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Comparative Study on Performance of Boost Converter with Fuzzy Logic and Adaptive TSK-type Neural Fuzzy Controllers

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Abstract

DC-DC converters are used to attain regulated DC output voltage against variable load resistance and unstable DC input voltage. The application of DC-DC Boost converters are growing wide in the many areas (eg: HEV, domestic inverter etc). Different methods are used to regulate the output voltage of Boost converter. Conventionally, PID controllers are normally used, which experiences a serious limitation of sensitivity to disturbances and system non-linearity.

In this paper, to obtain superior controller for Boost converter, Fuzzy Logic Controller (FLC) and an intelligent Adaptive TSK-type Neural fuzzy Controller (ATNC) is designed and simulation results are compared. Finally, the simulation results show that the proposed ATNC scheme provides better output voltage tracking with minimal overshoot and settling time over fuzzy controllers.

Keywords: Boost converter,Hybrid Electric Vehicle (HEV), Proportional–Integral–Derivative (PID), Adaptive TSK-type Neural fuzzy Controller (ATNC) , Fuzzy Logic Control (FLC).

INTRODUCTION

DC-DC converters are found tremendous applications due to the wide use of electronic equipments (eg: Computer, Ceiling elevator, Mine excavations) and utilization of renewable energy sources (eg: HEV). DC-DC converters are used to attain regulated DC output voltage against variable load resistance and unstable DC input voltage. In computer, 1.5V from single cell must be stepped up using Boost converter to 5V or more to operate various electronic circuitries. Toyota model HEV uses a 500V motor, which needs nearly 417 cells. The number of cells used can be reduced to 168 cells, by introducing the Boost converter circuitry which step-up 202 V from 168 cells to 500V.

Small signal model is usually adopted for the design of controller for Boost converter [1, 2]. Since this model is not applicable in case of system with non-linearity, more efficient state space modeling approach is adopted in this paper. The main role of controller for Boost converter is to regulate the output voltage and improved efficiency even though there is variation in input voltage and load conditions (output current). Most of papers have concentrated on design of PID controller [3, 4] and its tuning is performed using Ziegler-Nichols method. In this paper, performance of Fuzzy Logic Controller (FLC) and Adaptive TSK-type Neural fuzzy Controller (ATNC) in controlling Boost converter is compared in terms of performance metrics such as damping ratio and settling time. ATNC is a fusion of the Human–like thinking capability of the Fuzzy Inference System and Learning ability of Neural network, thereby incorporating the abilities for learning and adaptation of neural networks with Fuzzy system. Here, the error between output of converter and its reference value are used to tune the input membership function parameters of FLC and ATNC; then propagating the same back into the controller. Both FLC and ATNC offers more computing advantages by eliminating the construction of complex mathematical models, thereby decreasing the computational time needed. Performance of proposed controllers for Boost DC-DC converter is analyzed from simulation results for different line and load conditions by measuring its settling time.

This paper is organized into the five sections. Following the Introduction, the description of the circuit frame work of a DC-DC Boost converter and system modeling is introduced in Section II. Section III describes the design procedure of FLC and ATNC controller. In section IV, simulation results are studied. Finally, the conclusion is drawn in section V.

MODELLING OF BOOST CONVERTER

Boost converter is a DC-DC power converter basically for stepping –up the input voltage at the load end. The conventional framework of Boost converter is as displayed in Fig.1, fundamentally accommodates two switches (mostly a diode and a transistor) and single energy storage component. Capacitors are fundamentally included as filter to the output stage of boost converter in the interest to eliminate the ripples of output voltage.

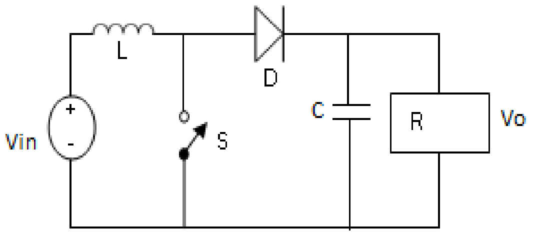


Figure 1: Conventional Boost Converter framework

For modeling the Boost converter, state- space averaging method is used and differential equations for both ON and OFF modes are composed. In ON mode, switch S is closed which increases the inductor current and the corresponding circuit is manifested in Fig. 2 (a). Eq (1) and (2) are the written by using KVL and KCL from Fig. 2(a).

