Design and Implementation of Closed Loop Control System for Buck Converter Using Different Techniques

Article *in* IEEE Aerospace and Electronic Systems Magazine · January 2016

DOI: 10.1109/MAES.2017.150261

Magdy Saoudi
university of technology and applied sciences suhar

Hamed Metwally
Zagazig University

DOI. No. 10.1109/MAES.2017.150261

Feature Article:

Design and Implementation of Closed-Loop Control System for Buck Converter Using Different Techniques

***Magdy Saoudi, Ahmed El-Sayed, Hamid Metwally,* Zagazig University, Zagazig, Egypt**

INTRODUCTION

Comparing between different techniques for the design and implementation of closed-loop control systems for buck converters is carried out. Controllers used for this comparison are integral, proportional plus integral (PI) controllers and artificial intelligence are represented in fuzzy logic controller (FLC) and tuned fuzzy logic controller (TFLC). Design and implementation of a control system demand the role of effective techniques that offer simple and pragmatic solutions in society to meet the performance requirements despite system disturbances and uncertainties [1]. The occurrence of nonlinear phenomena in buck converters makes their analysis and control difficult [2]. Classical linear techniques have stability limitations around the operating points [1]–[3]. Hence digital and nonlinear stabilizing control methods must be applied to ensure large-signal stability [3]. Fuzzy control has also been employed to control buck converters because of its simplicity, simplicity of design and simplicity of implementation [4], [5]–[10]. Fuzzy controllers are easily suited to nonlinear time-variant systems and do not require an accurate mathematical model for the system being controlled. They are usually designed based on expert knowledge of the converters [5]. In this survey, the design procedures of integral, proportional plus integral, fuzzy logic, and tuned fuzzy logic controllers are presented.

THE PROPOSED BUCK CONVERTER

The buck converter topologies with parameters are given in Table 1. These parameters have been obtained through trial and error that verify equation v_{out}/v_g=0.5 when the value of the duty cycle is 50% to illustrate the result of each controller type on this converter performance. The proposed controller design procedures can be generally applied to any buck converter topology for stability enhancement, and output voltage regulation over a wide range of operating conditions. The effect of the on-line changes of reference voltage on the output voltage regulation is discussed. In the case of integral and proportional plus integral controllers, values of integral gain (K_i) for the integral controller and proportional and integral gains (K_p&K_i) for the PI controller are determined from MATLAB. Then these gains are used in mikroC and Proteus programs for buck converter design. In the case of fuzzy logic, the controller determines the operating condition from the measured values and takes the appropriate control actions using the rule base created from the expert knowledge. In the case of tunes, the FLC uses a proportional plus integral and derivative (PID) controller for tuning the output of FLC to improve the output voltage configuration.

Authors' current address: M. Saoudi, H. Metwally, Electrical Power and Machines, Zagazig University, Sharkia, 44762 Egypt; A. El-Sayed, Engineering Management, Zagazig University, Sharkia, 44762 Egypt. E-mail: (eng_ahm_2014@yahoo.com).
Manuscript received November 26, 2015, revised March 21, 2016, May 16, 2016, and ready for publication May 22, 2016.
Review handled by H. Liu.

DISCUSSION

MATHEMATICAL MODEL OF BUCK CONVERTER

The buck converter has an output voltage that is lower than the input voltage. Figure 1 shows the buck converter with a voltage controller and here it is assumed that all components are ideal and the load consists of a resistor with resistance *R*. The converter has an output low-pass filter consisting of an inductor with induc-

Table 1.

The Proposed Buck Converter Parameters

Variable	Parameter	Value
Vg(V)	Source input voltage	15
F_s(KHz)	Switching frequency	2
L(mH)	Magnetizing inductance	10
C(μF)	Output filter capacitance	100
Rc(mΩ)	Equivalent series resistance (ESR) of capacitor	5
R(Ω)	Load resistance	1

tance L and capacitor with capacitance C. While the transistor is on, the inductor current $i_L(t)$ increases since the input voltage is higher than the output voltage when the transistor is turned off; the diode must start to conduct since the inductor current cannot stop instantly. The voltage across the diode is zero when it is conducting and the inductor current will decrease. Figure 2(a) shows the waveform of the control signal. The converter is usually designed with a low magnitude of ripples in the output voltage. For the resistance and inductance (RL) circuit, the current increases and decreases exponentially as shown in Figure 2(b). The voltage across the diode is equal to the input voltage or equal to zero. The output filter of the converter filters this voltage waveform and the magnitude of the ripple in the output voltage depends on the filter design. If the inductor current becomes zero before the transistor is turned on, it will stay at zero until the transistor is turned on since the diode can only convey in one way. If the converter is controlled so that the inductor current is zero during some portion of the switching period, it is supposed to be operating in discontinuous conduction mode. Otherwise, it operates in continuous conduction mode.

The switching period Ts of the converter is determined by the control signal δ (t), as indicated in Figure 2(a). In this figure, the switching period is held constant. The average output voltage is controlled by changing the width of the pulses. In Figure 2(b). the falling edge is controlled, i.e., when the transistor should turn off. The duty cycle $d(t)$ is a real value in the interval 0 to 1 and it is equal to the ratio of the width of a pulse t_{on} to the switching period T_s. The duty cycle is actually a discrete-time signal.

