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Design and Assessment of Digital PID and Fuzzy Controller for DC-DC Converter

Kartik Sharma[1]
[1] *Department of Electrical Engineering Rajasthan Technical University, Kota Rajasthan, India*

Abstract: ***DC-DC converters have now become an essential part of all the electronic equipment, as a power supply is a key component of any electronic equipment. Applications of DC-DC converters include integration of renewable sources, power supplies, controlled electric drives etc. Digital design of fuzzy logic controller (FLC) and an IIR digital filter based PID controller for the DC-DC converter is presented in this research paper. The FLC shows good performance where linear control techniques are unable to produce the desired result. The digital design of FLC presented in this paper can be implemented on DSP for generating switching duty cycle for converters. Apart from the FLC, this paper elucidates a digital controller based on digital filter architecture that supports fixed-point algorithm. In digital controller, the control strategy can be altered or reprogrammed without the need of significant hardware changes. The digital controller improves response of DC-DC converter by varying loop-gain, cross-over frequency and phase margin. Closed loop control of buck converter using the two controllers is presented and the results are obtained for varying operating conditions such as load changes, input voltage variations etc. and verified using MATLAB/Simulink.***
Keywords: ***Boost; Buck; DC/DC Converters; Digital PID Controller; Fuzzy Controller.***

I. INTRODUCTION

The DC voltage from controlled/uncontrolled rectifiers, renewable energy sources is unregulated in nature. DC/DC converters supply a fine and adjustable DC voltage to a variable load from such unregulated DC sources. These converters are utilized in applications such as battery chargers, renewable sources integration, maximum power tracking in solar PV, DC motor drives etc. [1]. Buck & Boost converters are two elementary forms of DC/DC converters according to conversion of output level from given input level. All other topologies are derivatives of either buck or boost or a combination of these two, as they will either increases or decreases the input voltage [2]. Conventionally, analog controllers have been used for obtaining controlled output from DC/DC converters. The analog control system (ACS) works in genuine time and it have high bandwidth and theoretically infinite resolution [3]. Digital control has developed as a preferred solution for DC/DC power converters from previous few years. The price of digital ICs is falling steadily so, the cost-prohibitive aspect of digital control technology has vanished [4]. Digital control of DC/DC power converters is more finer than analog control as the advanced control algorithms like adaptive control and non-linear control can be simply executed by utilizing digital control [2]. Direct digital design of compensator without the need of discrete model of converter is proposed in [5]. The response of a system is mainly decided by initial samples of the compensator and this opinion is used to fit a digital PID template to attain required response [6]. State space averaging (SSA) method is used to calculate small signal transfer function (SSTF) of DC/DC converters from which ideal close-loop response is produced by substituting designing parameters. The open-loop response in discrete time is then obtained by transformation methods [7]. An averaged continuous-time model, considers switching duty cycle as input and defines the system's slow dynamics to avoid complications faced due to hybrid nature of system. A mathematical depiction derived using SSA method for Buck-converter in continuous conduction mode (CCM) is conferred in [8]. A digitally controlled DC/DC converter is comprised of power-stage, an analog to digital converter (ADC), digital PID controller and digital PWM [9]. For a digitally controlled converter, derivation of exact SSTF in discrete time is presented in [10]. This model relies on well-known approach for discrete-time modelling and the standard transform, considering modulation effect, sampling and delays produced in control loop. Digital implementation with existing resources like resolution of A/D and D/A (PWM) blocks and the computation time is a matter of attention [11]. In digital domain, any system can be contemplated as digital filter as they modify the wave-shape of signal and thus the harmonic amplitude. So, any design in digital domain can be constructed by digital filters. The discrete system model is built using only z^{-1} blocks and gain blocks [12]. A digital PID controller representation using digital IIR filter is demonstrated in [13] and this architecture supports the fixed point implementation of the controller. The poles and zeros of boost converter are reliant on the switching duty cycle, so bode plots can exhibit significant deviation. Therefore, PID controller may be unable to respond adroitly to significant fluctuations in operating points [14]. Online frequency measurement from bode plot

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is used as tuning algorithm for determination of digital controller parameters for DC/DC converters [15]. The objective of adaptive control or auto-tuning of controller parameters according to system's dynamic behavior can be achieved by programmability feature of digital controllers. Digital controllers are able to precisely adjust switching frequency, to implement algorithms as well as reconfigure the power stage using power switch segmentation [13] The analog TPS40k controller is compared with UCD921x digital controller for buck switch-mode converters [16]. Design of a digital controller for a buck DC/DC converter using state-space average (SSA) technique is presented in [17] that shows the potency of digital controller for converters through the execution of control algorithm on TMS320F2812 DSP. A comparative study of performance of fuzzy and PID controllers for high output voltage boost converter is demonstrated and implemented on DSP [18]. Digital implementation of controllers is most appropriate to explore the control techniques which targets better dynamic response. Time optimal response is also a remarkable field of interest for converter application. Time optimal response results a sequence of control actions which takes minimum time against external disturbances. So, for DC/DC converters it is a sequence of precisely timed pulses. DC-DC converters are extensively used today in power processing for regulated power supplies, electrical drives, renewable energy conversion system, electric traction etc. The dynamic performance of DC-DC converters can be enhanced by application of robust control schemes such as fuzzy logic controller [19, 20]. From many years, converters have been controlled using analog and linear control techniques. DC-DC converters shows non-linear peculiarity due to fluctuating operating points, which affects performance of converter. To achieve better performance, there are two solutions. One is to develop more exact model of converter and second is to use a non-linear controller. The exact model of system is extremely complex to use for controller design. A FLC is capable of adapting fluctuating operating points, so it is utilized as non-linear controller for DC-DC converters [14, 21, 22]. To obtain stable operation of buck and boost converter, classical PI and FLC based control strategy is presented in [18, 23, 24]. To rectify the problem of nonlinear nature of DC-DC converter, a FLC is used as it does not require precise mathematical model of plant. A general FLC design that can be used for wide variety of DC-DC converters is inspected in reference [25]. A FLC for full-bridge soft switching converter is designed and verified in [26]. A DC-DC converter is proposed in [27] for solar energy-hydrogen conversion system and as the electrolysis load is nonlinear, FLC is a choice in place of other linear controllers. In [14, 28] digital design and hardware implementation of FLC using DSP is demonstrated. The implementation of linear controllers on DSP is simple and straightforward but implementation of FLC based non-linear controller is a typical task due to huge calculations and complexities involvement. FLC based controller is implemented on eZdsp F2812 module with TMS320F2812 DSP for Boost converter is conferred in [14]. Robustness of FLC is demonstrated in presented work by obtaining results for practical operating conditions of DC-DC converter such as, varying load resistance and varying input voltage. The proposed FLC can be used for other configurations of DC-DC converters without or small modifications in rule base. The two controllers designed in this paper are: digital PID controller and a FLC for implementation on digital signal processors. Presented in this paper a complete process of digital controller design using digital filter technique that enables re-programmability. The IIR filter based design of digital PID controller can be implemented on low-cost fixed-point processors for fast and effective response with less memory and processor requirements. The fuzzy logic controller presented gives a robust control for the DC-DC converter.

