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# Comparative Evaluation of Intelligent Controller for a Buck-Boost Converter

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**Abstract:** This study compares the performance of neural network controller, fuzzy logic controller and PI controller applied to a buck boost converter. The design of neural network controller is based on online learning method using Back Propagation algorithm. Design of fuzzy logic controller is based on heuristic knowledge of the converters behavior. The design of PI control is based on the frequency response of the converter. The controllers are developed to stabilize the output voltage of the converter and improve the performance of the buck-boost converter during transient operations. Simulation results obtained during load and line variations shows that the online neural network control was able to achieve faster transient response and had a stable steady state response.

**Key words:** Buck-Boost converter, fuzzy controller, neural network, PI controller, state

## INTRODUCTION

DC-DC converters find their way in many important applications that are used daily. They are been widely used in computer hardware and industrial applications. Basically, the DC-DC converters are of two types a buck converter that decreases the voltage level from an input DC source and a boost converter that increases the voltage level from an input DC source. Alternatively, a combination of buck and boost converter is the buck-boost converters which has the abilities to decrease or increase the voltage level from an input DC source. Inherently, the Buck-Boost converter is also called Non Minimum Phase (NMP) System that has a Right Half-Plane (RHP) zero (Erickson, 1991). Designing a, the control system for a non Minimum Phase System is more difficult than that for a Minimum Phase System (Siotine and Li, 1991; Arulselvi *et al*., 2004; Alvarez-Ramirez *et al*., 2001). It is necessary that designing a controller for a non minimum phase system should avoid the cancellation of unstable pole/zero to guarantee the internal stability of the Closed-Loop System. Conventionally, PI (or PID) control logic is proposed for the buck-boost converter using Root-Locus or Pole-Placement Methods (Arulselvi *et al*., 2004; Alvarez-Ramirez *et al*., 2001; Cortes *et al*., 2004; Tsang *et al*., 2008); Sreekumar and Agarwal, 2007; Ioannidis *et al*., 1998; He and Luo, 2006; Ding *et al*., 2007; Guo *et al*., 2002). However when the system parameters are uncertain these methods fail determining suitable PI (or PID) control gains. Therefore, different intelligent control techniques have been proposed to deal with the control system design for the plants with uncertain parameters (Forsyth *et al*., 1999; Tan *et al*., 2006; Wu and Mok, 2007; He and Luo, 2006).

Due to their simplicity PI and PID controller have been widely used in these converters, since they require a controller with a high degree of dynamic response. However, implementing this control method to the power converters will suffer from dynamic response of the converter output voltage regulation. In general, PI controller produces long rise time when the overshoot in output voltage decreases. In order to improve dynamic response of DC-DC buck and boost converters, several intelligence controllers such as fuzzy logic control, neural network control and hybrid neuro-fuzzy control methods have been reported by Mattavelli *et al*. (1997), Gupta *et al*. (1997), Ofoli and Rubaai (2006), Rubaai *et al*. (2005), Cheng *et al*. (2007), Leyva *et al*. (1997), Mahdavi *et al*. (2005) and Elbuluk *et al*. (1998). Simulation of the fuzzy logic control to the Buck-Boost converter has been developed by Mattavelli *et al*. (1997).

The fuzzy logic controllers are developed utilizing linguistic variable and common rule without requiring the exact model. They have shown promising result while dealing with nonlinear system by achieving good voltage regulation (Rubaai *et al*., 2005). However, they lack of formal analysis and synthesis technique (Rubaai *et al*., 2005).

Another option of intelligent control is the use of Neural Network Controllers (NNC) which is suitable for

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non-linear system and has the ability to update the internal controller parameter. NNC have been used in several DC-DC converters, power electronic and drive applications (Leyva *et al*., 1997; Mahdavi *et al*., 2005; Elbuluk *et al*., 1998; Yatim and Utomo, 2006). However, NNC lack sophisticated learning schemes. In order to improve performance of the NNC online learning schemes has been developed.

