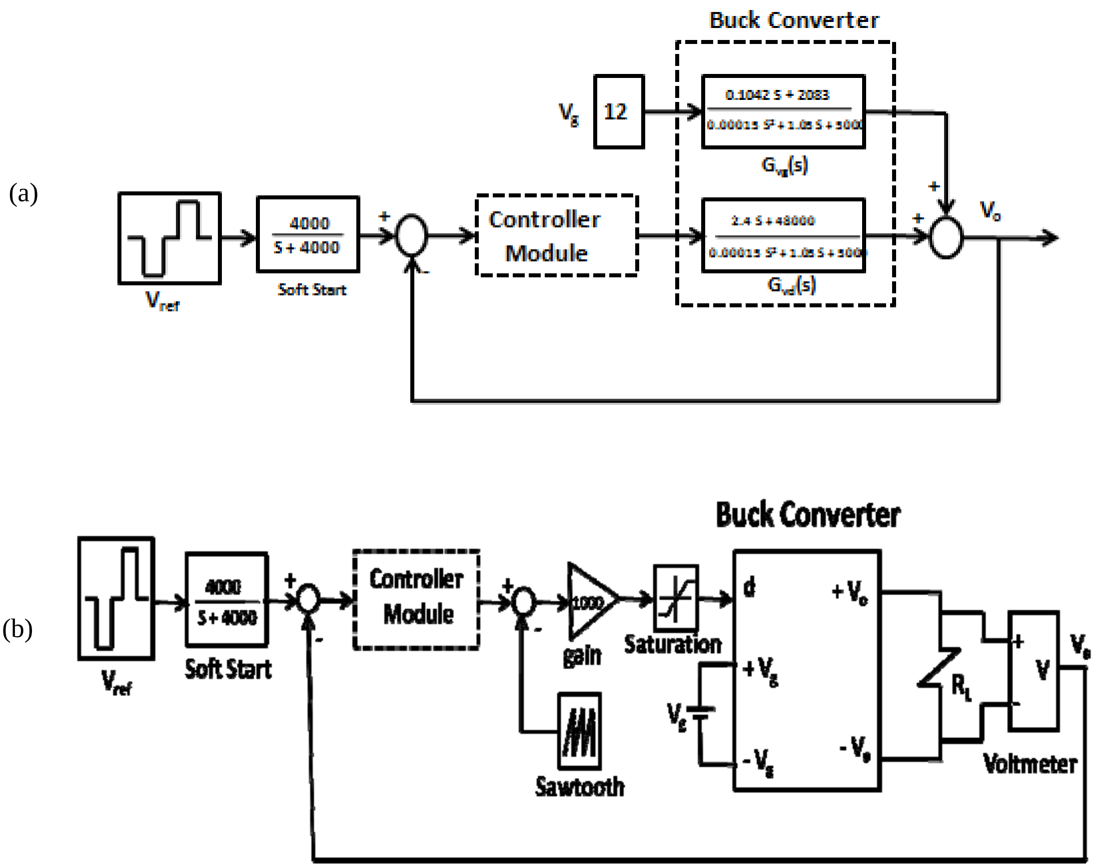


Fig. 3. Simulink model of a controlled buck converter, (a)when it is mathematically modeled, (b)when it is electrically modeled.

(1) The converter control – to – output transfer function:

$$G_{vd}(s) = \frac{2.4\, s + 48000}{0.00015\, s^2 + 1.05\, s + 5000} \tag{11}$$

(2) The converter line – to – output transfer function:

$$G_{vg}(s) = \frac{0.1042\, s + 2083}{0.00015\, s^2 + 0.534\, s + 5000} \tag{12}$$