II. MODELLING OF BUCK DC/DC CONVERTER.

Linear compensators for converters are designed using the mathematical modelling of system. To obtain a specific performance objective, a precise model is needed and it can be derived by using SSA. This section presents open-loop control-to-output transfer function of uncompensated DC/DC buck converter. SSTF of buck converter is of 2nd order and it can be derived by SSA as given by (1). Fig. 1 illustrates schematic of buck converter for which SSTF is evaluated.

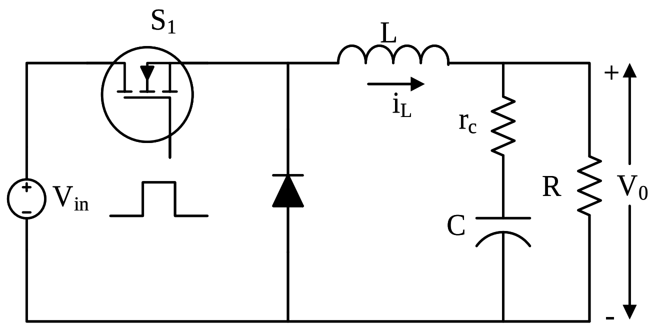

Fig. 1. Buck converter schematic.

A zero in left half of s-plane is introduced by series equivalent resistance (ESR) of output capacitor that plays a vital role in defining the characteristics of converter.

$$\frac{\hat{v}_0(s)}{\hat{d}(s)} = \frac{V_{in}(1+sR_cC)}{1+s\left(R_cC+\left(\frac{RR_l}{R+R_l}\right)C+\frac{L}{R+R_l}\right)+s^2LC\left(\frac{R+R_C}{R+R_l}\right)} \quad (1)$$

Here, V_{in} is input source voltage, V_o is output load voltage, D is duty ratio, C is output capacitor, L is inductor and R is resistance of load. R_l and R_c are series equivalent resistances of inductor 'L' and capacitor 'C'. Assuming $R_l = 0$ in (1), the simplified equation is given as (2).

$$\frac{\hat{v}_0(s)}{\hat{d}(s)} = \frac{V_{in}(1+sR_cC)}{1+s\left(R_cC+\frac{L}{R}\right)+s^2LC\left(\frac{R+R_C}{R}\right)} \quad (2)$$

Here, $\hat{v}_0(s)$ and $\hat{d}(s)$ are small signal perturbations of output voltage and switching duty cycle [2]. Buck converter design parameters and values of components are displayed in TABLE I. Control-to-output transfer function as shown in (2) is used for development of controller for converter.

TABLE I. BUCK CONVERTER DESIGN PARAMETERS AND VALUES

Parameter	Nomenclature	Value
Capacitor	C	35.8µF
Inductor	L	34.8µH
Load Resistor	R	13.9Ω
ESR of Capacitor	R_C	69.64mΩ
Input DC voltage	V_{in}	24V

By feeding values of converter parameters from TABLE I in (2), the transfer function of converter can be evaluated. Fig. 2 illustrates frequency response (FR) characteristics of buck converter without controller.

$$\frac{\hat{v}_0(s)}{\hat{d}(s)} = \frac{5.98\times10^{-5}s+24}{1+s(4.99\times10^{-6})+s^2(1252\times10^{-12})} \quad (3)$$

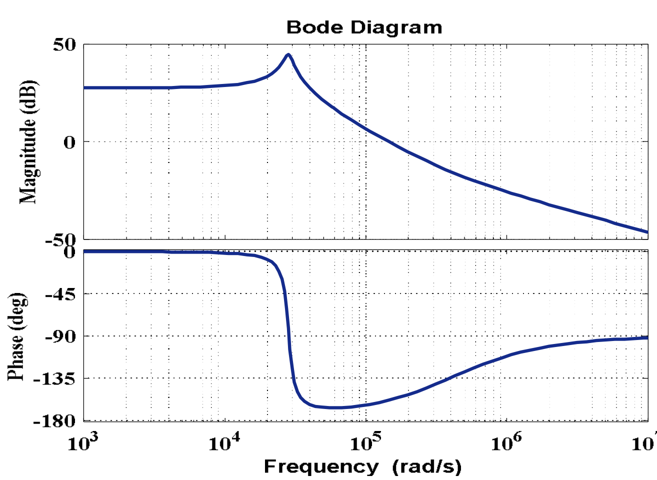

Fig. 2. Uncompensated buck converter magnitude and phase response.

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The output of open-loop buck converter is independent of load but it relies on input voltage directly, so load regulation is fine. Variation in input voltage causes proportional changes in output. So, line regulation is required to be improved and for this, closed-loop control is used.

