Preprints of the 21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

Laguerre Neural Network Driven Adaptive Control of DC-DC Step Down Converter

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Abstract: DC-DC step-down/buck converters are prominent part of DC power supply system. The dynamics of DC-DC step down converter are nonlinear in nature and are largely influenced from both parametric and external load perturbations. Under its closed loop operation, obtaining a precise output voltage tracking besides satisfactorily inductor current response is a challenging control objective. In this regard, this article proposes a novel Laguerre neural network estimation technique for the approximation of unknown and uncertain load function, followed by its subsequent compensation in the adaptive backstepping controller. A detailed design of the proposed estimator and adaptive backstepping controller along with closed loop asymptotic stability have been presented. Further, the proposed control mechanism is evaluated through extensive numerical simulations while subjecting the converter to input voltage, reference voltage and load resistance perturbations. Furthermore, the results are verified by testing the proposed controller on a laboratory prototype with DSP based TM320F240 controller board. The transient performance metrics such as settling time and peak overshoot/undershoot are evaluated and compared against adaptive backstepping control and PID control methods. Finally, the analysis of results reveals that the proposed control methodology for DC-DC step down converter offers a faster transient output voltage tracking with smooth and satisfactory inductor current response over a wide operating range.

Keywords: DC-DC converter, adaptive control, neural network, perturbations, estimation technique

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1. INTRODUCTION

Recent advancements in the emerging areas of electrical engineering such as renewable energy and smart grid technologies has favoured substantial usage of DC-DC step down chopper/buck converters for DC voltage regulation. Some of the other prominent applications of DC-DC step down converters include adapters in electric vehicles, communication systems, motor drives, high voltage DC transmission, automotive industry, electronic gadgets, computers and robotics ((Rashid (2003); Wai et al. (2008); Nizami and Mahanta (2015); Rivetta et al. (2006)). In such applications, it is highly desirable to maintain a good precision in the output voltage, besides maintaining a smooth inductor current profile for the satisfactory performance of the converter when connected to diverse external loads. However, due to the underlying challenge, obtaining an accurate model for the DC-DC step down converter faces the following issues: (i) it belongs to the class of switched mode circuit where frequent switching between different modes of operation occur, leading to voltage drops in the power diode and MoSFET/IGBT switch (ii) the voltage across load terminals is highly sensitive to input voltage change, load resistance change and parametric perturbations and (iii) nonlinear behavior of the inductor due to its large magnetic flux density in its ferromagnetic core (Wang et al. (2017)). In view of these concerns, maintaining a high efficiency, stronger disturbance rejection ability, faster dynamical response of output voltage tracking and overall closed loop stability in DC-DC step down converter is a great challenging task.

Conventional controllers proposed in the literature include Proportional-plus-Integral (PI)/Proportional-plus-Integral-plus-Derivative (PID) controllers (Guo et al. (2009); Tousif Khan N and Sundareswaran (2014)), which are designed using small signal analysis and further linear control theory is applied to it. However it carries the limitation of not providing precise control over a wide operating range. On the other side the recent improvements in the computational capabilities of hardware platforms have encouraged the real time implementation of nonlinear control techniques, i.e robust control, adaptive control, optimal control, fuzzy control, neural network based control, geometric control and sliding mode control (Shuai et al. (2008); Sira-Ramirez (1991); xin (2014); Zuo Wang et al. (2017); D. Cortaos et al. (2002); Hebertt Sira-Ramarez et al. (2013); Guangliang Ma et al. (2018)).

Among them the sliding mode control (SMC) (Utkin (1977); Edwards and Spurgeon (1998)) has gained popularity due to its merits of immunity to matched perturba-

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tions (such as input voltage change in case of DC-DC step down converter) and ease of hardware implementation. Nonetheless, the high frequency chattering phenomenon exhibited in SMC leads to considerable voltage drops in the semiconductor switches and also lead to wear and tear of the switching elements. However, the inability of SMC method to ensure invariance against mismatched perturbations is the discouraging factor. Of late the backstepping control (Kar and Behera (2009)) technique has been become popular due to its easier applicability to the system expressed in strict feedback form, systematic and recursive design framework, simplicity in its practical implementation and ability to reject linearly parameterized uncertainties. However, the computation of control signal in this technique requires precise knowledge of real time system parameters and external loading. Hence in this work, the most uncertain load resistance parameter is approximated by means of proposed online Laguerre neural network and thereafter the estimated values is is compensated along with other parameters of the DC-DC step down converter in the adaptive backstepping controller framework.