(3) The steady-state operating conditions:

$$I_{L_o} = 5\, A \tag{13}$$

$$V_{C_o} = 5\, V \tag{14}$$

$$D_o = 0.521 \tag{15}$$

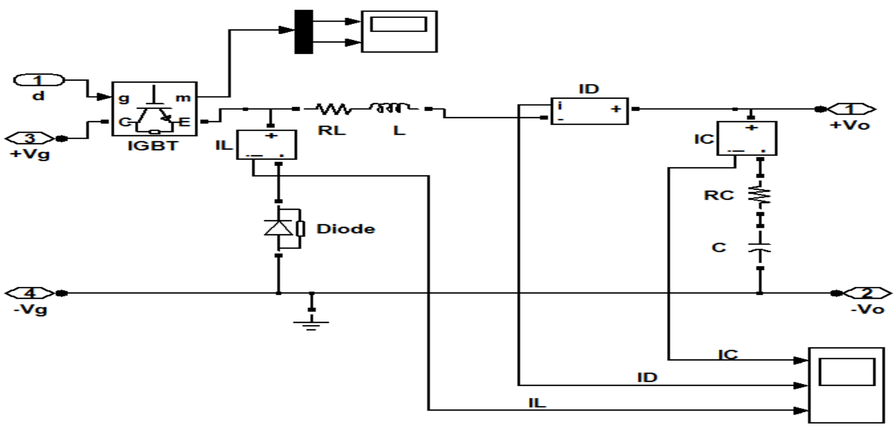


Fig. 4. The electrical model of the buck converter

The basic design approaches for various controller modules will be discussed. Also, the output voltage regulation is evaluated for each controller type, when the converter is electrically modeled and mathematically modeled.

5. BASIC DESIGN OF PID COMPENSATOR

The design guidelines for the linear averaged feedback controllers of a dc–dc switching converter on a given steady state operating condition are explained in [Erickson (1999), Dixon (2001), Su *et al.* (2002)]. Compensators are added in the forward paths of feedback loops to shape the loop gain, such that desired performance is obtained. PI controllers are used to increase the low-frequency loop gain, improve the rejection of low-frequency disturbances and reduce the steady-state error [Erickson (1999)].

Fortunately, basic approaches for optimal feedback compensator design could be accomplished quickly and easily in the MATLAB/SIMULINK environment. The “siso tool (‘bode’)” command in the control system toolbox provides a GUI so that the closed-loop frequency response can be interactively changed by online modifying of the pole-zero pattern of the feedback controller. When the desired frequency is obtained, users are also given the corresponding transfer function of the feedback controller in the same interface [Su *et al.* (2002)].

The system closed loop gain when $V_{RAMP} = 3$ & $G_C(s) = 1$:

$$T(s) = \frac{0.8\, s + 16000}{0.00015 s^2 + 1.05 s + 5000} \tag{16}$$

Hence, the corresponding compensator can be expressed as follows:

$$\therefore G_c(s) = \frac{35466.433\,(s + 3744)}{s\,(s + 5.644 \times 10^4)} \tag{17}$$