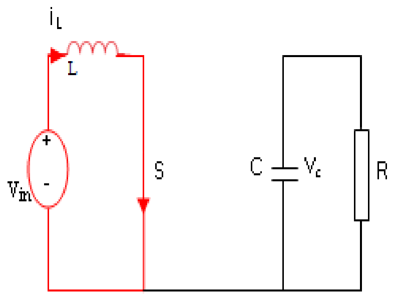


Figure 2(a). Boost Converter circuit during ON state

$$v_{in} - L\, di_L / dt = 0 \tag{1}$$

$$v_c / R + C\, dv_c / dt = 0 \tag{2}$$

During OFF mode, switch S is made open which results in the flow of inductor current through the diode 'D' and the parallel arrangement of capacitor and load, shown as in Fig. 2 (b). Eq (3) and (4) are the written by using KVL and KCL from Fig. 2(b)

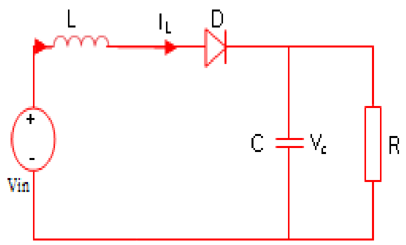


Figure 2(b). Boost Converter circuit during OFF state

$$v_{in} - v_c - L\, di_L / dt = 0 \tag{3}$$

$$i_L - v_c / R + C\, dv_c / dt = 0 \tag{4}$$

State space representation is as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/R_C \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_{in} \tag{5}$$

Here $x_1 = i_L$ is the average inductor current and $x2 = v_c = v_o$ is the average output voltage.

DESIGN PROCEDURE OF CONTROLLERS

Design Procedure of Fuzzy Logic Controller

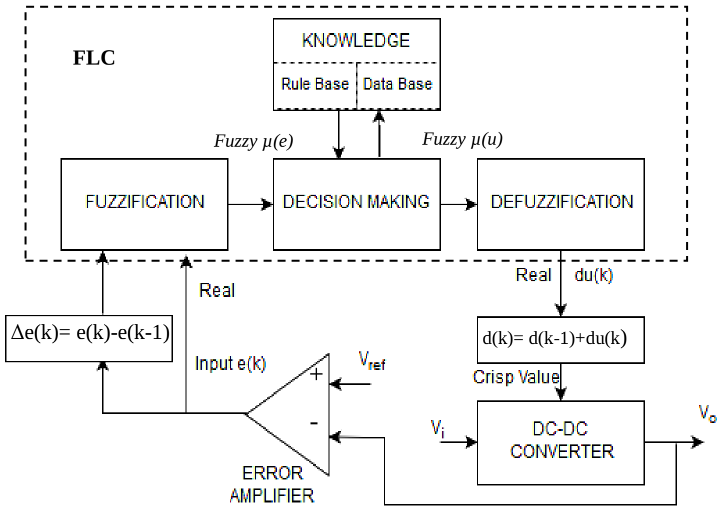


Figure 3: Conventional Fuzzy Logic Controller

The conventional FLC shown in Fig: 3 perform of the following process:

Identification of Inputs and Outputs

In this step, design analyses the fundamental inputs that influence efficiency of the system. Here it is important to make sure that the voltage output (V_0) is same as that of reference voltage (V_{ref}). The controller is fed with the following inputs:

1) The error '*e*' in the output voltage of Boost converter given by Equation (6),

$$e[k] = V_{ref} - V_o \tag{6}$$

Where 'V_0' is actual output voltage of DC–DC converter at the k^{th} sampling time, 'V_{ref}' is reference output voltage.