III. CONTROLLER DESIGN FOR DC-DC CONVERTERS

A. Fuzzy Logic Controller

Artificial intelligence techniques are adapted for solving complex control problems. Fuzzy logic is one of the artificial intelligence technique which provides expedient method for designing nonlinear controllers from heuristic information. Conventional controllers are designed on behalf of closed-loop control characteristics such as: stability, rise time, settling time, overshoot and steady state error. Frequency response measurement, root-locus plot, state space method etc. are used for linear conventional controller design, which needs in-depth knowledge of mathematical model of system. FLC is quite different from conventional control, as it is based on expert knowledge of system. FLC provides a simple methodology to represent and implement human's expertise about controlling the system. A FLC has four main parts as demonstrated in Fig.3.

1) Fuzzification interface that converters crisp data input to membership degree according to shape of membership function (MF)
2) Rule base that contains expert's linguistic knowledge required for achieving good control.
3) Fuzzy inference that uses rule base and degree of MF to derive fuzzy output.
4) Defuzzification interface that converts fuzzy output into crisp or numeric value.

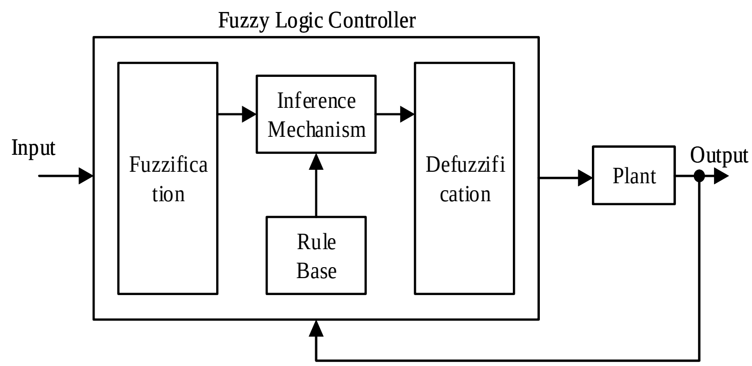

Fig. 3. Structure of FLC.

A digital design of FLC is proposed in this paper that can be implemented on DSP to generate switching pulses for converter. In the proposed control schema as shown in Fig.4, the voltage output of buck converter is compared with set point value and then the produced error is passed through an analog to digital converter. The digital values of error (e) and change in error (ce) are fed to FLC. Complete internal structure of proposed controller is shown in fig. 5.

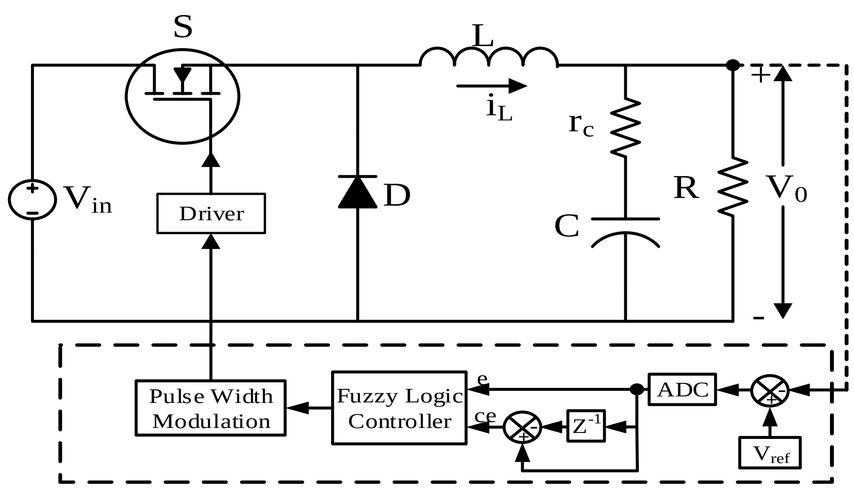

Fig. 4. FLC based closed loop control of buck converter.

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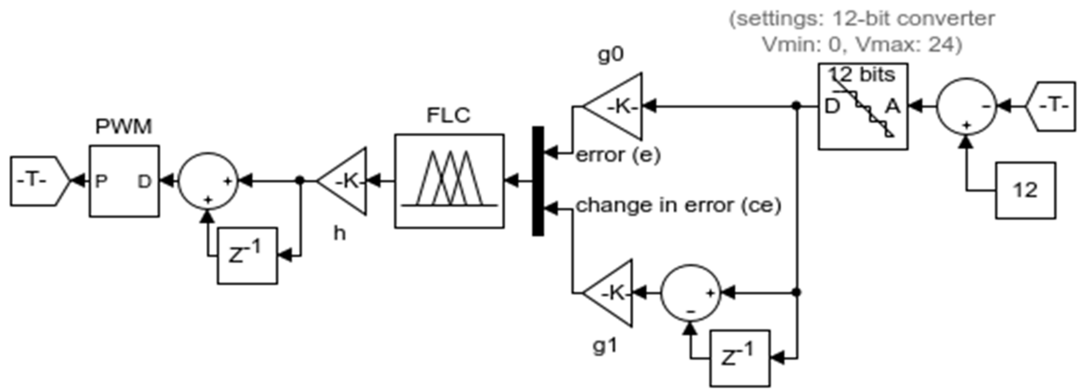

Fig. 5. Complete structure of proposed controller.

In the proposed controller shown in Fig. 5, the inputs are scaled by factors g_0 and g_1 and output from FLC is scaled by a factor h. These scaling factors can be tuned to get a better response. The input scaling factors are selected such that, the input to the FLC maintains itself within the range of MFs. The output scaling factor is selected to obtain the actual control output. Most of the DSPs have a 12-bit ADC, so a 12-bit ADC is considered here in this paper.

B. Defining Inputs and Outputs

By varying switching duty cycle, he output voltage of Buck converter can be controlled and it is desirable that the converter always track the reference voltage. FLC for DC-DC converter is designed to have two inputs. First input is error in output voltage and second input is change in error from (k-1)th sample to kth sample shown in (4). The FLC output is control action which is utilized for generating switching pulses.

$$e(k) = V_{ref} - V_{o(ADC)}$$
$$ce(k) = e(k) - e(k-1)$$

Here V_{ref} is reference voltage desired at output and $V_{o(ADC)}$ is converted digital value of output voltage.