In this section, a linear time-invariant model of the buck converter is derived by means of state-space averaging during MOSFET on as in Figure 3(a) and during MOSFET off as in Figure 3(b). The converter can be described as switching between different time-invariant systems and the state-space description of each one of these systems is first derived. These state-space descriptions are used as a starting point in the method of state-space averaging. This method is applied to the buck converter and the result is a linear time-invariant model in state-space description. Eventually, several transfer functions are drawn out from this model until reaching the control-to-output transfer function held by

$$G(s) = \frac{\hat{v}_o(s)}{\hat{d}(s)} = \frac{RV_g\left(1+sR_cC\right)}{R+s\left(L+RR_cC\right)+s^2\left(R+R_c\right)LC} \tag{1}$$

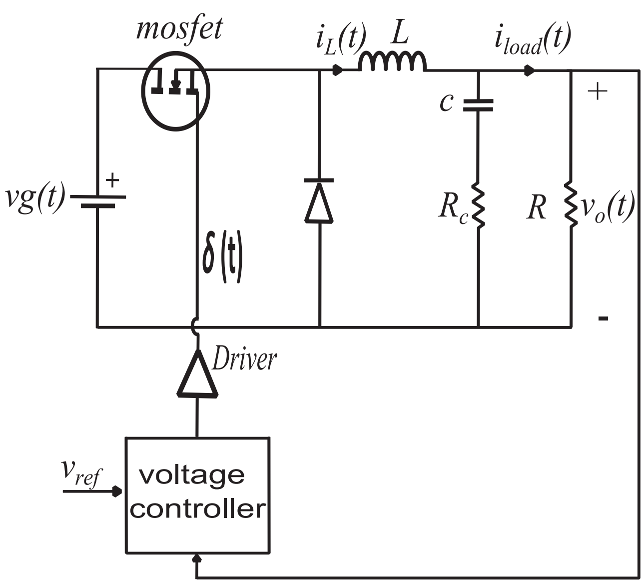


Figure 1.
The buck converter with a voltage controller.

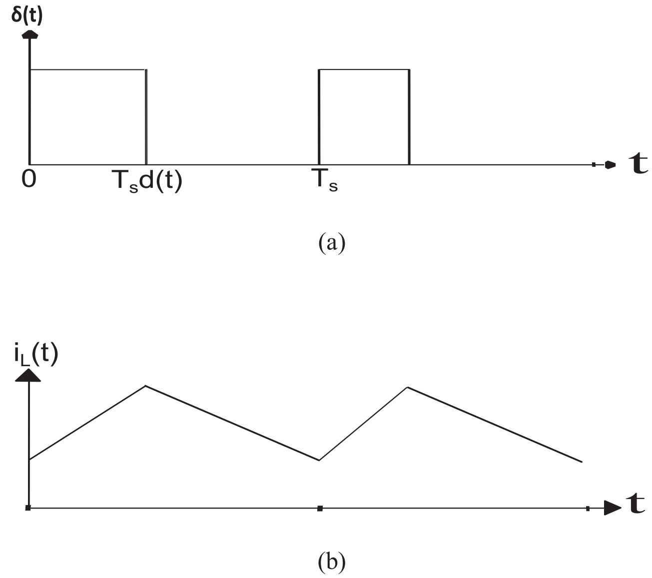


Figure 2.
(a) The waveform of the control signal. (b) The waveform of the inductor current.

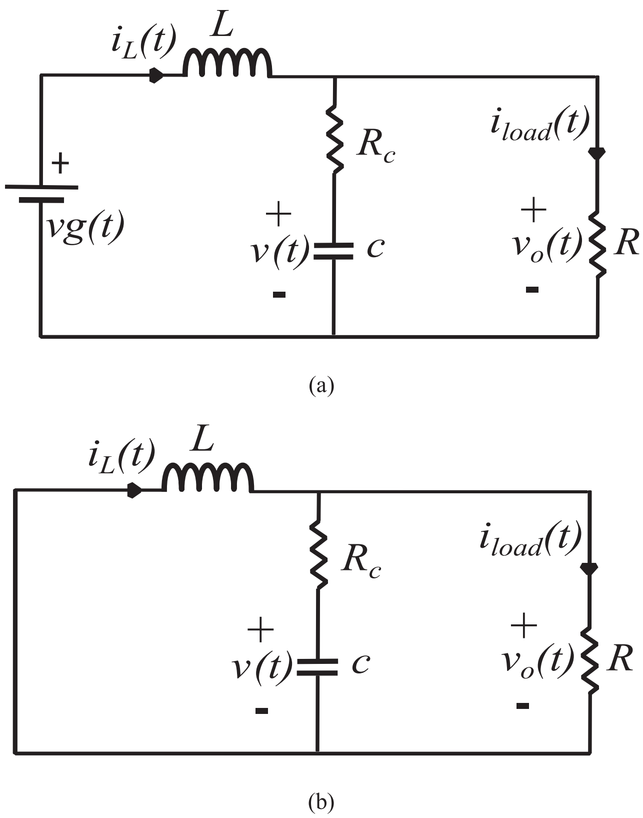


Figure 3.
(a) The circuit of the buck converter during $t_{on.}$ (b) The circuit of the buck converter during $t_{off.}$

DESIGN OF BUCK CONVERTER USING INTEGRAL (I) CONTROLLER

Integral (I) controller is a special case of PID controller, but with no use of the proportional (P) and the derivative (D) parts of the error. So control signal U for an integral controller is presented below

$$U = K_i \int \Delta dt \quad (2)$$

where K_i is integral gain, Δ is the error or deviation of actual process value (PV) from the set point (SP).

$$\Delta = SP - PV \quad (3)$$

The integral (I) controller transfer function *C(s)* is given below

$$C(s) = K_i / S \quad (4)$$

Fortunately, the basic approaches for optimal feedback compensator design could be accomplished quickly and easily in the MATLAB environment. MATLAB provides a graphical user interface (GUI) so that the closed-loop frequency response can be interactively changed by online modifying of the pole-zero pattern of the feedback controller as shown in Figure 4. When the desired frequency is obtained, users are also presented the corresponding transfer function of the feedback controller in the same interface.

To determine integral gain constants, the position of root locus for a buck converter is modified online as shown in Figure 4(a) to get K_i=36 at the minimum settling time=0.0852 s and rise time=0.0352 s as shown in Figure 4(b).

Then mikroC software is used for programming the microcontroller that controls the MOSFET of the buck converter based on the previous K_i value. And so the programmed microcontroller controls constructed buck converter in Proteus software as indicated in Figure 5.

The simulation result of the system of Figure 5 is recorded in Figure 6.

As clearly shown in Figure 6, the following results are obtained for the buck converter controlled by the integral controller:

- The output voltage (red) follows the reference voltage (green).
- Rise time equals 0.05 s.
- Steady state error equals (+/- 0.1) v.