## BUCK-BOOST CONVERTER

A Buck-Boost converter is a type of step-down and step-up DC-DC converter. The output of Buck-Boost converter's output is regulated based on the duty cycle of the Pulse Width Modulation (PWM) input at fixed frequency. The output voltage of converter is less than the input voltage when the duty cycle ($d_c$) is above 0.5. However, when the duty cycle is above 0.5 the output voltage of converter is higher than the input voltage. A Buck-Boost converter's basic power stage is shown in Fig. 1. From Fig. 1, $V_I$ is input voltage source, $V_O$ is output voltage, Sw is switching component, D is diode, C is capacitance, L is inductance and R is the load resistance:

$$x(t)= A_1x(t)+B_1d_c(t) \tag{1}$$

$$v_0(t) = C_1x(t)+D_1d_c(t) \tag{2}$$

$$v_o(s) = [C_1(SI-A_1)^{-1}B_1+D_1]d_c(s) \tag{3}$$

$$x(t) = \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} \tag{4}$$

$$A_1 = \begin{bmatrix} -\dfrac{(R+r_c)r_L+Rr_c(1-D)}{(R+r_c)L} & \dfrac{R(1-D)}{(R+r_c)L} \\ -\dfrac{R(1-D)}{(R+r_c)C} & -\dfrac{1}{(R+r_c)C} \end{bmatrix} \tag{5}$$

$$B_1 = \begin{bmatrix} \dfrac{(R^2(1-D)+R(r_c+r_L)+r_cr_L)V_1}{L(r_L(R+r_c)+Rr_c(1-D)+R^2(1-D)^2)} \\ \dfrac{RDV_1}{(r_L(R+r_c)+Rr_c(1-D)+R^2(1-D)^2)C} \end{bmatrix} \tag{6}$$

$$C_1 = \begin{bmatrix} \dfrac{-Rr_c(1-D)}{R+r_c} & \dfrac{R}{R+r_c} \end{bmatrix} \tag{7}$$

$$D_1 = \frac{Rr_cDV_1}{r_L(R+r_C)+Rr_C(1-D)+R^2(1-D)^2} \tag{8}$$

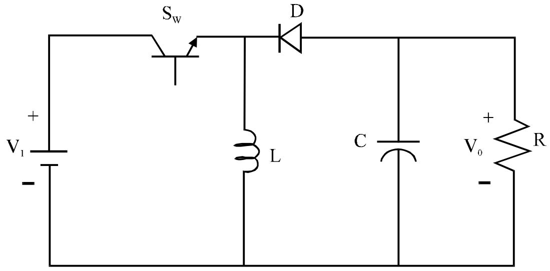

Fig. 1: Buck-Boost converter

Table 1: Parameters of buck boost converter

| SymbolS | Parameter | Values |
|---|---|---|
| L | Inductance | 220 μH |
| C | Capacitance | 220 μF |
| R | Load resistance | 20 Ω |
| V1 | Input voltage | 12 V |
| Vo | Output voltage | -24 V |

Where:

$d_c$ = The DC component of the duty cycle

$i_L(t)$ = the inductor current

$v_C(t)$ = The capacitor voltage

$i_L$ = The DC components of the inductor current

$v_C$ = The capacitor voltage

The effect of the equivalent series resistance of the inductor and the capacitor is denoted by $r_L$ and $r_C$, respectively. $V_1$ is the DC component of the input voltage. Therefore, in accordance with Eq. 8 if it is assumed for a moment that $r_L = 0$ then Eq. 9 shows the transfer function from the duty cycle to the output voltage:

$$\frac{v_0(s)}{d_c(s)} = \frac{V_{in}}{LC}\,\frac{\left(s\dfrac{LD}{R(1-D)^2}-1\right)(sCr_c+1)}{s^2+s\dfrac{L+Rr_cC(1-D)}{LRC}+\dfrac{(1-D)^2}{LC}} \tag{9}$$

In this research, $r_L = 0.2$, $r_C = 0.1$ and $D = 0.7$ then for the values shown in Table 1, the transfer function from the duty cycle to the output voltage is given by Eq. 10:

$$G_p(s) = \frac{v_0(s)}{d_c(s)} = 0.14\times\frac{(s+45455)(s-38696)}{s^2+1347.81s+4.77.10^6} \tag{10}$$

## CONTROLLER DESIGN FOR BUCK-BOOST CONVERTER

**Design of PI controller:** PI controller is designed for a buck-boost converter. The controllers can be introduced in feedback or feed forward path to control the steady state error and transient performance. In most of the practical control systems the input to the controlling device is error.

In case of PI controller the input to the controlling device is proportional as well as integral of the error function. The order of the system is increased when the system is combined with the controller. The effect of compensation on the system dynamics cannot be visualized easily. The higher the order of the system the more it becomes unstable.