2) The variation of successive errors denoted by '$\Delta e[k]$' and is given by Equation (7)

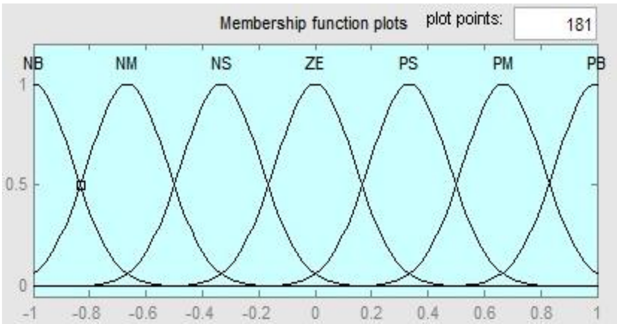
$$\Delta e[k] = e[k] - e[k-1] \tag{7}$$

The two inputs are then fed into the fuzzy controller. The output of the controller is change the duty cycle '*du(k)*'. Duty ratio '*d(k)*', at the k^{th} sampling time is calculated by adding the fuzzy controller output '*du(k)*' to the previous sampling period's duty cycle '*d[k−1]*'

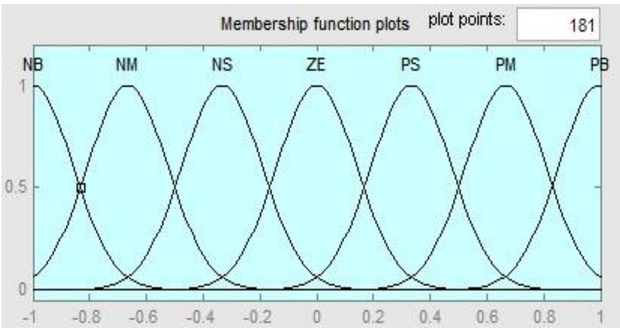
$$d[k]=d[k-1]+du[k] \quad (8)$$

Fuzzifying the Inputs and Outputs

Each universe of discourse is partitioned into fuzzy subsets. In this paper, there are 7 fuzzy subsets in the fuzzy controller for the boost converter: {NB, NM, NS, Z, PS, PM, PB}. The membership function for inputs '$\mu(e)$' and '$\mu(\Delta e)$' is the Gaussian one shown in Figure 4.



Membership function for $\mu(e)$



Membership function for $\mu(\Delta e)$

Figure 4: Membership functions for $\mu(e)$ and $\mu(\Delta e)$

Advancement of rule base

The rule base is derived from general knowledge of dc–dc converter behavior, and is adjusted based on experimental results. A 7 × 7 rule base was also designed and implemented for the boost converter. Rule Base is normally expressed as a set of Fuzzy Linguistic rules and can be expressed as:

Rule 1: If e is A_1 and Δe is B_1, then $du = p_1 e + q_1 \Delta e + r_1$

Rule 2: If e is A_1 and Δe is B_2, then $du = p_2 e + q_2 \Delta e + r_2$

.

.

Rule 49: If e is A_7 and Δe is B_7, then $du = p_{49} e + q_{49} \Delta e + r_{49}$

Where $A_1, A_2 \ldots A_7$ and $B_1, B_2 \ldots B_7$ are the fuzzy sets in the antecedent and $p_1, p_2, \ldots p_{49}$; $q_1, q_2, \ldots q_{49}$; $r_1, r_2 \ldots r_{49}$ are the design parameters which are decided in course of the training process. The net output (*du*) is the weighted average of each output rules.

Each universe of discourse is divided into seven fuzzy subsets: PB (Positive Big), PM (Positive Medium), PS (Positive Small), Z (Zero), NS (Negative Small), NM (Negative Medium) and NB (Negative Big).

The set of fuzzy rules normally can be summarized in a table as shown in Table. 1.