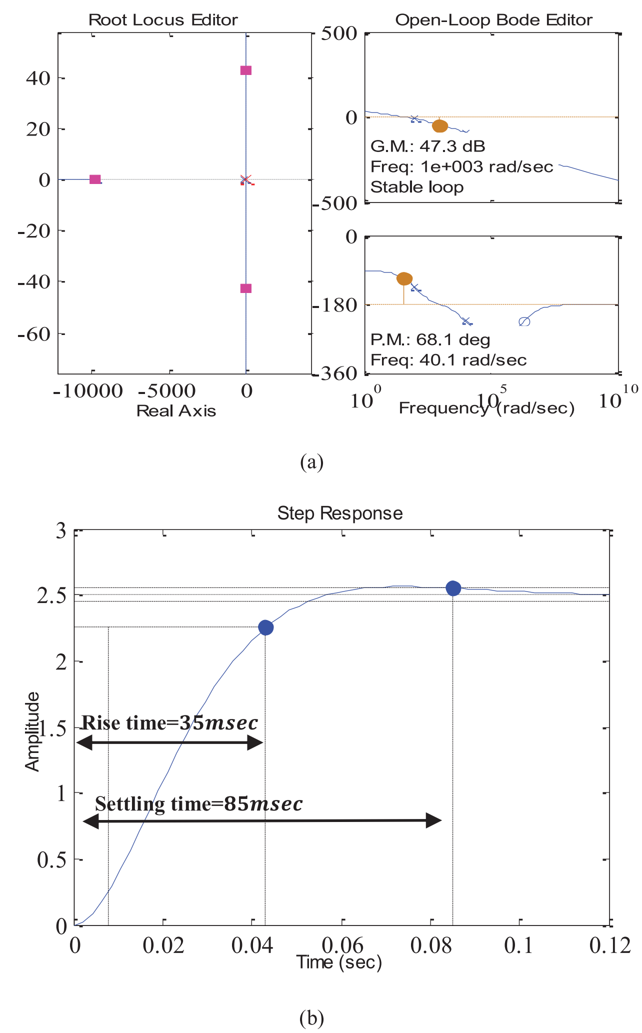


Figure 4.
(a) Root locus and open-loop bode plots of buck converter. (b) Step response of buck converter.

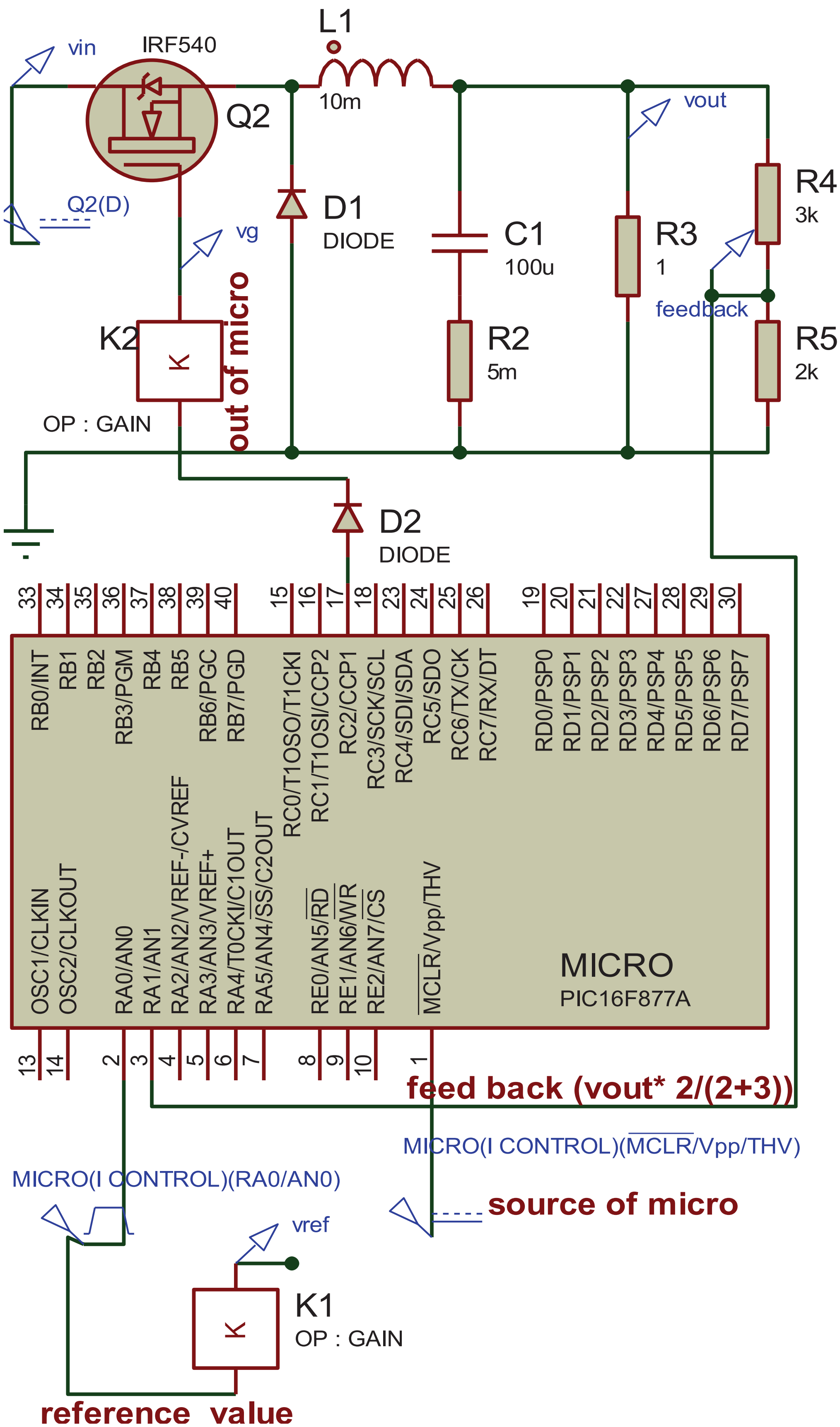


Figure 5.
Closed-loop control of buck converter using integral (I) controller.