Integral action remains active as long as error is present. Thus, it makes the steady state error zero so the PI controller is designed based on the frequency domain specification. The controller transfer function is given in Eq. 11:

$$G_c(s) = K_p + \frac{K_I}{s} \tag{11}$$

The phase margin $\phi_m$ at $\omega$ is determined from the settling time. Phase and magnitude response equation is given in Eq. 12 and 13:

$$\phi_m + \angle G(j\omega)H(j\omega)G_c(j\omega) = \angle 180 \tag{12}$$

$\phi_m$ is desired phase margin at $\omega$:

$$\left|G(j\omega)H(j\omega)G_c(j\omega)\right| = 1 \tag{13}$$

Solving these two Eq. 12 and 13, researchers get the $K_I$ and $K_P$ value:

$$G_c(s) = 0.087 + \frac{5}{s} \tag{14}$$

Figure 2 shows the frequency response of the system.

**Fuzzy logic controller:** Conventional controllers are derived based on the mathematical models of the system. They are characterized with design procedures and usually have simple structures. They provide satisfying results due to simple structure and hence are widely used in industries. However, when there is a variation in parameters or presence of disturbance or absence of Simple Mathematical Models, Fuzzy Logic Based Control System have shown superior performance to that obtained by Conventional Control algorithms.

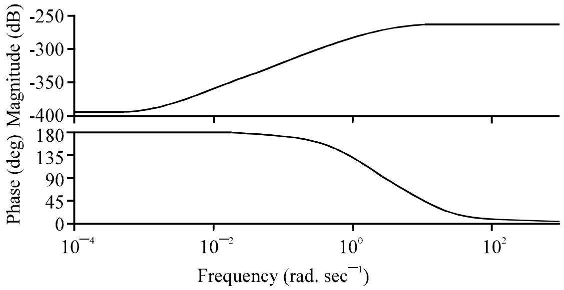

Fig. 2: Frequency response of the system

Fuzzy Systems can be considered a type of non-linear function interpolator (Viswanathan *et al*., 2005). Fuzzy logic controllers can be designed based on general knowledge and does not require an exact mathematical model of the system. Fuzzy controllers can be designed to adapt to varying operating points and has four main components the fuzzification interface that converts its input into information that the inference mechanism can use to activate and apply rules the rule base that contains the expert's linguistic description of how to achieve good control the inference mechanism that evaluates which control rules are relevant in the current situation and the defuzzification interface that converts the conclusion from the inference mechanism into the control input to the plant (Passino and Yurkovich, 1997). There are two inputs for the fuzzy controller for the Buck-Boost converters. The first input is the error in the output voltage given by Eq. 14 and second input is the change in error give by Eq. 15:

$$e = V_0 - V_{ref} \tag{14}$$

$$ce = e_k - e_{k-1} \tag{15}$$

The two inputs are multiplied by the scaling factors g0 and g1, respectively and then fed into the fuzzy controller. The output of the fuzzy controller is the change in duty cycle $\Delta d_c[k]$ which is scaled by a linear gain h. The scaling factors g0, g1 and h can be tuned to obtain a satisfactory response.

**Methods for computing the commanded duty cycle:** The new duty cycle can be calculated from the fuzzy controller's output using two methods $\Delta d_c[k]$. A block diagram model of the computing duty cycle is shown in Fig. 3. In this method, the fuzzy controller output $\Delta d_c[k]$ is scaled by the output gain h and then added to the previous sampling period's duty cycle $d_c[k-1]$:

$$d_c[k] = d[k-1] + h\Delta d_c[k] \tag{16}$$

Equation 16 represents a discrete time integration of the fuzzy controller output. Integrating the fuzzy

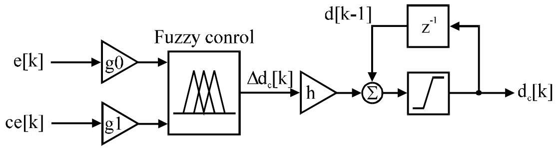

Fig. 3: Methodology of duty cycle calculation

controller's output increases the system type and reduces steady-state error. In the Fig. 3, an integrator is in series with the fuzzy logic controller while in the second structure, the integrator is in parallel with the fuzzy logic controller. Using this method the buck-boost converter's duty cycle was limited between 10 and 90%.