IV. FUZZIFICATION OF INPUTS

The inputs of FLC are converted from crisp value to a linguistic variable by fuzzification. The output of FLC is produced in the defined range of output MF. Triangular MF is used here for input and output variables, as shown in Fig.6 and Fig.7 respectively.

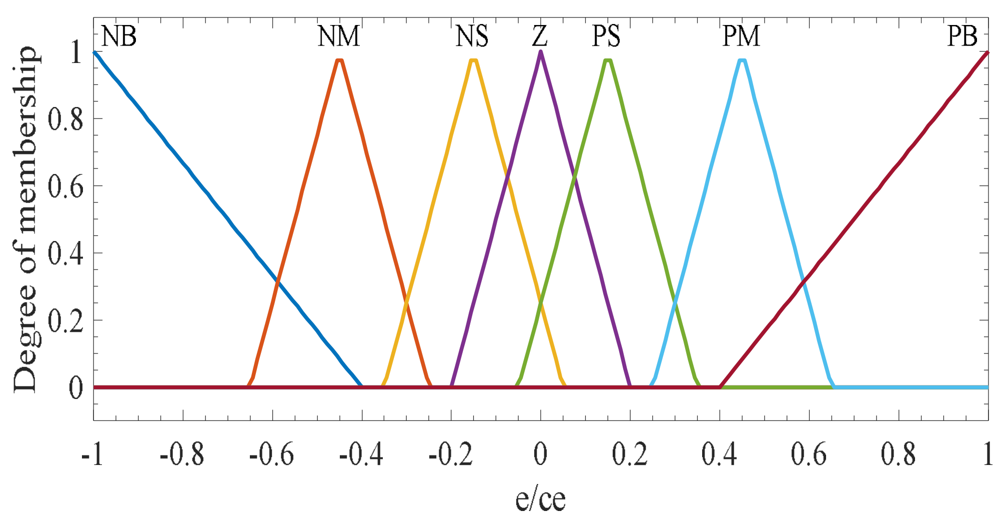

Fig. 6. Input MFs.

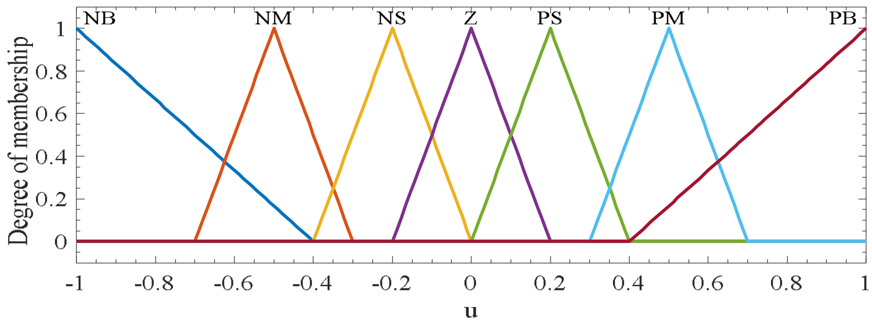

Fig. 7. Output MFs.

V. EVOLUTION OF RULE BASE

Rule base is the part of FLC that contains knowledge of proper action to be produced for given inputs. Rule base is derived on the basis of knowledge of converter operation. A 7 X 7 rule base as shown in TABLE II is designed and implemented in this paper. The structure of rules is as follows:

$$if\ \ input1\ is\ \left(mf\right)\ AND\ input2\ is\ \left(mf\right)\ then\ output\ is\ \left(mf\right)$$

TABLE II. 7 X 7 RULE BASE OF FUZZY CONTROLLER

ce/e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NM	NM	NS	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NM	NS	NS	Z	PS	PS	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PS	PM	PM	PB
PB	Z	PS	PM	PM	PB	PB	PB

VI. INFERENCE MECHANISM

During operation of FLC, the inputs lying in the defined range of MF have certain degree of membership. By using Mamdani's fuzzy implication of $\mu_e(e[k])$ and $\mu_{ce}(ce[k])$, weight factor w_i is evaluated, where $\mu_e(e[k])$ and $\mu_{ce}(ce[k])$ are degree of membership of input error and change in error respectively. The output of controller is calculated by product of weight factor and control output from individual rule (c_i). Thus the final control output produced is given by (5). Fig. 8 shows control surface obtained from the designed rule base.

$$z_i = \min\{\mu_e(\mathrm{e}[\mathrm{k}]), \mu_{ce}(\mathrm{ce}[\mathrm{k}])\} \times c_i$$

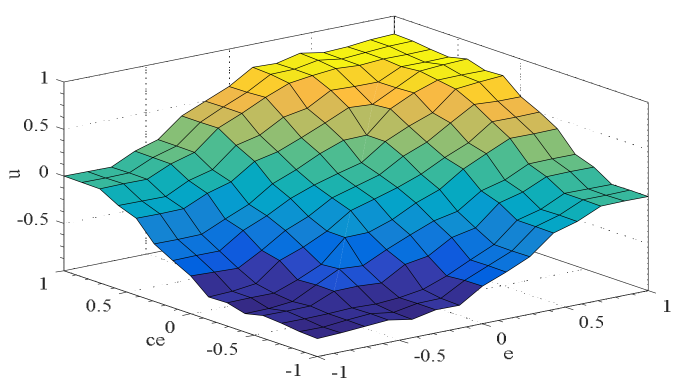

Fig. 8. Control Surface of FLC.

VII. DEFUZZIFICATION

To get a numeric or crisp value of control action, the output from FLC is defuzzified. A number of methods are available for defuzzification. Centre of area is well established method of defuzzification. The crisp value of control output is calculated according to the expression given by (6).

$$d[\mathrm{k}] = \frac{\sum_{i=1}^{N} z_i}{\sum_{i=1}^{N} w_i}$$

A. *Digital Controller Design:*

In general, following two methodologies are utilized to design a digital controller for DC/DC converters: In case of digital redesign, the controller is developed in continuous domain and then discretized to obtain digital form. In case of direct digital domain design, the system in continuous time domain is first discretized and then the controller is directly designed in discrete domain [29].