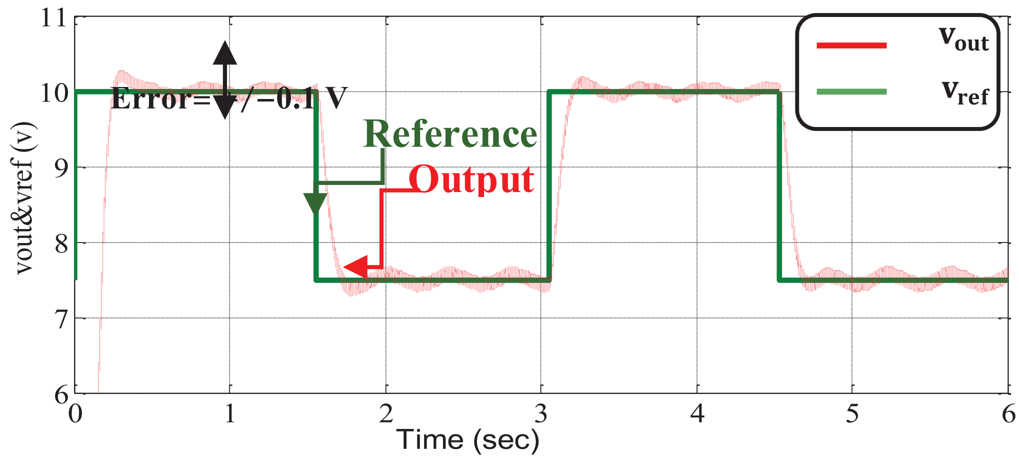


Figure 6.
Output voltage (v_{out}) (red) and reference voltage (v_{ref}) (green).

DESIGN OF BUCK CONVERTER USING PROPORTIONAL AND INTEGRAL (PI) CONTROLLER

A PI controller is a special case of a PID controller, but with no use of the derivative (D) part of the error. So control signal *U* for a PI controller is given below

$$U = K_p + K_i \int \Delta dt \tag{5}$$

where K_p, K_i is proportional, integral gain, Δ is the error or deviation of actual measured value (PV) from the SP

$$\Delta = SP - PV \tag{6}$$

The PI controller transfer function *C(s)* is given below

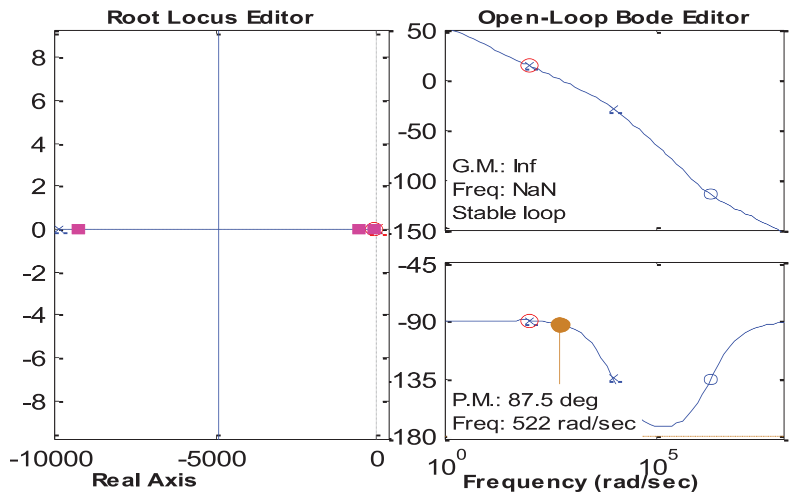
$$C(s) = K_p + K_i / S \tag{7}$$

As carried out with an integral controller, MATLAB is used to calculate K_p and K_i of the PI controller. General approach to PI tuning:

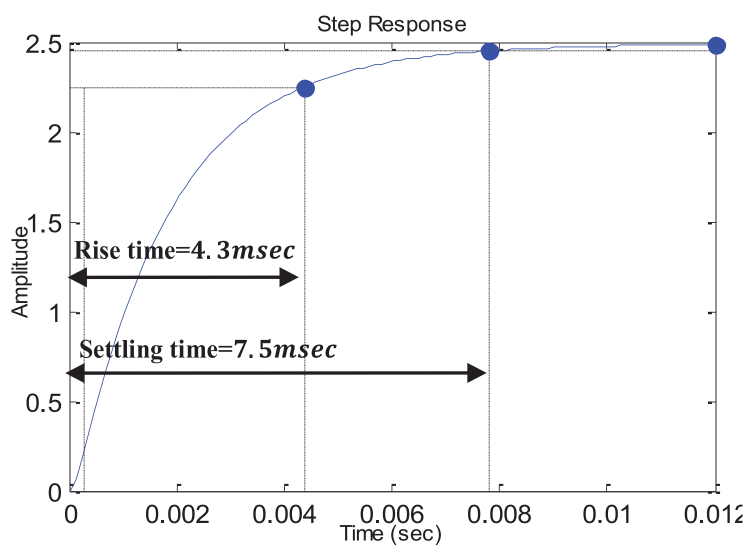
1. Firstly set K_i= zero.
2. Increase K_p until desired response has been obtained
3. Add integral gain and modify K_i until the removed steady state error.

To determine PI gain constants, the position of the root locus for the buck converter is modified online as shown in Figure 7(a) to get Kp&K_i equal to 4&415 at minimum settling time=0.00746 s and rise time=0.00425 s as shown in Figure 7(b).

Then mikroC software is used for programming the microcontroller to control the MOSFET of the buck converter based on previous K_p&K_i values. And so the programmed microcontroller controls the constructed buck converter circuit in Proteus software as indicated in Figure 8.



(a)



(b)

Figure 7.
(a) Root locus and open-loop bode plots of buck converter. (b) Step response of buck converter.