Remaining part of the paper is organized as follows. The system description, its operation and problem formulation is discussed Section 2. A detailed design of the proposed Laguerre Neural Network based adaptive backstepping controller along with closed loop stability is discussed in Section 3. Simulation results carried out to test the efficacy of proposed control is presented in Section 4. Real time experimental validation of proposed control is provided in Section 5. Finally, the conclusions drawn from the work and acknowledgement are presented in Section 6 and section 7 respectively.

2. SYSTEM DESCRIPTION AND PROBLEM FORMULATION

The circuit topology of DC-DC step down chopper/buck converter is shown in the Fig.1. The converter consists of a low level DC input voltage E, a power electronics switch S_w, a filter inductor L, a filter capacitor C, a power diode D for the purpose of current freewheeling and an external resistive load R. The dynamical model of the circuit is obtained by considering the voltage drop across the capacitor v_O and current flowing through the inductor i_L, as the two states of the system. Hereafter v_O and i_L are referred as states x_1 and x_2 respectively. Applying fundamental electrical laws we obtain the following dynamical equations.

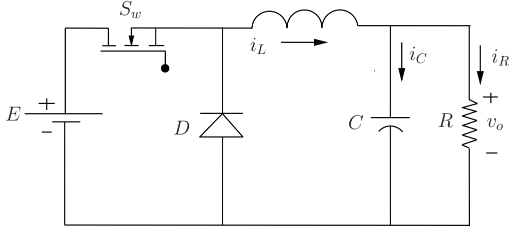
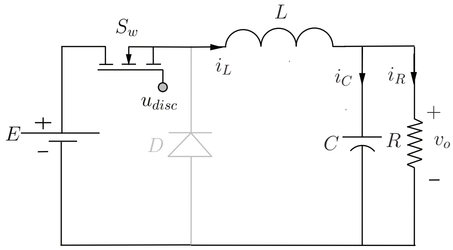


Fig. 1. DC-DC Step-down/buck Converter

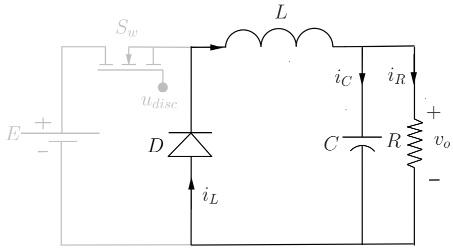
$$\dot{x}_1 = -\frac{x_1}{RC} + \frac{x_2}{C} \tag{1}$$

$$\dot{x}_2 = -\frac{x_1}{L} + \frac{uE}{C} \tag{2}$$

In (2), the term u is known as control switching signal required to operate the power switch S_w. Furthermore, $u = 1$ and $u = 0$ denotes the closing of opening of switch S_w in the converter respectively. The corresponding operational modes of the DC-DC step down converter are presented in Fig. 2. As a control task, here the objective is to generate appropriate gate pulses as the control input u, so as to operate the switch S_w accordingly. This suitable control action must lead to a faithful output voltage tracking along with closed loop asymptotic stability across wide operating range.



Buck Converter in ON Mode



Buck Converter in OFF Mode

Fig. 2. Operational modes of DC-DC Step-down/buck converter

3. PROPOSED CONTROLLER DESIGN

The controller design is based on adaptive backstepping control methodology for the asymptotic stabilization of tracking error dynamics. The perturbations in the external load resistance are estimated using the proposed single layer Laguerre neural network and subsequently compensated in the control action. The block diagram schematic of the proposed control and estimation mechanism is shown in Fig. 3. The subsequent subsections will discuss the proposed estimator and controller.