As we are much accustomed with frequency response (FR), it is convenient to design a controller using FR in s-domain. An analog controller is designed using FR characteristics and then mapped to discrete-time domain to obtain digital controller. A target crossover-frequency 'f_c' and target phase-margin 'φ_m' is assumed before compensator design. The uncompensated loop gain at target crossover-frequency is evaluated from FR and then required compensation in phase is calculated. The controller is designed as per required compensation. A digital controller compensated system should have following characteristics: Higher loop gain at low frequencies so that, steady state error get minimized and increase rejection of disturbances due to variation of voltage and current.

Higher crossover frequency (less than switching frequency) for quick transient response of converter.

The phase margin should be positive and sufficient to ensure stability of system.

The digital domain representation of a controller can be realized from digital filter configuration which enables programmable design of controller.

$$G_{con}(s) = K_p + \frac{K_i}{s} + s.K_d$$

Equation (7) represents analog PID controller in continuous time. A digital PID controller also follows (7), except the multiplication, integration and differentiation are performed numerically in digital computers. The response of system using digital controller is similar to that of analog controller, if numerical calculation is accurate.

Discrete time controller transfer function can be evaluated from analog PID controller by one of the methods like forward difference, backward difference, bilinear transformation etc. Here we used backward difference mapping method.

$$s = \frac{z-1}{z}$$

$$G_{con}(z) = K_p + \frac{K_i.z}{(z-1)} + \frac{K_d.(z-1)}{z}$$

$$G_{con}(z) = \frac{z^2(K_p + K_i + K_d) - z(K_p + 2K_d) + K_d}{z(z-1)}$$

$$G_{con}(z) = \frac{(K_p + K_i + K_d) - z^{-1}(K_p + 2K_d) + z^{-2}K_d}{(1-z^{-1})}$$

Discrete IIR filter transfer function with two zero and one pole is represented by (12)

$$G_{con}(z)=\frac{b_0+z^{-1}.b_1+z^{-2}.b_2}{(1-z^{-1})}$$

Comparing (11) and (12) gives values of IIR filter coefficients in terms of fundamental PID controller coefficients.

$$\begin{aligned} b_0 &= K_p + K_i + K_d \\ b_1 &= -(K_p + 2K_d) \\ b_2 &= K_d \end{aligned}$$

A digital filter can be represented using several structures such as: parallel, cascaded, direct form etc. Here direct form realization of an infinite impulse response (IIR) type digital filter is used to exhibit required poles and zeros in digital PID controller.

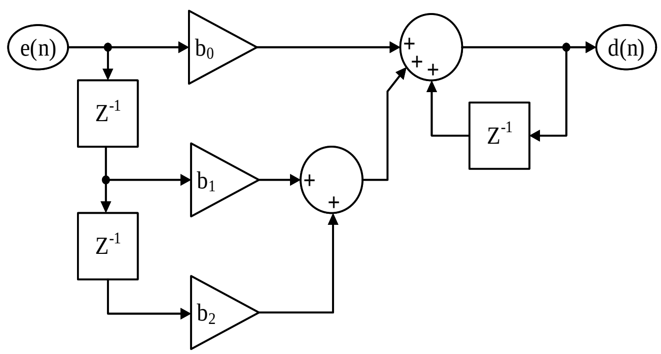

Fig. 9. Direct form representation of IIR digital filter.

The digital PID controller realization from IIR digital filter using direct form is represented in Fig. 9, have two zeros required for compensation and a pole at origin for minimization of steady state error in system. The output of DC/DC converters is a function of input dc voltage, switching duty-cycle and load current as depicted in (2). A constant output voltage is desirable during disturbances like abrupt load variation, sudden change in input dc voltage or load current. Thus, a negative feedback control is employed in DC/DC converters so that the duty ratio automatically adjusts to maintain a constant output dc voltage. Fig. 10 shows complete block schematic representation of digital control for converters. Two components are essential while transiting from analog to digital domain. These components are: analog-digital (A/D) converter and sample & hold circuit.

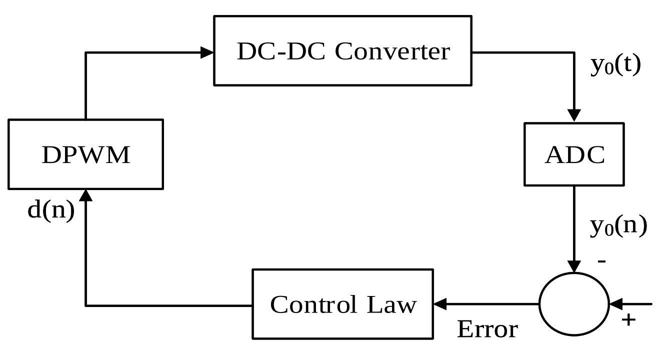

Fig. 10. Block representation of digitally controlled DC-DC converter.

Digital PID controller substantially improves loop-gain, crossover frequency and phase-margin according to target values decide for given DC/DC converter. Fig. 11 shows close-loop scheme for Buck-converter with digital PID compensator. A digital pulse width

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modulator (DPWM) is used with digital controllers and it differs from analog PWM as it uses digital carrier for generation of PWM signal for switch. DPWM uses counter based or delay line based generation of saw tooth carrier wave.