Table 1: Rule Table for a FLC & ATNC to calculate *du(k)*

Error

Change of Error: de \ e	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z
NM	PB	PB	PB	PM	PS	Z	NS
NS	PB	PB	PM	PS	Z	NS	NM
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NB	NB	NB
PB	Z	NS	NM	NB	NB	NB	NB

Inference Mechanism

The inference result of each rule consists of two parts, the weighting factor, w_i, of the individual rule, and degree of change in duty ratio *Ci*, according to the rule. The weighting factor w_i is obtained by means of Mamdani's MIN fuzzy implication of membership degrees $\mu_e(e)$ and $\mu_{\Delta e}(\Delta e)$, C_i is retrieved from control rule table. The inferred output of each rule using Mamdani's MIN fuzzy implication is written as:

$$w_i = min\{\mu_e(e), \mu_{\Delta e}(\Delta e)\} \ldots\ldots(9)$$

The change in duty cycle inferred by the i[th] rule:

$$z_i = w_i \times c_i \ldots.(10)$$

Since the inferred output is a linguistic result, a defuzzification operation is performed next to obtain a crisp result.

Defuzzification

The last component of FLC is defuzzification. Several defuzzification methods have been proposed [11,12]. They are Center of Area (COA), Center of Sum (COS), Height Method (HM), Mean of Maxima (MOM), Center of Largest Area (COLA), and First of Maxima (FM) and Height Weighted Second Maxima (HWSM). Mean of Maxima (MOM) method is used in this paper.

Design Procedure of ATNC Controller

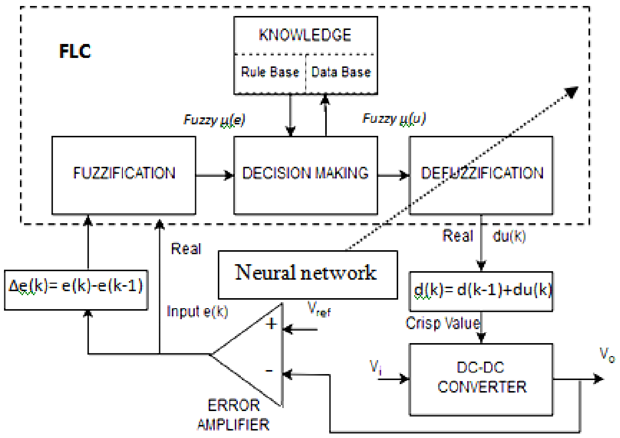


Figure 5: Block diagram of ATNC for Boost converter

Boost converter is designed subjected to the state space average model given in Eq (5). By merging the concept of Fuzzy and Neural system, an intelligent Adaptive TSK-type Neural fuzzy controller is designed for Boost DC-DC converter and is presented in Fig.5.

The proposed five-layered ANFIS structure [18-20] is as shown in Figure 6.

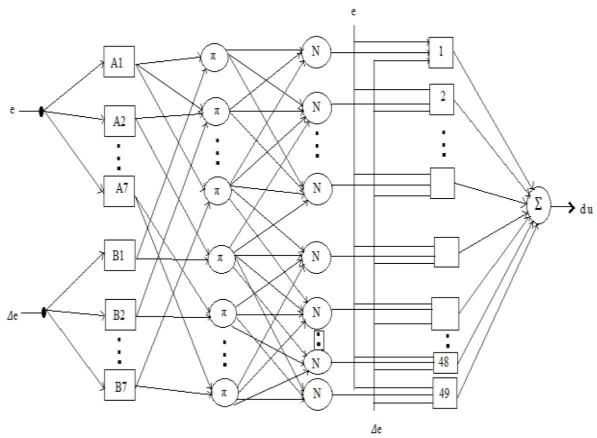


Figure 6: Architecture of five layered Adaptive TSK-type Neural Fuzzy Controller (ATNC)

Layer 1 (Fuzzification layer): Fuzzification operation is executed by individual nodes in this layer by utilizing the Membership Function. Here in this paper, fuzzy membership function is represented by Gaussian membership function and can be formulated by:

$$O_i^1 = \mu_{Ai}(e) = exp\left(\frac{-(e-c_{ij})^2}{\sigma_j^2}\right) \quad (11)$$

$$O_i^2 = \mu_{Bi}(\Delta e) = exp\left(\frac{-(\Delta e-c_{ij})^2}{\sigma_j^2}\right) \quad (12)$$

Where i=1, 2,….7; j=1, 2…7 and c_{ij} is the center of the membership function.