3.1 Laguerre Neural Network

Inspired from the universal approximation properties of neural networks, the proposed work incorporates Laguerre neural network (Borwein et al. (2008); Koepf (1997)) with online estimation of unknown and uncertain time varying load resistance R term. Thereby, the unknown function here required to be approximated is given by $f(\cdot) = x_1/RC$ from (1). Considering the properties of function approximation and Stone Weierstrass Theorem, the uncertain function can be estimated as $f(\cdot) = {W^*}^T \Phi(x_1) + \varepsilon$

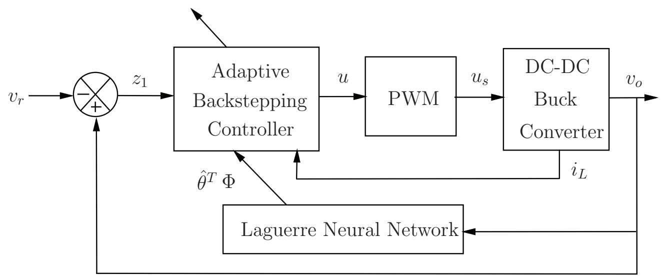


Fig. 3. Schematic block diagram representation of the proposed control system

with $W^* := [w_1^* \; w_2^* \; w_3^* \dots w_\rho^*]^T$ as the neural weights of the network and the bounded estimation error is denoted as ε. Further, $\Phi(x_1) := [L_0(x_1) \; L_1(x_1) \; \dots \; L_{\rho-1}]^T$ is used as a bases vector. Due to the requirement of faster and precise estimation of unknown term, this work resorts to Laguerre polynomial in the single functional layer neural network. Thereby, the term $L_i(x_1)$, $i = 0, \dots, (\rho - 1)$ represents the Laguerre polynomials given by the recurrence formula, $L_{i+1}(x) = \dfrac{(2i + 1 - x)L_i(x) - iL_{i-1}(x)}{i + 1}$ and ρ denotes the dimension of the polynomial function space. Further, initial Lauguerre polynomials are defined as $L_0(x) = 1$ and $L_1(x) = 1 - x$.

3.2 Controller Design

The design of controller is based on the backsteping control methodology (P.V. (1992); Laxmidhar Behera, Indrani Kar (2009)) which is integrated with the proposed Laguerre Neural Network for the estimation of unknown load resistance function. In the proceeding session, the design procedure is discussed in detail.

Let the tracking error variables be defined as,

$$z_1 = x_1 - v_r, \quad z_2 = \frac{x_2}{C} - \alpha(\cdot) \tag{3}$$

where v_r is the reference output voltage. Next considering the first subsystem z_1 and further using the system model (1)-(2), then the error dynamical equations can be found as

$$\dot{z}_1 = -W^{*^T}\Phi(x_1) + z_2 + \alpha(\cdot) \tag{4}$$

Next selecting appropriative virtual control input $\alpha(\cdot)$ for z_1 subsystem in order to make it asymptotically stable. Thereby considering the Lyapunov function $V_{z_1} : \mathbb{R} \times \mathbb{R}^\rho \times \mathbb{R}_+ \to \mathbb{R}_+$ as,

$$V_{z_1} = \frac{1}{2}z_1^2(t) + \frac{1}{2\gamma}\tilde{W}^T(t)\tilde{W}(t) \tag{5}$$

where the term $z_1(t)$ is the error in output voltage tracking and $\tilde{W}(t) = W^*(t) - \hat{W}(t)$ is the error in estimation.

Next, the first time derivative of V_{z_1} is obtained as follows,

$$\dot{V}_{z_1} = z_1(-W^{*^T}\Phi(x_1) + z_2 + \alpha(\cdot)) - \tilde{W}(t)\dot{\hat{W}}(t) \tag{6}$$

Now selecting $\alpha = -c_1 z_1 + \hat{W}^T\Phi(x_1)$ and $\dot{\hat{W}}(t) = -\gamma\Phi(x_1)z_1(t)$ will result in $\dot{V}_{z_1} = -c_1 z_1^2 + z_1 z_2$. As per the design procedure $z_2 = 0$ would be obtained by taking control input u leading to negative definiteness of $\dot{V}_{z_1}$ driving asymptotic stability of z_1.