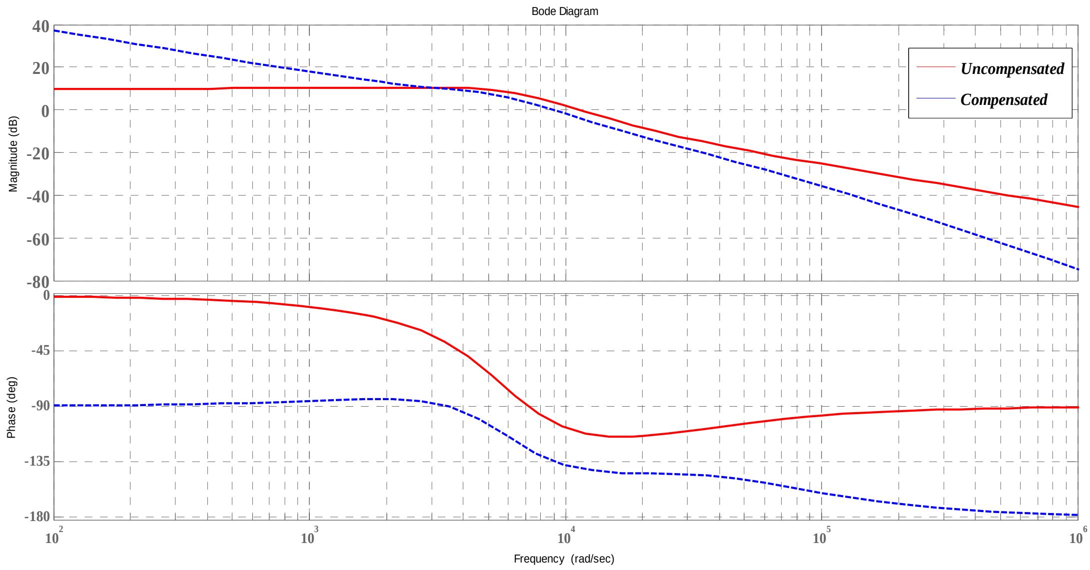


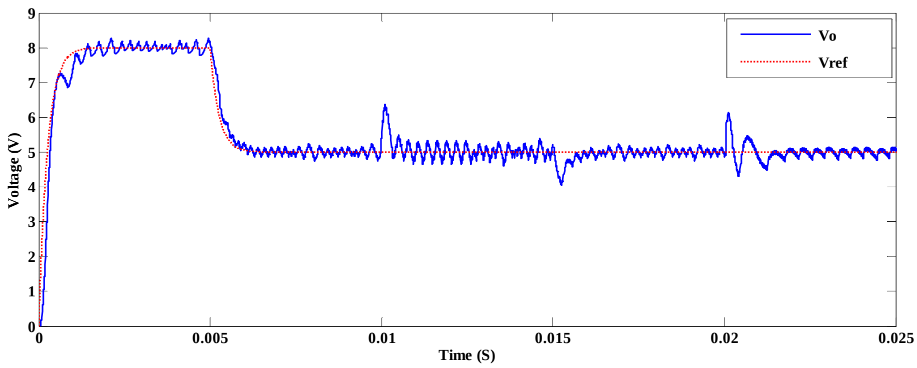
Fig. 5. The closed loop gain [T(s)] frequency response for the compensated and uncompensated system

The proposed PI controller fulfills the following features:

1. The 0-dB crossover frequency (f_c) of the closed-loop gain = 9000 rad/sec. So it lies in the range of $\frac{1}{10} f_s$ to $\frac{1}{3} f_s$. Since the averaged mathematical models are accurate only up to one-third of the switching frequency (f_s) [Su *et al.* (2002)].
2. A compensator real zero provides a -1 loop gain slope above $f_c/2$ and lower frequencies. Hence, provides optimum bandwidth, and critically damped transient response.
3. The gain characteristics should have a -1 slope as it transverses the unity gain crossover frequency [Dixon (2001)].
4. The added compensator real pole converts the -1 slope at f_c to -2 slope at higher frequencies, to attenuate the switching noise.
5. An integrator is included in the feedback controller to eliminate the output voltage steady state error.
6. The loop gain below the crossover frequency is large enough to inhibit the influences of disturbances.
7. The compensator zeros and poles locations are adjusted to obtain an appropriate phase margin of 45.6^o. A phase margin of 45° - to - 60° is essential to meet both the stability and low ringing transient response.

As obviously shown in the figure below, the PI controlled buck converter exhibits an overshoot of 1.6% when the supply voltage increased from 12V to 20V, then it reaches the steady state at the reference voltage within 1msecs. Also, it exhibits an undershoot 1.6% when the supply voltage decreased from 20V to 12V, then it reaches the steady state at the reference voltage within 1mSec.

(a)



(b)

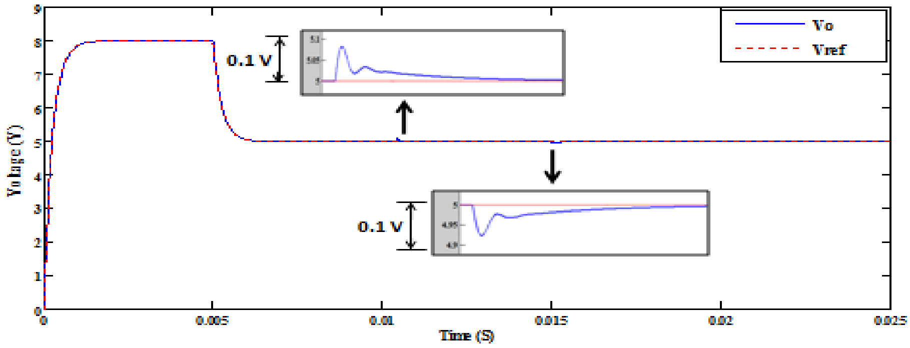


Fig. 6. The output voltage of the PI controlled buck converter under different line & loading variations, (a) when the converter is electrically modeled. (b) When the converter is mathematically modeled

This PID compensator is practically implemented using analog TL494 PWM, as shown in Fig. 7.