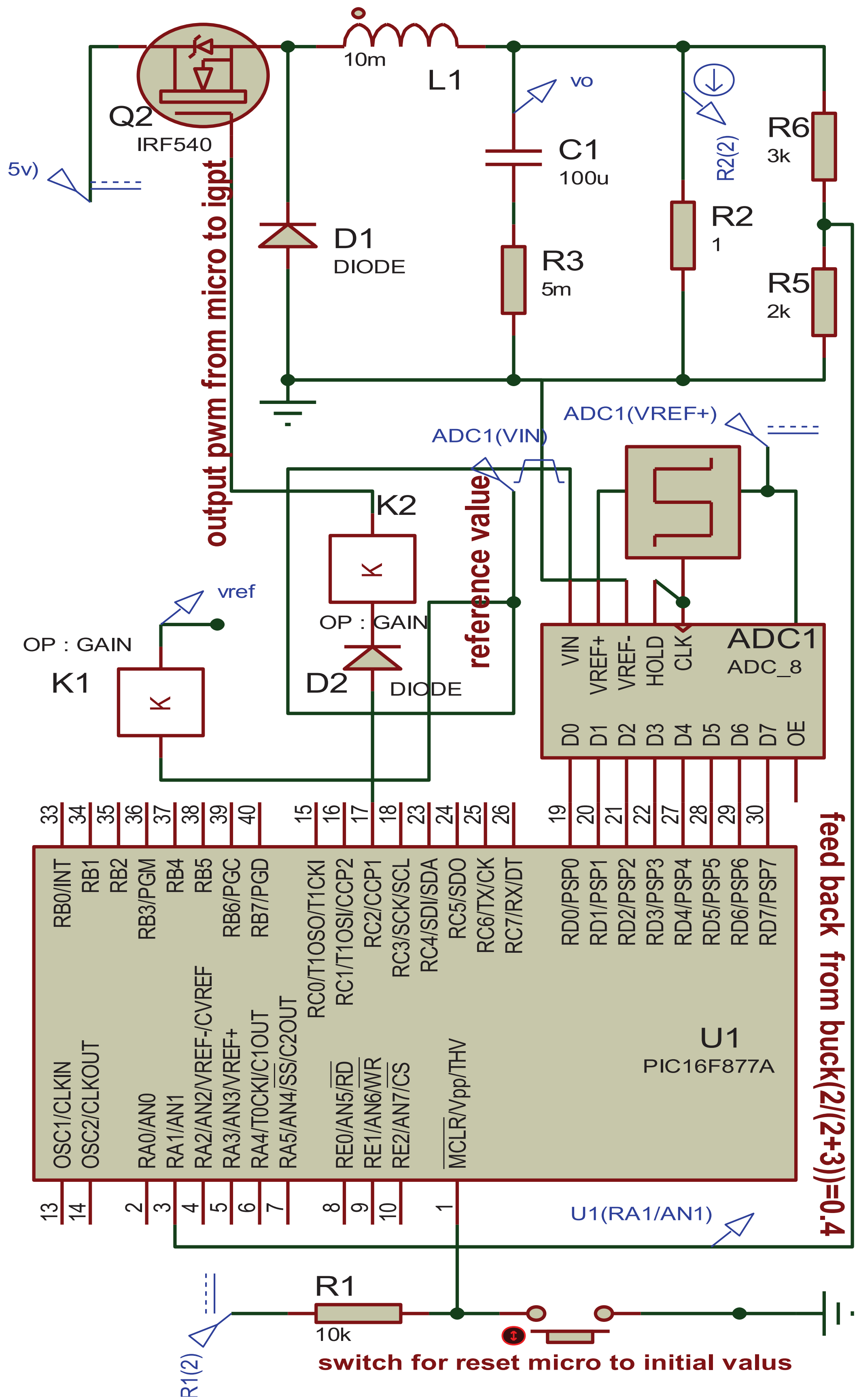


Figure 8.
Closed-loop control of buck converter using PI controller.

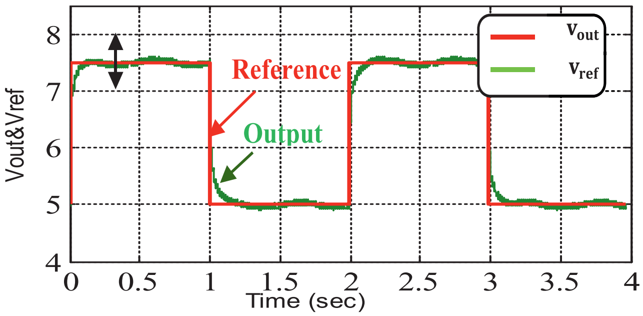


Figure 9.
Output voltage (v_{out}) (green) and reference boltage (v_{ref}) (red)

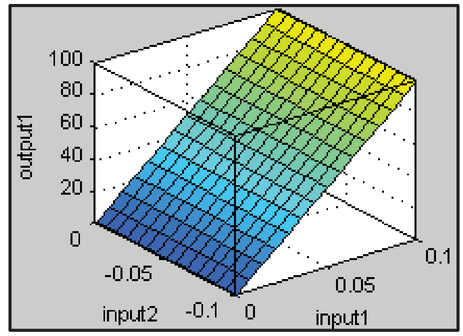


Figure 10.
Change surface of fuzzy controller.

Figure 9 shows the simulation results of the circuit shown in Figure 8.

As shown on Figure 9, the PI controlled buck converter exhibits the following results:

- The output voltage (green) follows the reference voltage (red).
- Rise time equals 0.01 s.
- Steady state error equals (+/− 0.05) v.

DESIGN OF BUCK CONVERTER USING FUZZY LOGIC CONTROLLER (FLC)

Fuzzy logic, proposed by Lofty Zadeh in 1965, emerged as a tool to deal with uncertain, imprecise, or qualitative decision making control problems. Controllers that combine intelligent and conventional techniques are commonly used in the intelligent control of complex dynamic systems. Therefore, embedded fuzzy controllers automate what has traditionally been a human control activity.

So FLC is a control algorithm based on a linguistic control strategy, which is derived from expert knowledge into an automatic control strategy. FLC doesn't need any difficult mathematical calculation like the other control systems. So it is one of the available answers today for a broad class of challenging controls.