Next in order to derive the expression for $u(t)$, which will be required to asymptotically stabilize the error variable z_2. Thereby the Lyapunov function is taken as $V_{z_2} : \mathbb{R} \times \mathbb{R}_+ \to \mathbb{R}_+$ given by, $V_{z_2} = z_2^2/2$. Thereby, the first time derivative yields

$$\dot{V}_{z_2} = z_2(-\frac{x_1}{LC} + \frac{uE}{LC} - \dot{\alpha}) \tag{7}$$

Expressing $u(t) = \dfrac{LC}{E}\left(-z_1 - c_2 z_2 + \dfrac{x_1}{LC} + \dot{\alpha}\right)$ results in $\dot{V}_{z_2} = -c_2 z_2^2 - z_1 z_2$. At last in order to guarantee the closed loop stability of complete DC-DC step down converter dynamics equipped with proposed designed adaptive controller, a total Lyapunov function candidate is considered as $V_z = V_{z_1} + V_{z_2}$. Next $\dot{V}_{z_1}$ and $\dot{V}_{z_2}$ are calculated in the upcoming text. However, the derivative of V_z is found to be $\dot{V}_z = -\sum_{i=1}^{2} c_i z_i^2 < 0$. Thereby the negative definiteness of $\dot{V}_z$ is guaranteed and proved. This further leads to,

$$-\int_{t_0}^{\infty} \dot{V}_z dt \le V_z(t_0) - V_z(\infty) \le \int_{t_0}^{\infty} z^T \mathcal{Q} z dt \le \infty \tag{8}$$

where, $z := [z_1 \quad z_2]^T$ and $\mathcal{Q} := \text{diag}\{c_1, \; c_2\} > 0$. The above expressions on closed loop signals yields

$z(t) \in \mathcal{L}_2 \cap \mathcal{L}_\infty$ and $\dot{z}(t) \in \mathcal{L}_\infty$ in addition to boundedness of weight estimation, i.e., $W(t), \dot{W}(t) \in \mathcal{L}_\infty$. Henceforth, using Barbalat's signal convergence lemma, the asymptotic stability of $z(t)$, i.e, $\lim_{t\to\infty} z(t) = 0$ means that $z_1(t)$ finally decays asymptotically to zero.

Further, it must be noted that the actual control signal u obtained is of continuous form. This signal is further modulated using a pulse width modulation (PWM) method by judiciously choosing the carrier wave to result in a discontinuous control signal u_{disc} to operate the power switch S_w.

4. SIMULATION RESULTS

To test the performance of the proposed control scheme, numerical simulations are conducted on MATLAB platform with a step size of $50\mu s$. The parameters of step-down/buck converter includes; input voltage $E = 25V$, inductor $L = 59mH$, capacitor $C = 220\mu s$, nominal load resistance $R = 20\Omega$ and switching frequency $f_s = 20kHz$. Further, the efficacy of proposed controller is established over; (i) adaptive backstepping control (ABSC) (Tousif Khan Nizami and Chitralekha Mahanta (2016)) scheme developed for buck converter with gains same as the proposed controller; $c_1 = 6000$, $c_2 = 20$, number of neurons $\rho = 5$ and adaptive gain $\gamma = 25 * 10^{-6}$, and (ii) conventional linear PID controller with tuned gains; $k_p = 100$, $k_i = 20$ and $k_d = 0.01$ under following test conditions.

4.1 Start-up response

The closed loop dc-dc step-down/buck converter response during start-up, while tracking a reference output voltage $v_r = 10V$ is shown in Fig. 4 (a) and Fig. 4 (b). The Fig. 4 (a) shows the performance of output voltage under