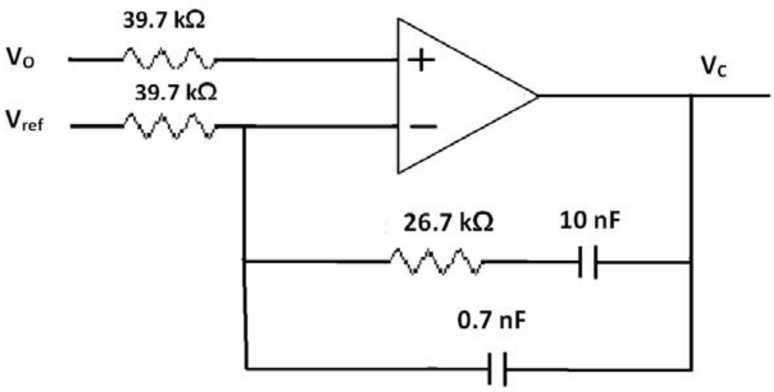


Fig. 7. The PID compensator practical implementation

6. THE INDUCTOR CURRENT WAVEFORM

PWM converters are usually designed to operate in continuous conduction mode (CCM) due to better output voltage regulation, and less inductor current ripples for a specified loads. Another reason might be the fact that modeling the converters in DCM is usually more difficult compared to the CCM operation, which usually results in straight forward models [Rahimi (2008)].

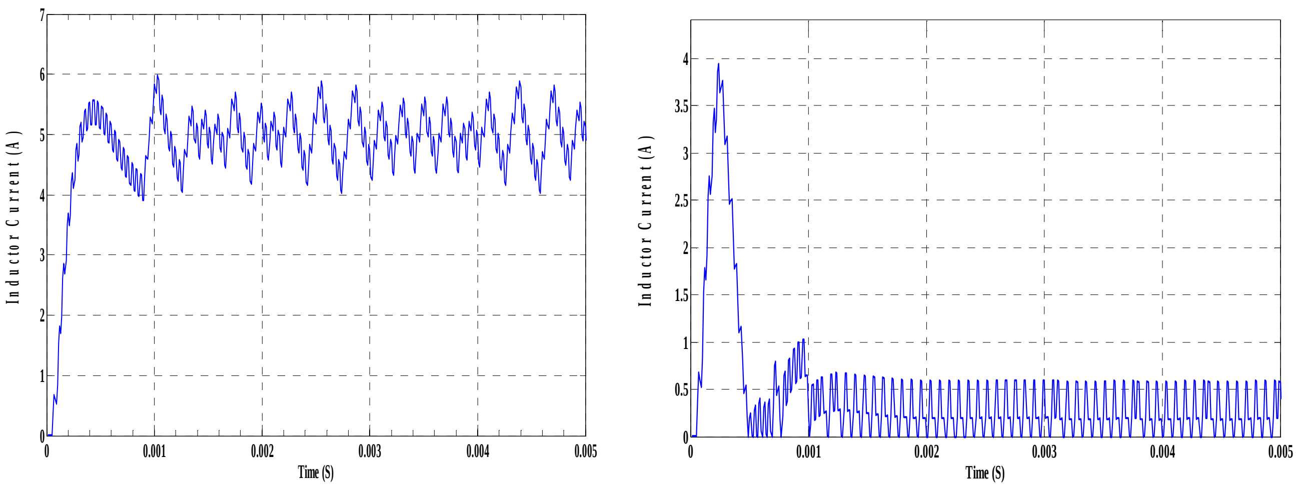


Fig. 8. The inductor current waveform when the converter operates in CCM, and DCM.

For the 5V output regulated voltage, Fig. 8 depicts the simulated inductor current waveform of a 30 Watt load when the converter working in CCM when at R_{Load}=1Ω, and in DCM at R_{Load}=20 Ω.