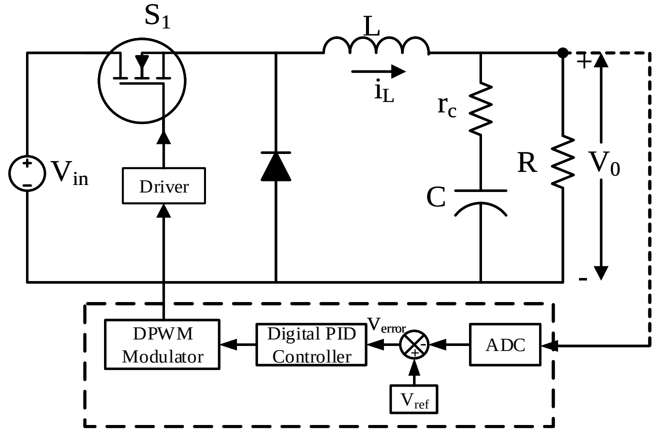

Fig. 11. DC-DC buck converter with digital control.

VIII. SIMULATION RESULTS

A. *Fuzzy Logic Controller*

For testing the line regulation, input voltage is changed from 16V to 32V with variation of 8V in each step. Similarly, for testing the load regulation, load resistance is varied in a wide range from 1Ω to 100Ω. The output voltage and inductor current of buck converter for 24 V input DC voltage, 0.8616 A output current are shown in Fig. 12 and Fig. 13 respectively.

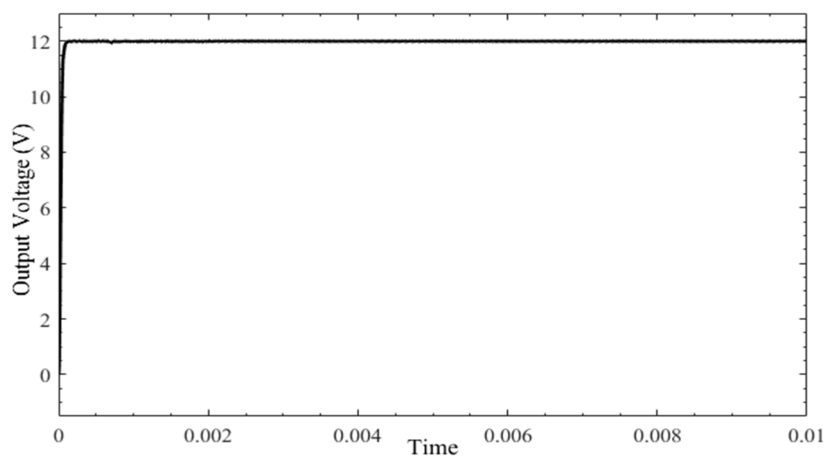

Fig. 12. Output voltage of Fuzzy controlled converter.

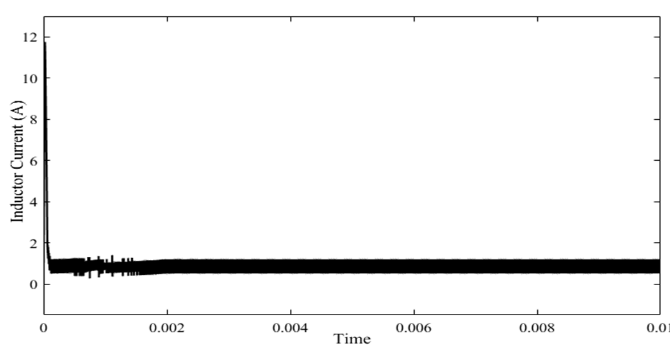

Fig. 13. Inductor Current of Converter.

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The buck converter is tested for reference voltage tracking by changing reference voltage value from 4 V to 12V with a variation of 2V in each step. It can be observed from Fig. 14 and Fig. 15, that the output voltage tracks the reference with very small rise time, settling time and overshoot.

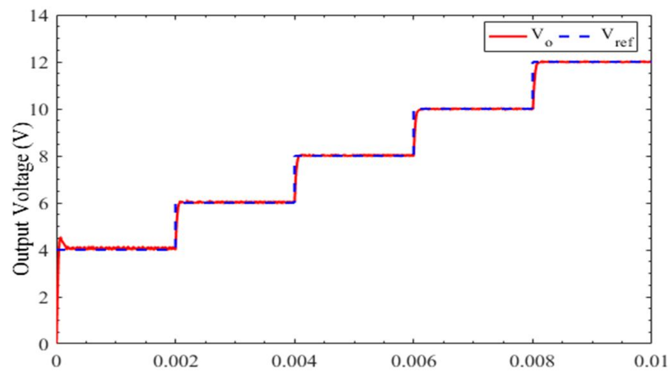

Fig. 14. Response of proposed FLC for Reference voltage tracking.

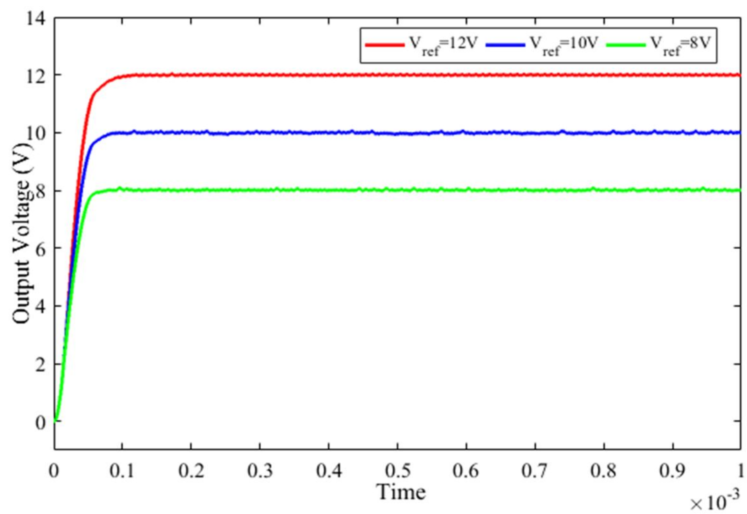

Fig. 15. Response of proposed FLC for different values of reference voltage.