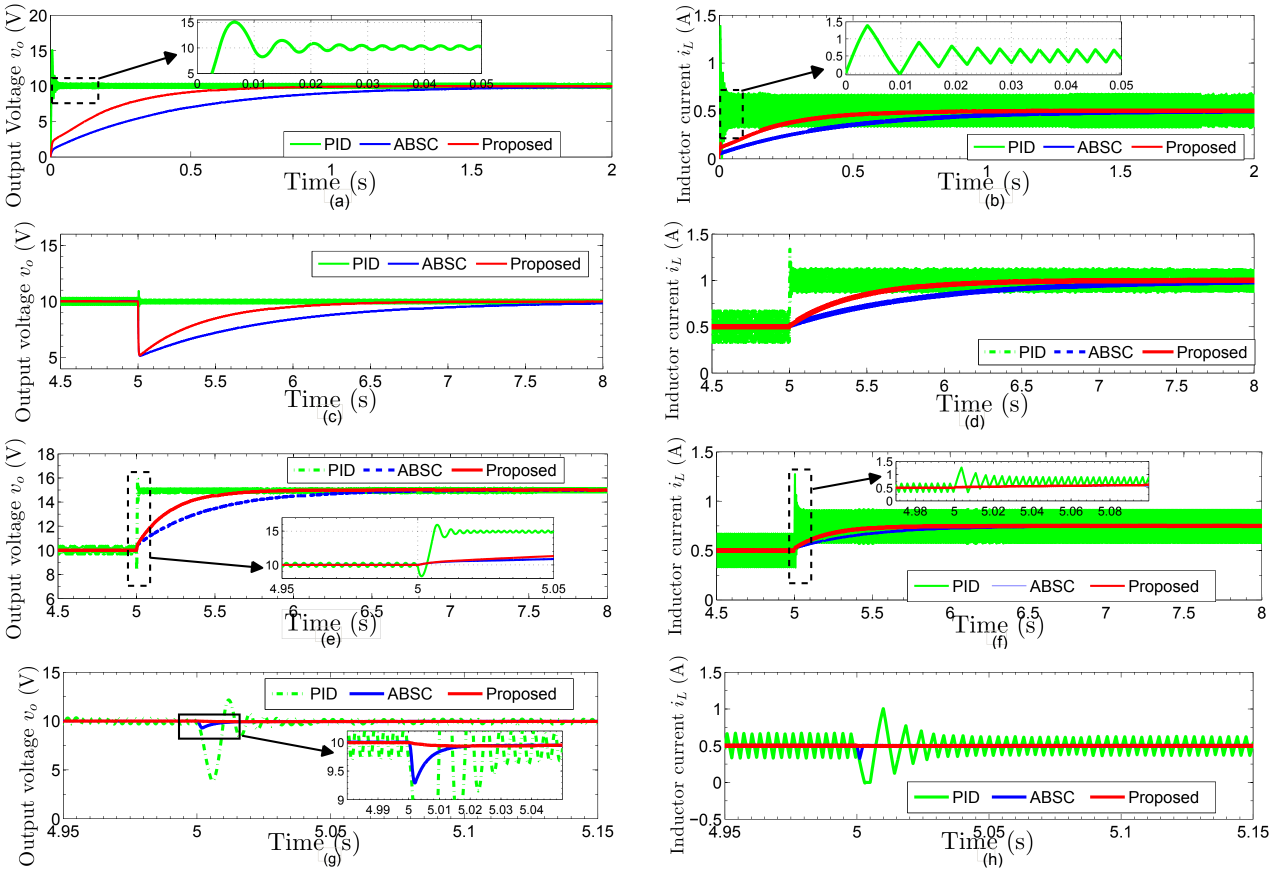


Fig. 4. Simulation results: (a) start-up response of output voltage v_o; (b) start-up response of inductor current i_L; (c) response of output voltage v_o due to sudden change in load resistance from 20Ω to 10Ω at time $t = 5s$; (d) response of inductor current i_L due to sudden change in load resistance from 20Ω to 10Ω at time $t = 5s$; (e) response of output voltage v_o due to reference voltage v_r change from $10V$ to $15V$ at time $t = 5s$; (f) response of inductor current i_L due to reference voltage v_r change from $10V$ to $15V$ at time $t = 5s$; (g) response of output voltage v_o due to sudden change in input voltage E from $25V$ to $18V$ at time $t = 5s$; (h) response of inductor current i_L due to sudden change in input voltage E from $25V$ to $18V$ at time $t = 5s$.

the action of conventional PID, adaptive backstepping and proposed control. The response of PID controller although is quick, yet it produces peak overshoot P_o of 50% from reference voltage which is unacceptable in sensitive applications. On the other side, the ABSC (Tousif Khan Nizami and Chitralekha Mahanta (2016)) produces no peak overshoot, but yields slow response and settles in a time of $1s$. On contrary, the proposed control method produces no peak overshoot and faster settling time of $500ms$, leading to 50% betterment in response time in respect to ABSC (Tousif Khan Nizami and Chitralekha Mahanta (2016)). Similarly, the Fig. 4 (b) shows the behavior of inductor current i_L during start-up tracking. The PID controller generates high peak overshoot and significant steady state ripple in current which may damage the device. Whereas, the proposed control yields better i_L response compared to both PID and ABSC method.