FLC controller has three principal components:

1. Fuzzifier: A fuzzyfication interface that converts input data into suitable linguistic values.
2. Rule Base and Data Base: Both are known as knowledge base that consists of a data base with the necessary linguistic definition and control rule set
3. Decision Making: A decision making logic, which is simulating a human.

To design a fuzzy controller, fuzzy input shape and fuzzy output shape must be constructed, then rules that control the relation between the input and output of the fuzzy controller must be determined to make the surface of the fuzzy controller change as shown in Figure 10. In

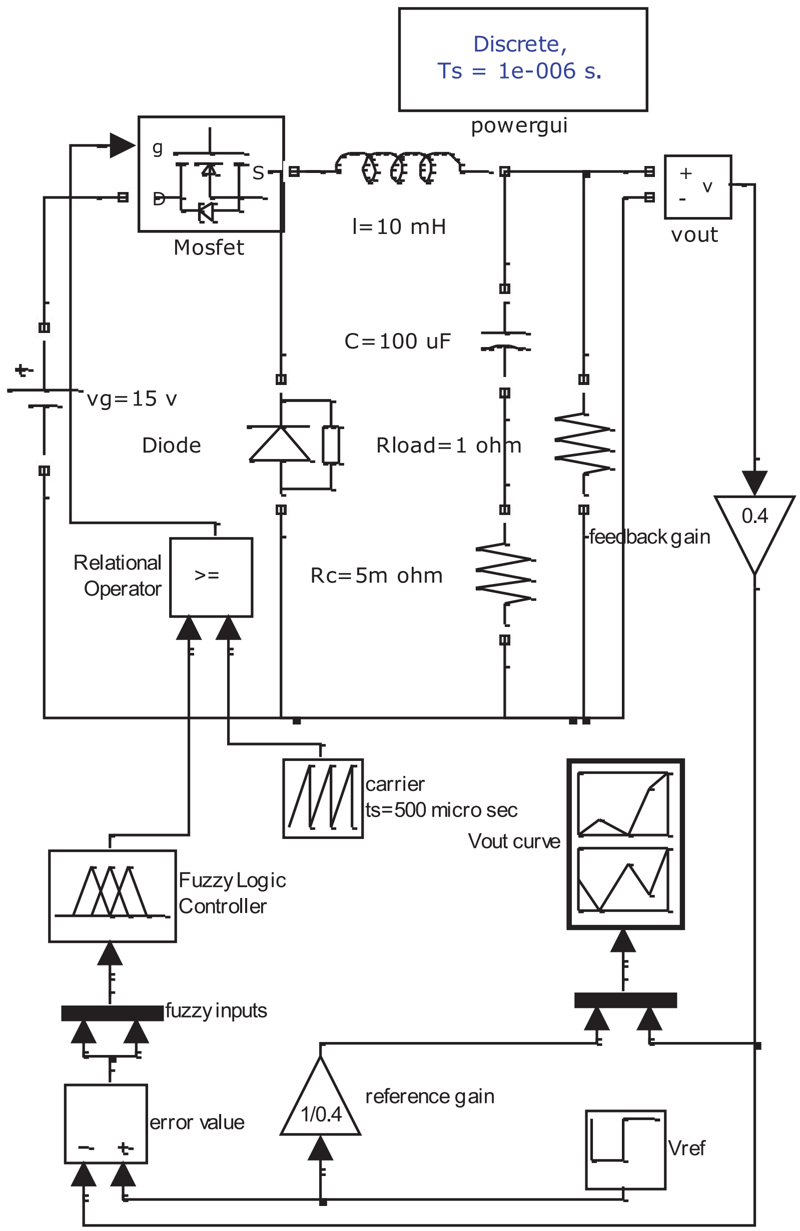


Figure 11.
Closed-loop control for buck converter using an FLC.

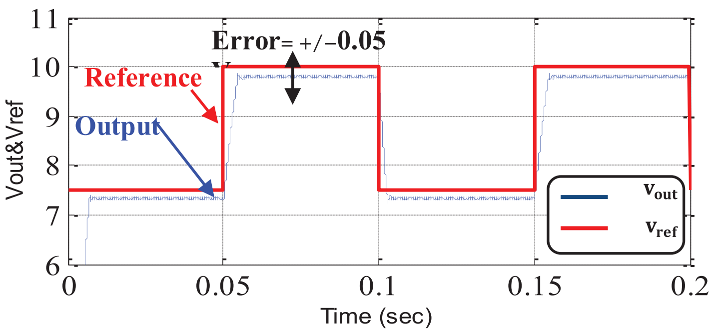
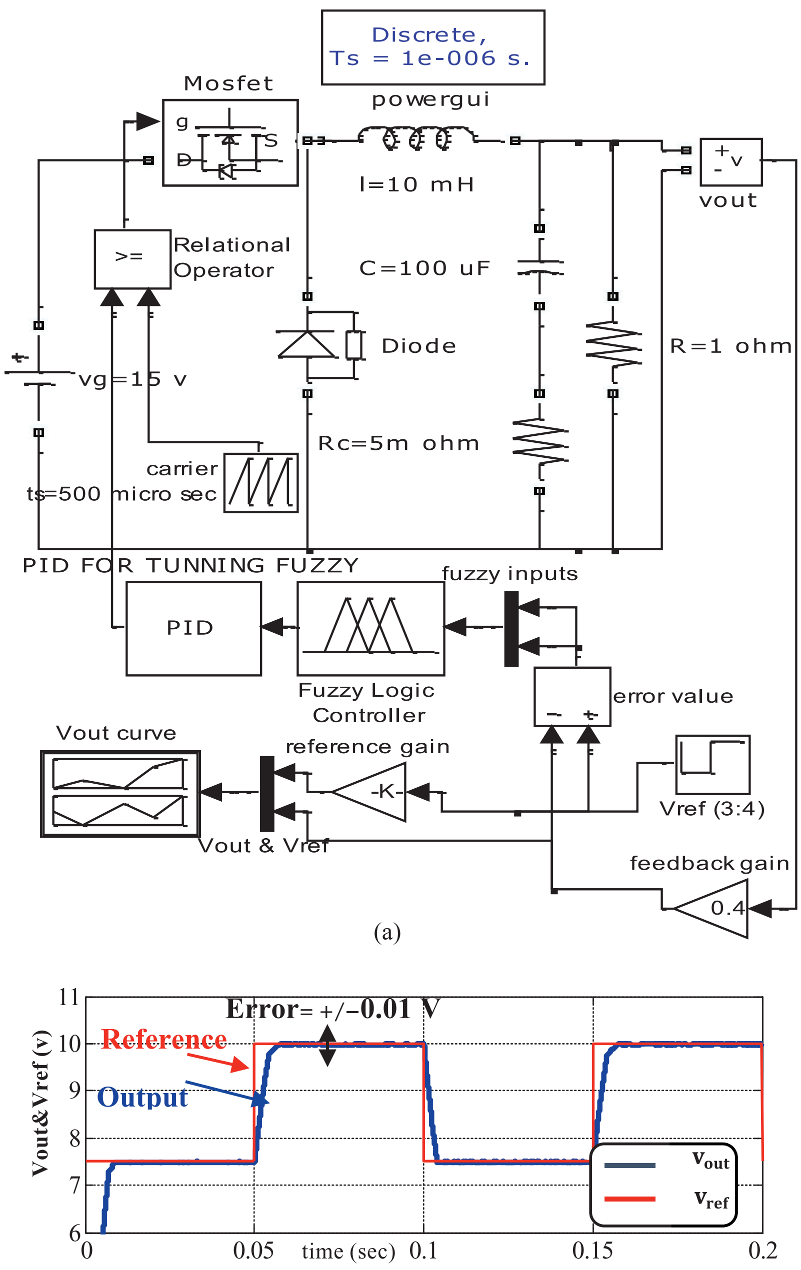