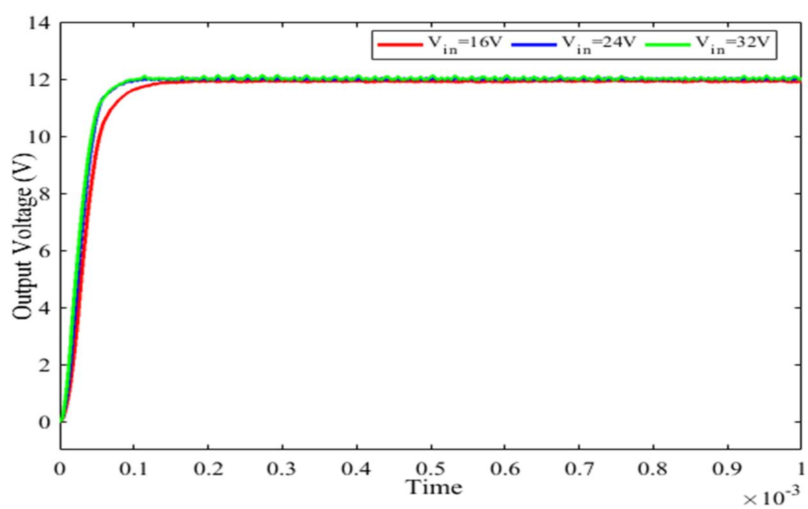

Fig. 16. Response of proposed FLC for different values of input voltage.

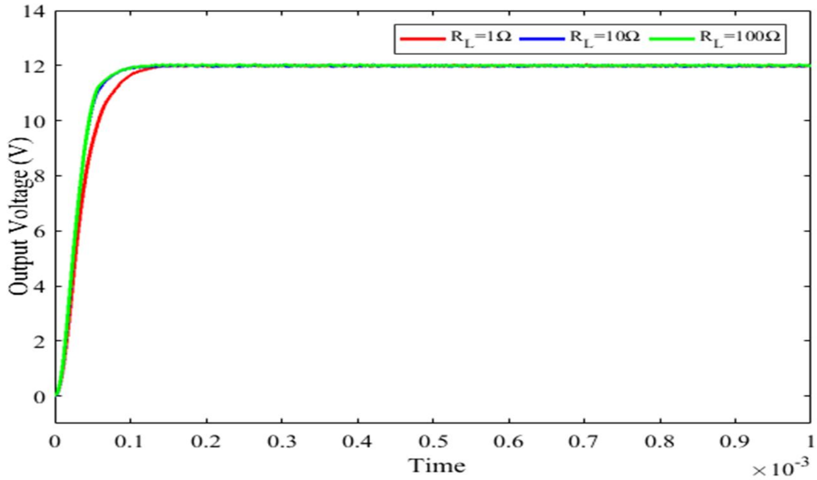

Fig. 17. Response of proposed FLC for different values load resistance.

IX. DIGITAL PID CONTROLLER

The digital controller demonstrated here is applied to a fundamental DC/DC converter. A 24V to 12V buck converter is considered and simulated using MATLAB/Simulink. The converter is subjected to practical conditions such as input voltage and load variations and it is observed that the output voltage regulation is obtained for an extensive range of input voltage and load resistance. Fig. 8 shows output voltage reference tracking response of Buck converter. The reference is changed at regular time interval of 40 msec and it is observed that the target value is achieved with very small settling time. Fig. 10 shows response of Buck and converter for varying input voltage. Fig. 12 shows response of Buck converter for varying load resistance values.

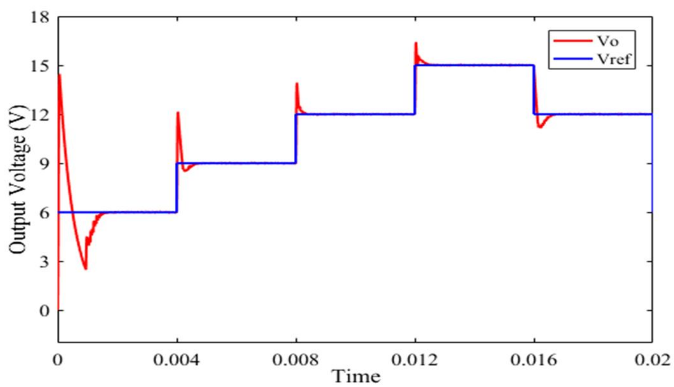

Fig.8. Reference voltage tracking of buck converter with digital PID controller.

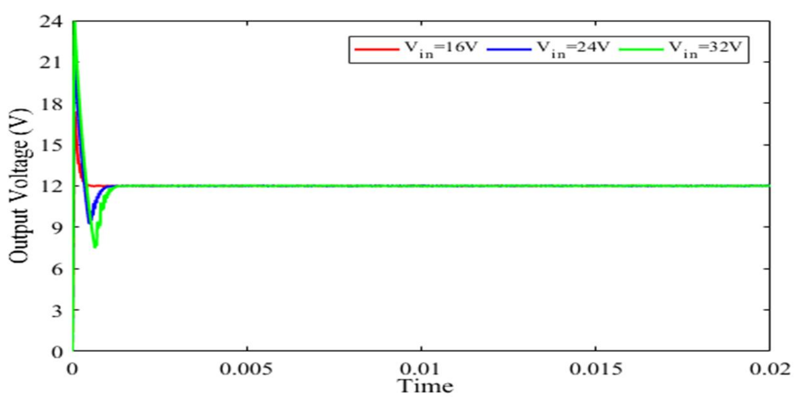

Fig.9. Response of Buck converter for varying input voltage.