7. FUZZY LOGIC CONTROLLER DESIGN

In order to accomplish the stability enhancement, voltage deviation (V_e) and the change of the error voltage (dV_e) of the resistive load were taken as the input to the fuzzy logic controller. The FLC inputs; V_e and dV_e are defined respectively as,

$$V_e(k) = V_{ref}(k) - V_o(k) \tag{18}$$

$$dV_e(k) = V_e(k) - V_e(k-1) \tag{19}$$

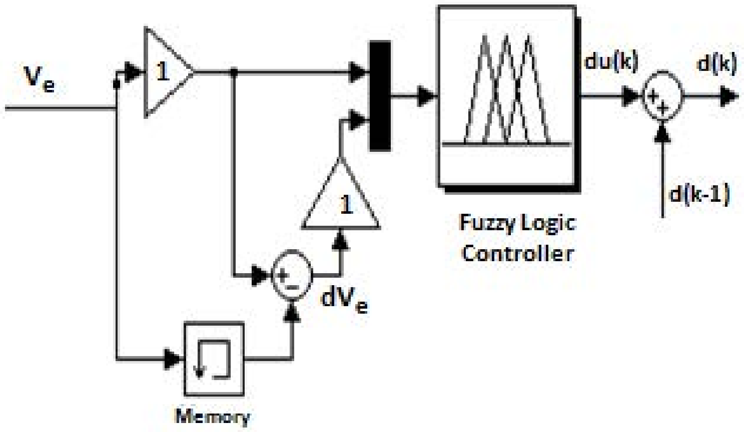


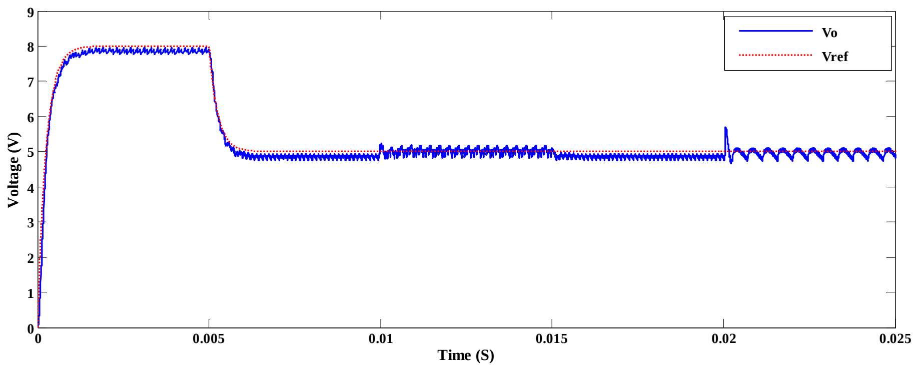
Fig. 9. Simulink model of a FLC module.

Where V_o is actual output voltage of DC–DC converter at the k_{th} sampling time, V_{ref} is reference output voltage. The output of the FLC is the change of the duty ratio ($d_u(k)$), using bisector defuzzification method. Hence, the duty ratio d(k), at the k_{th} sampling time, is defined as

$$d(k) = d(k-1) + d_u(k) \tag{20}$$

Then it is send through the PWM out to DC–DC converter to generate desired switching action.

(a)



(b)

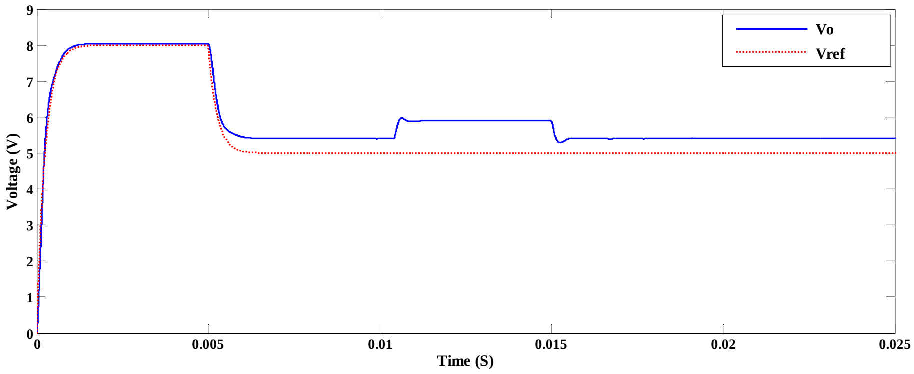


Fig. 10: The output voltage waveform of FLC controlled buck converter under different line & loading variations, (a) when the converter is electrically modeled. (b) When the converter is mathematically modeled