Figure 12.
Output voltage (v_{out}) (blue) and reference voltage (v_{ref}) (red).



(a)

(b)

Figure 13.
(a) Closed-loop control for buck converter using a TFLC. (b) Output voltage (v_{out}) (red) and reference voltage (v_{ref}) (blue).

this figure, input1 reflects the negative error, which represents the higher value of the required output and input2 represents the positive error, which represents less than the desired output, while output1 represents the value of the duty cycle that controls in the firing of the MOSFET.

Then a closed-loop buck converter using an FLC is constructed in MATLAB/Simulink as shown in Figure 11.

Finally, a simulation program for the circuit in Figure 12 is run to get the shape of the output voltage with respect to the reference voltage as shown in Figure 12.

As shown on Figure 12, the fuzzy controlled buck converter exhibits the following answers:

- The output voltage (blur) follows the reference voltage (red).
- Rise time equals 0.007 s.
- Steady state error equals (+/− 0.05) v.

DESIGN OF BUCK CONVERTER USING TUNED FUZZY LOGIC CONTROLLER (TFLC)

A PID controller is used to tune the previously mentioned FLC for eliminating the output steady state error and improving the output voltage configuration.

The proportional, integral, and derivative controller gains are estimated by trial and error procedure, based on the mentioned design concepts in control tutorials for Matlab, PID tutorial. For this proposed buck controller, the recommended proportional gain constant K_P = 10, and the integral gain constant K_i =5, and the derivative gain constant K_D =5. So this PID controller could be represented as in Figure 13(a).

Figure 13(b) shows the simulation results of the circuit shown in Figure 13(a).

From Figure 13(b), the fuzzy controlled buck converter exhibits the following results:

- The output voltage (blue) follows the reference voltage (red).
- Rise time equals 0.007 s.
- Steady state error equals (+/− 0.01) v.

EXPERIMENTAL VERIFICATION

To verify the concept, the buck converter with the parameters given in Table 1 has been constructed as pictured in Figure 14.

The connection diagram of the test rig is shown in Figure 15. Results in the case of integral and PI

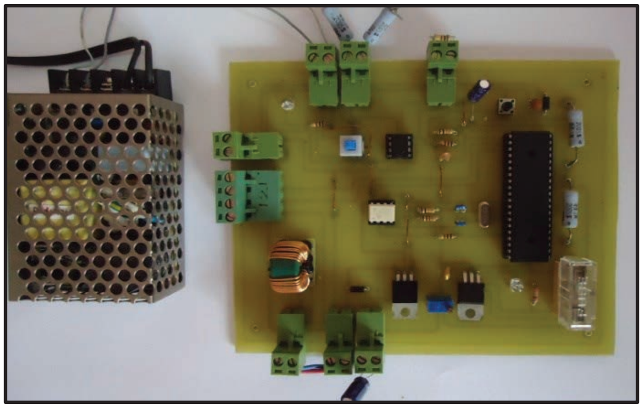


Figure 14.
Designed buck converter circuit.

Figure 15.
Buck converter circuit connected to an oscilloscope.

controllers are obtained using an oscilloscope as shown in Figure 15 based on switching frequency equals 2 kHz as shown in Figure 16.

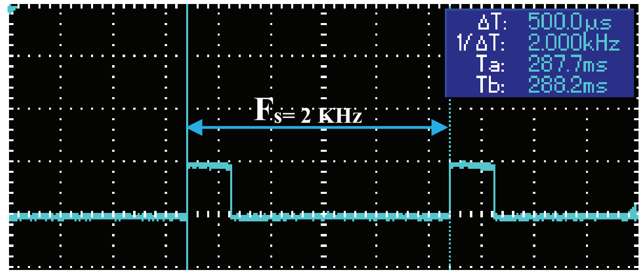


Figure 16.
2 kHz switching frequency.

RESULTS OF BUCK CONVERTER USING INTEGRAL (I) CONTROLLER

After programming of microcontroller as integral (I) controller, we get the following results:

Figure 17(a) shows that the output voltage follows the reference and Figure 17(b) shows that rise time equals 0.024 s.