**Fuzzification:** Fuzzification is the first step in the design of a fuzzy logic controller and it defines membership functions for the inputs. Each universe of discourse is divided into fuzzy subsets. There are 7 fuzzy subsets in the fuzzy controller for the Buck-Boost converter: {NL, NB, NS, Z, PS, PB, PL} where, N indicates negative, Z represents zero and P indicates positive. Of the 7 subsets, there are three subsets for the positive and negative parts of the universe of discourse, respectively. The number of fuzzy subsets was determined based on the experimental results of converters.

There are tradeoffs when selecting the number of fuzzy subsets as well as the shape of membership functions. There has been significant research into the impact of membership function shape on control system performance (Shi and Sen, 2000; Cheng *et al.*, 2007). In order to minimize computational complexity a triangular membership functions is used in this study.

**Rule base:** The rule base is derived from general knowledge of buck-boost converter behavior and is adjusted based on experimental results. There is a tradeoff between the size of the rule base and the performance of the controller. A 7×7 rule base was also designed and implemented for the converter. Experimental results indicate that the fuzzy controller with a 49×49 rule base exhibit less oscillation during steady state and faster transient response was achieved by increasing the output gain h (Guo *et al.*, 2005). For the same universe of discourse, more membership functions result in finer control. The output of the controller had less variation for small changes in both input and a more accurate control was achieved therefore, oscillation in the output voltage and duty cycle was reduced (Passino and Yurkovich, 1997).

**Inference mechanism:** The results of the inference mechanism include the weight factor $w_i$ and the change in duty cycle $c_i$ of the individual rule (Gupta *et al.*, 1997). The weight factor $w_i$ is obtained by Mamdani's min fuzzy implication of $\mu_e(e[k])$ and $\mu_{ce}(ce[k])$ where $w_i = \min\{\mu_e(e[k]), \mu_{ce}(ce[k])\}$ and $\mu_e(e[k])$, $\mu_{ce}(ce[k])$ are the membership degrees (Gupta *et al.*, 1997). Control $c_i$ is taken from the rule base. The change in duty cycle inferred by the ith rule $z_i = w_i \times c_i$ is given by:

$$z_i = \min\{\mu_e(e(k)), \mu_{ce}(ce[k])\} x c_i \tag{17}$$

**Defuzzification:** The center of average method is used to obtain the fuzzy controller's output which is given in Eq. 18 where N is the number of rules that are active (Passino and Yurkovich, 1997):

$$\Delta d_c[k] = \frac{\sum_{i=1}^{N} z_i}{\sum_{i=1}^{N} w_i} \tag{18}$$

## Neural network conntroller

### Structure of Neural Network Controller (NNC):

Neural network controllers are controllers that provide better stabilization. To design the neural network control, some information about the plant is required. In this research, an Online base Neural Network Controller (OLNNC) is proposed. The structure of the proposed neural network control of a Buck-Boost converter is as shown in Fig. 4. Based on the number of neurons in each layer of the proposed OLNNC architecture, the network has a 2-3-1 structure. In the input layer consists of two input neurons. The first input neuron is error signal between desired signal and actual signal. The second input neuron is difference between previous error signal and current error signal.

The connections weight parameter between jth and ith neuron at mth layer is given by $w_{ij}$ while bias parameter of this layer at ith neuron is given by $b_i^m$. Transfer function of the network at tth neuron in mth layer is defined as:

$$n_i^m = \sum_{j=1}^{s^{m-1}} w_{ij} a_j^{m-1} + b_i^m \tag{19}$$

The output function of neuron at mth layer is given by:

$$a_i^m = f^m(n_i^m) \tag{20}$$

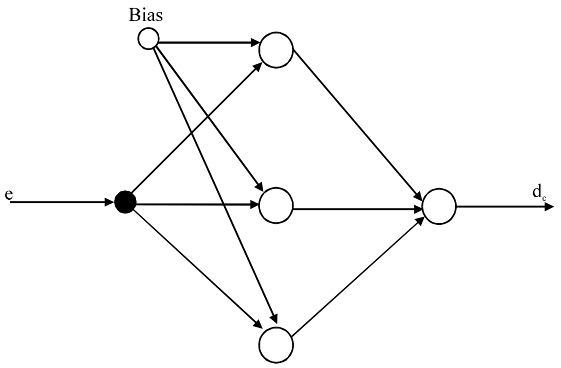

Fig. 4: Architecture of ONNC

where, f is the activation function of the neuron. The output layers uses unity activation function and the hidden layers use a tangent hyperbolic function. The activation function of the hidden layer is given in Eq. 21:

$$f^m(n_i^m) = \frac{2}{1+e^{-2n_i^m}} - 1 \tag{21}$$

The updating of the connection weight and bias parameters are given by Eq. 22 and 23:

$$w_{ij}^m(k+1) = w_{ij}^m(k) - \alpha\frac{\partial F(k)}{\partial w_{ij}^m} \tag{22}$$

$$b_i^m(k+1) = b_i^m(k) - \alpha\frac{\partial F(k)}{\partial b_i^m} \tag{23}$$

Where:

k = Sampling time
α = Learning rate
F = Performance index function of the network

**Online learning algorithm of BPOLNNC:** After the modeling of neural network architecture, the next stage is defining the learning model to update network parameters. This learning capability makes the ANN suitable to be implemented for the systems whose parameters which are difficult to define and vary with environment. The training process minimizes the error output of the network through an Optimization Method. Generally, in learning mode of the neural network controller a sufficient training data and input-output mapping data of a plant is required (Fig. 5).

The networks parameter updated based on the first order optimization scheme. The performance index sum of square error is given by:

$$F(k) = \frac{1}{2}\sum_i e_i^2(k) \tag{24}$$

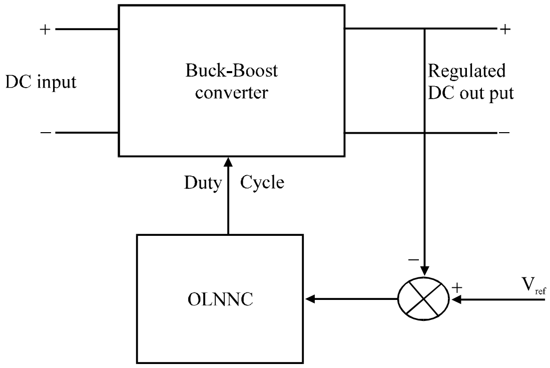

Fig. 5: BPOLNNC Model

$$e_i(k) = t_i(k) - a_i(k) \tag{25}$$

Where:

$t_i$ = Target signal
$a_i$ = Output signal of the last layer

The gradient descent of the performance index against the connection weight is given by:

$$\frac{\partial F}{\partial w_{ij}^m} = \frac{\partial F}{\partial n_i^m}\frac{\partial n_i^m}{\partial w_{ij}^m} \tag{26}$$

The sensitivity parameter of the network is defined as:

$$S_i^m = \frac{\partial F}{\partial n_i^m} \tag{27}$$

$$S_i^m = \frac{\partial F}{\partial a_i^m}\frac{\partial a_i^m}{\partial n_i^m} \tag{28}$$

Gradient of the transfer function again to the connection weight parameter is given by:

$$\frac{\partial n_i^m}{\partial w_{ij}^m} = a_i^{m-1} \tag{29}$$

From substituting Eq. 27 and 29 into Eq. 22 the updating connection parameter is given by:

$$w_{ij}^{m-1}(k+1) = w_i^{m-i}(k) - \alpha s_i^m(k) a_i^{m-1}(k) \tag{30}$$

With the same technique the updating bias parameter is given by:

$$b_i^{m-1}(k+1) = b_i^{m-i}(k) - \alpha s_i^m(k) \tag{31}$$

The DC input is given to the Buck-Boost converter. The measured output and difference in output and $V_{ref}$ (error) is send to the neural network. Based on the error the neural network will adjust the duty cycle of the converter.

## EXPERIMENTAL RESULTS

Experimental results of the Buck-Boost converter using PI controllers, the fuzzy controller and online neural network controller are presented and compared in this study. Experimental results including transient responses during startup and load changes under different input voltages are evaluated and compared. The experimental results are obtained from Matlab Simulation.