Corcau and Stoenescu (2007), Elmas et al. (2009) fuzzy membership functions with index representation method, and their rules are used in this proposed Mamdani-type FLC design. This proposed FLC algorithm is general and could be applied to any DC-DC converter topologies practically without any modifications. Elmas *et al.* (2009) proposed this algorithm for the 3 main dc-dc converter topologies; buck, boost, buck-boost using ST52T420 microcontroller.

The choice of input gains is motivated by the FLC input variables normalization (i_1, $i_2 \in [-1, 1]$); thus, we set $G_{ve} = 1$ and $G_{dve} = 1$. To obtain a trade off between computation time and control performances, we define, for each input, seven fuzzy membership functions uniformly distributed over the normalized universe of discourse, to construct Z and S shaped functions to cover the left and right extremities of the universe of discourse respectively [Guesmi *et al.* (2008)].

It is obvious that, using FLC only results in output steady state error. This error increases when the supply voltage increase. To enhance the system performance, an additional PI controller will be used.

8. PARALLEL COMBINATION OF PI & FLC

Combining in parallel the previously mentioned FLC & PI controllers improves the steady state error, and the system overshoots for different changes in the operating conditions.

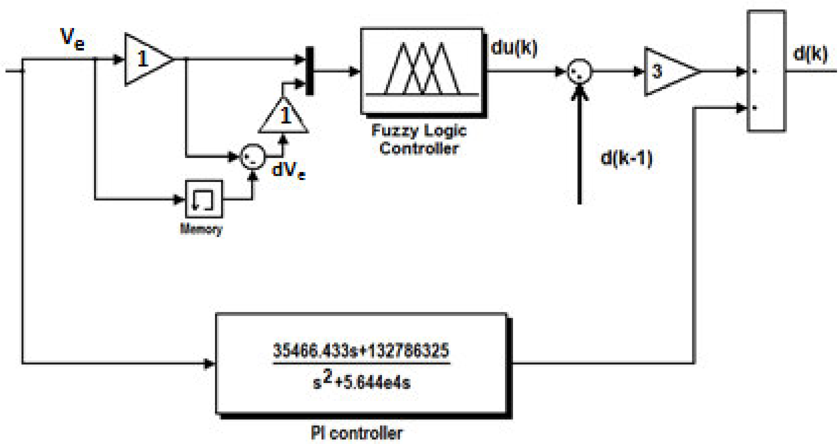


Fig. 11. Simulink model of "FLC in parallel with PI compensator" controller module