4.2 Sudden change in load resistance R

Next, the step-down/buck converter is subjected to a step change in the value of load resistance R from 20Ω to 10Ω at time $t = 5s$. The response obtained during this load perturbation is shown in Fig. 4 (c) and Fig. 4 (d). In Fig. 4 (c) it must be noted that the response of ABSC (Tousif Khan Nizami and Chitralekha Mahanta (2016)) technique is slow and reaches desired output in output voltage v_o in $1.3s$ with a peak undershoot P_u of 49%. On contrary, the proposed controller results in similar peak undershoot P_u while the time taken to settle is reduced to $600ms$. Although, the response of PID is faster under load perturbations, however it must be noted they yield intolerable peak overshoots in v_o and i_L during start-up and hence may not be suitable in practice.

4.3 Sudden change in reference voltage v_r

Further, the efficacy of proposed control is evaluated by bringing a step change in reference voltage v_r from nominal $10V$ to $15V$ at time $t = 5s$. The response of v_o and i_L obtained has been plotted in Fig. 4 (e) and Fig. 4 (f) respectively. It can be seen that similar to start-up response, the PID controller yields peak overshoot P_o in both the profiles of v_o and i_L. However, the response of ABSC (Tousif Khan Nizami and Chitralekha Mahanta (2016)) scheme yields no peak overshoot but results in slow tracking time of $1.1s$. Whereas, the proposed control also generates no peak overshoot P_o, yet provides faster tracking in $550ms$.

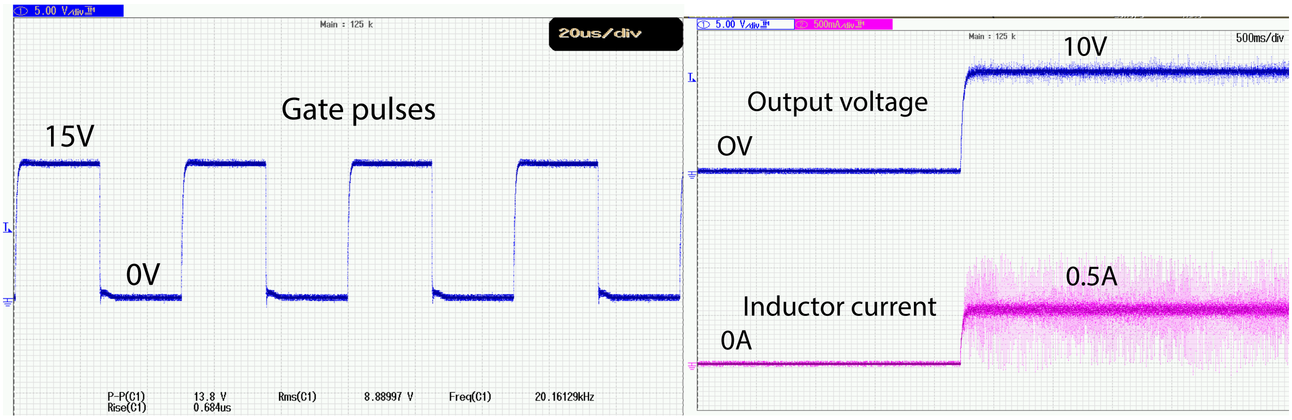


Fig. 5. Experimental response of proposed controller (Left→Right); Col. 1: Gate pulses; Col. 2: response of output voltage v_o and inductor current i_L during start-up.

4.4 Sudden change in input voltage E

Finally, the numerical simulations tests are performed by subjugating converter system to sudden change in the input voltage E from $25V$ to $18V$. The response of step-down converter is shown in Fig. 4 (g) and Fig. 4 (h) respectively. Both the results demonstrates that the proposed control methods produces better response in respect to performance obtained with both PID control and ABSC method.