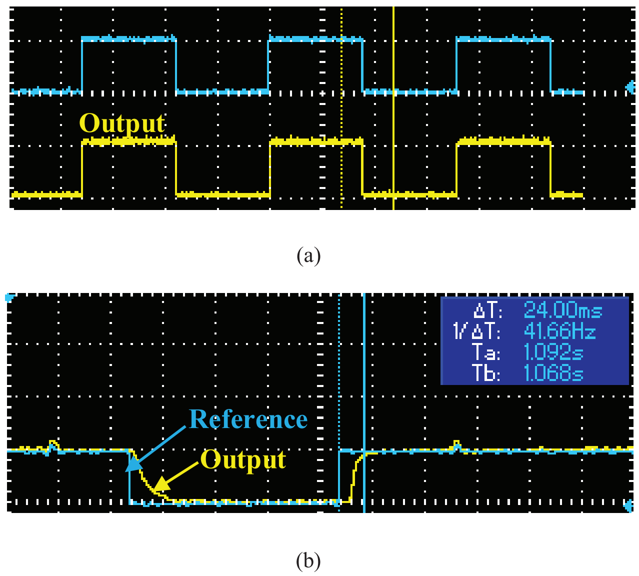


Figure 17.
(a) Output voltage and reference voltage. (b) Output voltage rise time.

RESULTS OF BUCK CONVERTER USING PROPORTIONAL AND INTEGRAL (PI) CONTROLLER

After programming of the microcontroller as the PI controller, we obtain the following effects: Figure 18(a) shows that output voltage follows the reference, and Figure 18(b) shows that rise time equals 0.01. So, rise time in the case of the PI controller is improved by comparison with the integral controller case.

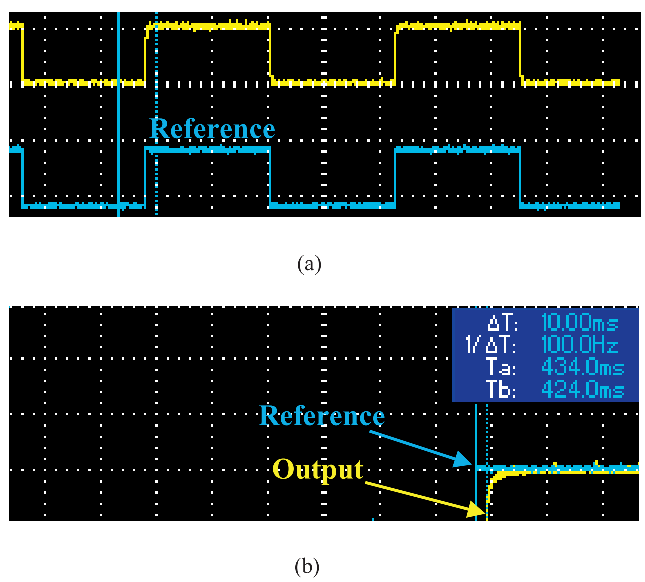


Figure 18.
(a) Output voltage and reference voltage. (b) Output voltage rise time.

CONCLUSION

In this paper, four control schemes have been proposed for DC-DC buck converter output voltage control. Design procedures of FLC,

Table 2.

Rise Time and Steady State Error		
Controller Type	**Rise Time (s)**	**Steady State Error (v)**
Integral (I) controller	0.024	±0.1
Proportional integral (PI) controller	0.01	±0.05
Fuzzy logic controller (FLC)	0.007	±0.05
Tuned fuzzy logic controller (TFLC)	0.007	±0.01

TFLC, I, and PI controllers have been discussed. A comparative survey of the output voltage regulation and rise time is introduced as shown in Table 2.

Hardware results show that the I and PI controllers cause an output steady state error that equals (+/− 0.1 and 0.05 v) and rise time that equals 0.024 and 0.01 s. Simulation results show that the TLFC causes an output steady state error that equals (+/− 0.01 v) and rise time that equals 0.007 s. TFLC has the smallest output voltage rise time and minimum output voltage oscillations. So TFLC has the best performance compared with other controllers as shown in Table 2. ◆

ACKNOWLEDGMENTS

The author would like to thank Eng. Mostafa Hasneen and Mohamed Fawzy, for their support, help, and knowledge.

REFERENCES

[1] Eker, I., and Torun, Y. Fuzzy logic control to be conventional method. *Energy Conversion and Management*, Vol. 47, 4, (2006), 377–394.

[2] Guesmi, K., Essounbouli, N., and Hamzaoui, A. Systematic design approach of fuzzy PID stabilizer for DC–DC converters. *Energy Conversion and Management*, Vol. 49, 10 (2008), 2880–2889.

[3] Khaligh, A., and Emadi, A. Suitability of the pulse adjustment technique to control single DC/DC choppers feeding vehicular constant power loads in parallel with conventional loads. *International Journal Electric and Hybrid Vehicles*, Vol. 1 (2007), 20–45.

[4] Gao, D., Jin, Z., and Lu, Q. Energy management strategy based on fuzzy logic for a fuel cell hybrid bus. *Journal of Power Sources* (2008).

[5] Guo, L., Hung, J. Y., and Nelms, R. M. Evaluation of DSP-based PID and fuzzy controllers for DC–DC converters. *IEEE Transactions on Industrial Electronics*, Vol. 185, 1 (2009), 311–317.

[6] Samosir, A. S., and Yatim, A. M. Dynamic evolution control for synchronous buck DC–DC converter: Theory, model and simulation. *Simulation Modeling Practice and Theory*, Vol. 18, 5 (2010), 663–676.

[7] Bouchafaa, F., Hamzaoui, I. and Hadjammar, A. Fuzzy logic control for the tracking of maximum power point of a PV system. *Energy Procedia*, Vol. 6 (2011), 633–642.

[8] Cheng, C. Design of output filter for inverters using fuzzy logic. *Expert Systems with Applications*, Vol. 38, 7 (2011), 8639–8647.

[9] Dereli, T., Bayasoglu, A., Altun, K., Durmusoglu, A., and Türksen, I. B. Industrial applications of type-2 fuzzy sets and systems: A concise review. *Computers in Industry*, Vol. 62, 2 (2011), 125–137.

[10] Messai, A., Mellit, A., Guessoum, A., and Kalogirou, S. A. Maximum power point tracking using a GA optimized fuzzy logic controller and its FPGA implementation. *Solar Energy*, Vol. 85, 2 (2011), 265–277.