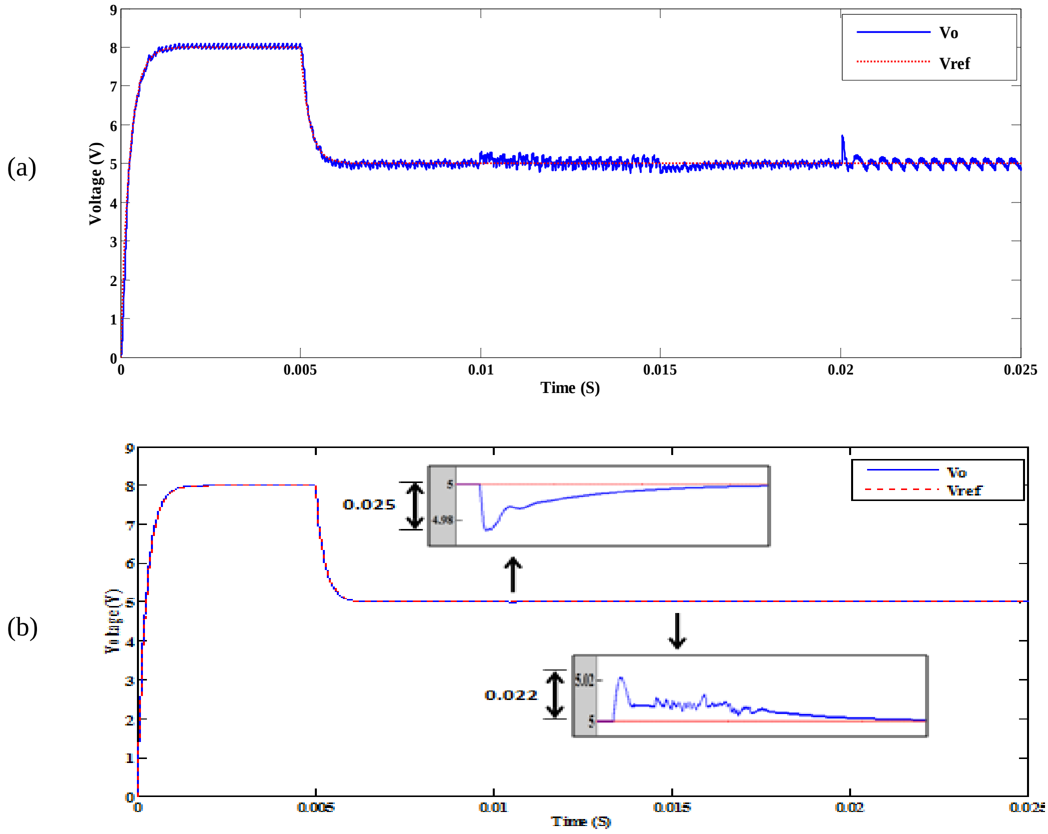


Fig. 12. The output voltage of the buck converter controlled by PI compensator in parallel with FLC under different line & loading voltage variations, (a) when the converter is electrically modeled. (b) When the converter is mathematically modeled.

It is clearly shown that the system exhibits an undershoot of 5% when the supply voltage increases at 10msec then returned to the reference voltage within 0.9 mSec. Also, When decreasing the supply voltage at 15msec, the system exhibits a maximum overshoot of 4.5% then returned to the reference voltage within 0.9 mSec.

9. FLC TUNED BY PI CONTROLLER

A PI controller is used to tune the previously mentioned FLC. To eliminate the output steady state error, an integral gain is required, and also a proportional gain is added to reduce the rise time, hence improve the system dynamic response.

The controller proportional and integral gains are estimated by trail & error procedure, based on the mentioned design concepts in [Control tutorials for Matlab, PID toturial]. For this proposed buck controller, the recommended proportional gain constant; K_P = 10, and the integral gain constant; K_I =30. So this PI controller could be expressed as

$$G(s) = \frac{100(s+1)}{s} \tag{21}$$

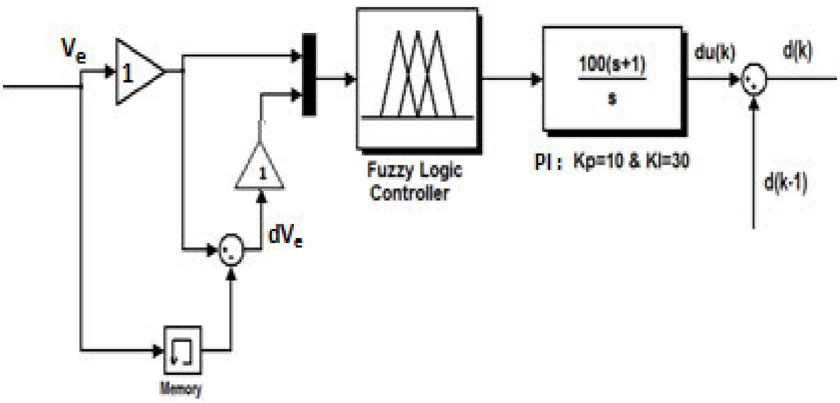


Fig. 13. Simulink model of a FLC tuned by PI controller module.