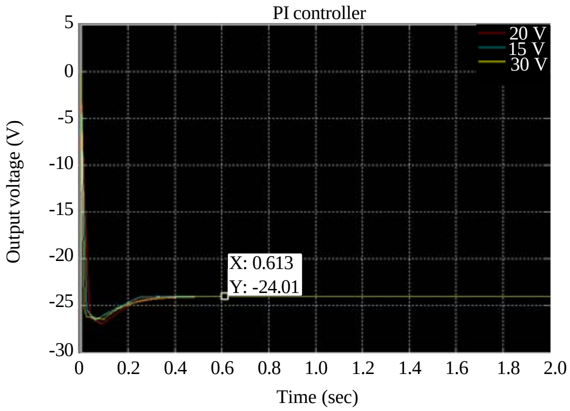

Fig. 6: Buck converter performance under PI control

For the experiment, the model Buck-Boost converter's input voltage was 12 V, the output voltage was -24 V and the nominal duty cycle was 66%. Startup transient response was evaluated voltage variation from 15-30 V. Transient response of load for 100% load increase (from 0.50-0.98 A) and 50% load decrease (from 0.98-0.50 A) were also evaluated for various input voltages in the range of 15-30 V.

**Experimental results of Buck-Boost converter using PI control:** The transient response obtained using the PI controller is shown in Fig. 6. The settling time at the nominal input voltage of 12 V was about 0.5 sec with about 8% overshoot. Both the settling time and overshoot increased when the input voltage increased from 15-30 V.

**Experimental results of Buck-Boost converter using fuzzy control:** The transient response when the input voltage varied from 15-28 V is shown in Fig. 7. The settling time at the nominal input voltage of 12 V was about 0.14 sec with about 0.4% overshoot. When the input voltage increased from 15-30 V, the settling time remained the same. The overshoot increased when the input voltage increased from 15-30 V.

**Experimental results of Buck-Boost converter using ANN control:** The transient response when the input voltage varied from 15-30 V is shown in Fig. 8. The settling time at the nominal input voltage of 12 V was about 0.4 sec with about 0.01% overshoot. When the input voltage increased from 15-30 V, the settling time remained the same. The overshoot increased when the input voltage increased from 15-30 V.

**Comparison of experimental results of the Buck-Boost converter using PI controller and fuzzy controller ONNC:** From the experimental result ONNC and fuzzy logic controller settles very fast when compared with PI controller which take more time to settle. However, the overshoot is very less when using ONNC which is an advantage when compare to the other controllers. During the load and line variation Fuzzy, ONNC controllers produce better results.

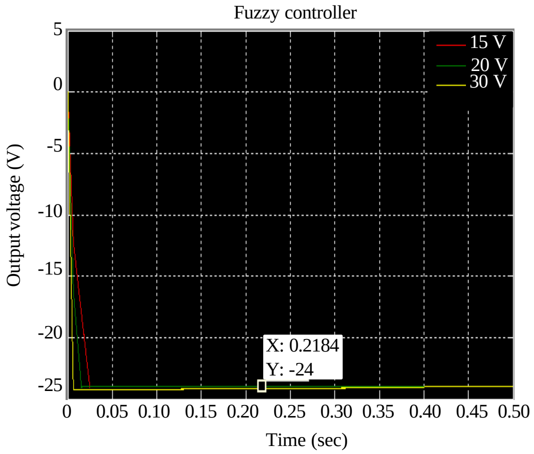

Fig. 7: Buck converter performance under fuzzy control

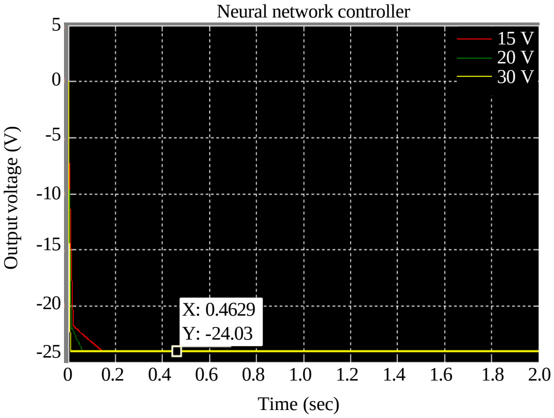

Fig. 8: Buck converter performance under PI control

## CONCLUSION

PI controllers, fuzzy controllers and online neural network controller were designed and implemented for a Buck-Boost converter. The linear controllers were designed for the converters using frequency response techniques. The PI controller was applied during steady state to achieve stable steady-state response. NNC was designed using online learning based on Back Propagation algorithm. The fuzzy controllers were designed based on in-depth knowledge of the plant, computer simulations and experimental results. The experimental results for the PI, ONNC and fuzzy controller were compared. Experimental results showed that fast transient response and stable steady-state responses could be achieved for the buck-boost converter using neural, fuzzy controllers. However, neural network controller settles fast with less overshoot when the line and load variation occurs.

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