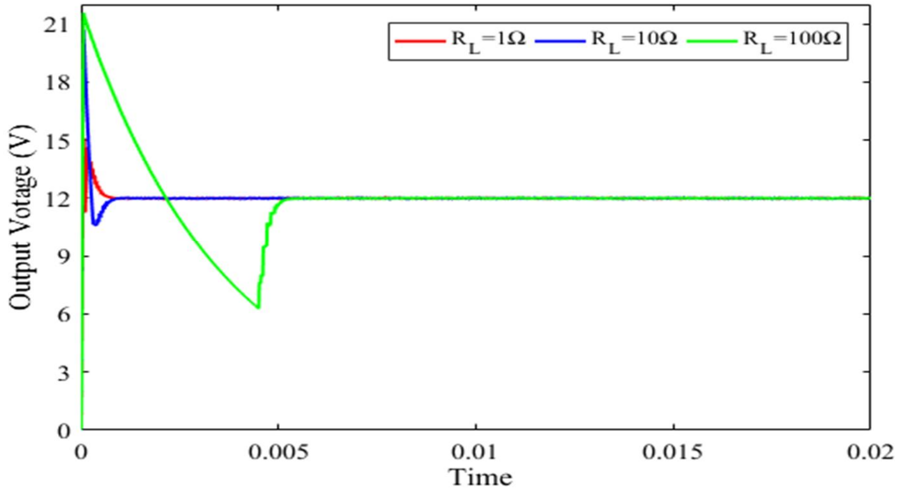

Fig.10. Response of Buck converter for varying load resistance value.

X. CONCLUSION

In this paper, digital design of robust FLC and IIR filter based digital PID controller for DC-DC buck converter is presented and simulated. Simulation results are obtained for practical operating conditions such as: varying input voltage, varying load resistance and reference voltage tracking. Simulation results shows that, as compared to other standard controllers FLC yielded better performance in terms of low overshoot and settling time. The FLC is able to adapt itself to other configuration of DC-DC converters. So, the design of FLC presented in this paper can be used as a general controller for DC-DC converters. The digital PID controller demonstrated in this paper for DC/DC converter is designed using digital re-design approach. To obtain desired characteristics in terms of loop gain, crossover-frequency and phase-margin, digital filter direct form based PID controller is designed. The controller takes less memory size and less time to execute due to reduced complexity of architecture. MATLAB/Simulink based simulation results are obtained for practical operating conditions, which show that the digital control effectively improves the performance of DC/DC converters under disturbances. The fixed-point implementation of controller relies on the target platform and the digital controller proposed in this paper supports fixed-point algorithm thus can be implement on low-cost processors. The two controllers presented in this paper have their own advantages, FLC is a robust controller that can deal with the non-linearity of the converters whereas the IIR digital filter based PID controller have simple architecture suitable for their fixed point implementation.

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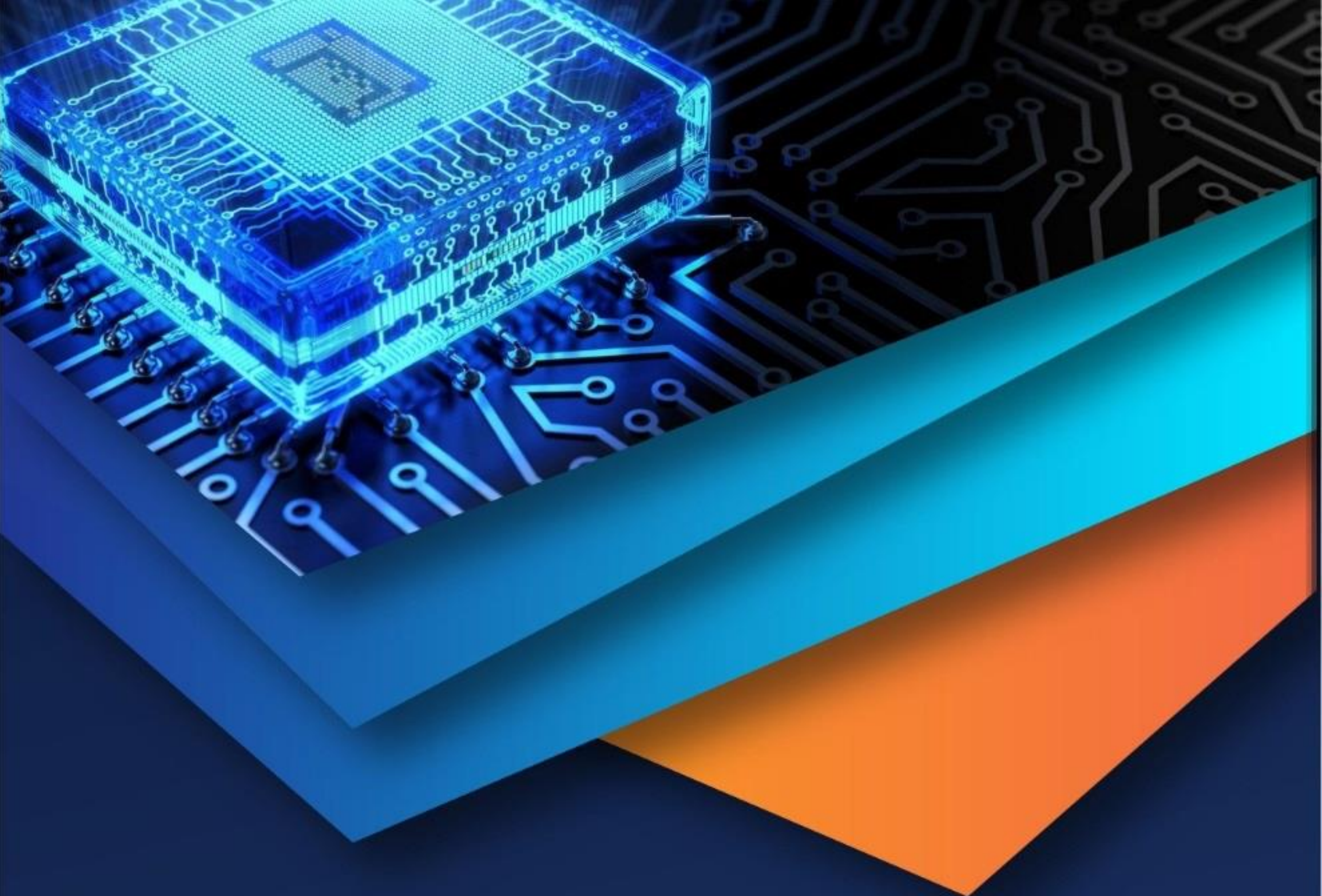

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