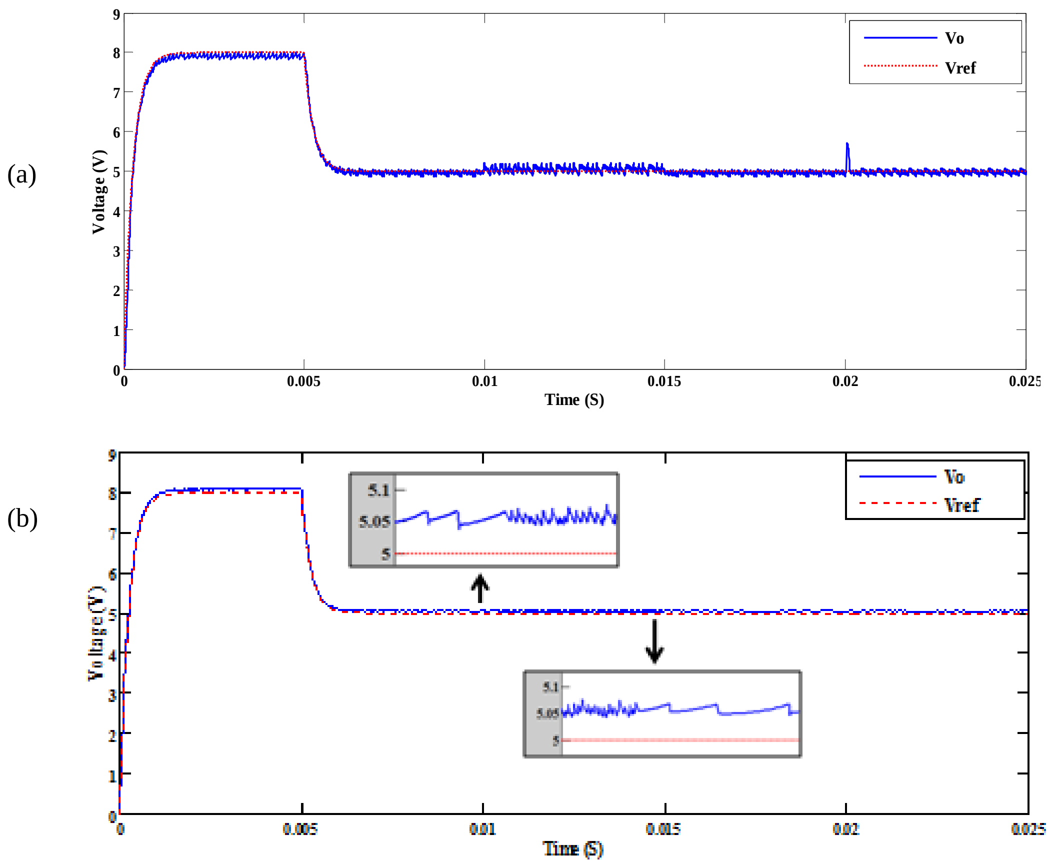


Fig. 14. The output voltage of the buck converter controlled by a FLC tuned by PI controller under line & loading variations, (a) when the converter is electrically modeled. (b) When the converter is mathematically modeled.

It can be shown that the voltage ripples and noise are directly proportional to the supply voltage. It is obvious that when the supply voltage increased, the output voltage oscillations increased and vice versa.

10. CONCLUSION

In this paper, four control schemes have been proposed for DC-DC buck converter output voltage regulation. Design procedures of FLC and PI controllers have been discussed. The effect of the parallel combination of the previously designed FLC and PI controllers on the output voltage regulation is illustrated. Also, the design of the PI controller required to tune the FLC output is discussed.

A comparative study of the output voltage regulation is introduced when the DC-DC buck converter is electrically modeled by its equivalent electrical circuit, and when mathematically modeling using its TF.

Advantages of electrically modeling the DC-DC converters are highlighted and approved throughout the simulation results and discussion.

Table 2. Maximum percentage peak - to - peak voltage ripples of different controllers when the buck converter is electrically and conventionally modeled

Converter Model / Controller Scheme	Electrical	Conventional
PI	**6**	**0**
FLC	**5**	**8**
PI parallel FLC	**5**	**0**
FLC tuned by PI	**4**	**1**

Simulation results emphasize that the FLC only causes an output steady state error, but its performance is greatly improved when combined with PI controller. Results confirm that FLC tuned by PI controller is superior to other control strategies because of fast transient response, minimum steady state error of less than 1%, and good disturbance rejection under various variations of operating conditions. Hence, it achieves the most tightly output voltage regulation with minimum output voltage oscillations of 4%.

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12. BIBLIOGRAPHY

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