In detail performance metrics have been tabulated in Table 1 and Table 2 to highlight the effectiveness of proposed Laguerre neural network driven ABSC scheme.

Table 1. Performance measures during start-up and reference change

Response	**Controller**	**During start-up** $v_r = 0V \rightarrow 10V$	**During reference change** $v_r = 10V \rightarrow 15V$
		t_s (s)	t_s (s)
Output v_o	ABSC	1	1.1
	Proposed	**0.5**	**0.55**

Table 2. Performance measures during load resistance and input voltage perturbations

Response	**Controller**	**during load change** $R = 20\Omega \rightarrow 10\Omega$		**during input change** $E = 20V \rightarrow 18V$	
		P_u (%)	t_s (s)	P_u (%)	t_s (s)
Output v_o	ABSC	49	1.3	10	0.4
	Proposed	**42**	**0.6**	**4**	**0.06**

5. EXPERIMENTAL RESULTS

The proposed control scheme is implemented in the laboratory by constructing a real time prototype of closed loop DC-DC step-down/buck converter. The specifications of hardware setup is provided in Table 3. The experimental arrangement is shown in Fig. 6. For the purpose of realizing the controller, DS1103 dspace based DSP TM320F240 has been utilized. The sampling interval in the hardware circuitry is set to $50\mu s$. Further an isolated voltage transducer LV-25P and Hall effect current sensor ACS-712T are employed for voltage and current sensing mechanism respectively. The experimental results are dicussed as follows.

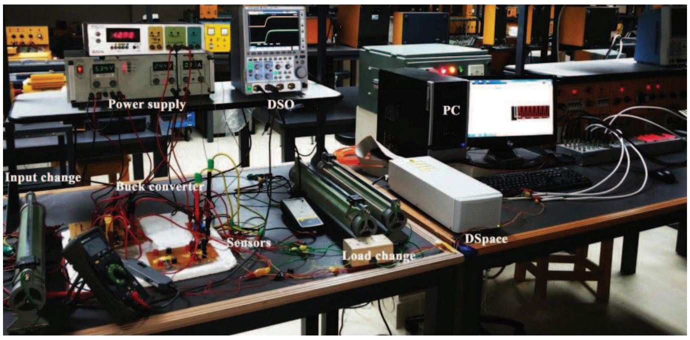


Fig. 6. Experimental hardware setup of buck dc-dc converter for validation of proposed control scheme.

The Fig. 5 shows the Gate pulses of 15V peak generated at a frequency of $20kHz$ for operating the power MoSFET in buck converter using the proposed control method. Similarly, Fig. 5 also presents the output voltage v_o and inductor current i_L response during startup of DC-DC step-down converter system using the proposed control. It can be noted that both the states yields smooth and quick start up under the effective action of the proposed Laguerre neural network assisted adaptive backstepping controller.

6. CONCLUSION

In this article, a novel Laguerre neural network driven adaptive backstepping control methodology is proposed for DC-DC step-down/buck converter system. The proposed Laguerre neural network based estimation technique

Table 3. Specifications

System parameters	**Rating**
Input DC voltage E	25V
Inductor L	$20mH$, 10A Reactor 195M10
DC Capacitor C	$220\mu F$, $450V$
Reference output voltage v_r	$10V$
Power Switch MOSFET S_w	IRFP460 500V, 18A
Power Diode D	6A4 MIC
Data Acquisition Device	CLP1103
Switching frequency f_s	20kHz
Nominal load resistance R	20Ω

provides real-time and faster online approximation of unknown and uncertain load term across wide operating range, thereby compensating it effectively in the control action. A detailed controller design has been presented along with Lyapunov stability proof. Extensive numerical simulations are conducted to exhibit the merits of proposed control over conventional adaptive backstepping and PID control methods. The obtained results are further authenticated on a laboratory prototype of closed loop step-down converter using DSP baord, which reveals that the results are in closer agreement to simulation finings. Hence, the efficacy of proposed control is proved.

7. ACKNOWLEDGEMENT

Funding in the form of the APJ Abdul Kalam Memorial International Travel Award, from the Automatic Control and Dynamic Optimization Society (ACDOS), is gratefully acknowledged.

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