Layer 2 (Rule Interface layer): Individual node in rule interface layer depicts its fuzzy rule and functions. Firing strength of individual node can be formulated by an algebraic product operation with intakes from preceding zone.

$$O_i^2 = \omega_i = \mu_{Ai}(e) \,.\, \mu_{Bi}(\Delta e) \quad (13)$$

Where i=1,2,….7.

Where $\mu_{Ai}(e)$ and $\mu_{Bi}(\Delta e)$ symbolizes the fuzzy membership function of error and change in error.

Layer3 (Normalization Layer): This layer's nodes enumerate the normalized firing strength of each rule.

$$O_i^3 = \overline{\omega_i} = \frac{\omega_i}{\sum \omega_i} \quad (14)$$

Where i= 1,2…..49 and ω_i =firing strength of a rule.

Layer 4 (Consequent Layer): This layer's node outputs the weighted consequent part of the rule table.

$$O_i^4 = \varpi_i u_{ci} = \varpi_i (p_i e + q_i \Delta e + r_i) \quad (15)$$

Where i= 1,2…49 and $\{p_i,q_i,r_i\}$ is the parameter set of this node.

Layer 5 (Output layer): This layer estimates the final output by the interaction to single output linguistic variable. The outcome of ATNC model is the change in duty cycle can be represented as:

$$O_i^5 = = \frac{\sum \omega_i u_{ci}}{\sum \omega_i} \quad (16)$$

Where i=1,2,…49

Specification of ATNC structure implemented in the proposed paper is tabulated as in Table 2.

Table 2: Specifications of Proposed ATNC

Parameters	Description/Value
Fuzzy structure	Sugeno-type
MF type	Gaussian
Output MF	Linear
Number of inputs	2
Number of outputs	1
Number of fuzzy rules	49

SIMULATION RESULTS AND DISCUSSION

Control System Setup

The performance of proposed Boost Converter control is now examined by simulations using MATLAB 2011a with a 3MHz processor. The framework of the proposed Boost converter controlled by both FLC and ATNC is shown in Fig. 6.The specification for the 25V, 50W Boost converter is tabulated in Table 3. The Boost converter was designed for an output voltage of 25V with input line voltage varying from 8V to 20Vand load variations from 10Ω to 100 Ω.

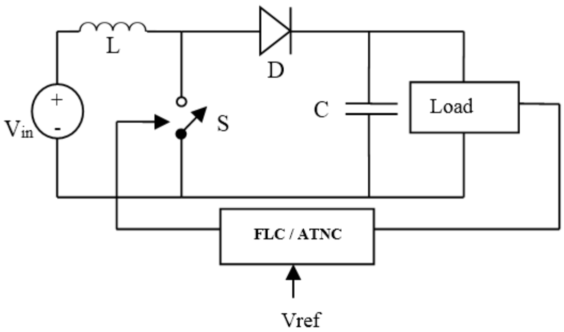


Figure 7: ATNC for controlling Boost Converters

Table 3: Specification of Boost Converter

Circuit Components	**Values**
Input Voltage , V_{in}	8 – 20 V
Output Voltage, V_o	25V
Inductor, L	275μH
Capacitor , C	540μF
Load Resistance, R_{load}	10Ω to 100 Ω

From the simulations, the boost converters initiates from the zero state and are depicted to validate the successfulness of the proposed ATNC controller over FLC. Examination of output voltage versus time simulation graph as in Fig. 8 to 17 is executed to summaries the Table 4 and compared the following:

i) Peak Overshoot

ii) Settling Time

Simulation Results

The simulation of the proposed system computed the control signal '*du(k)'* from the two input signals:- error signal '*e(k)'* and change in error signal 'Δ*e(k)'* and is displayed in Fig. 8.

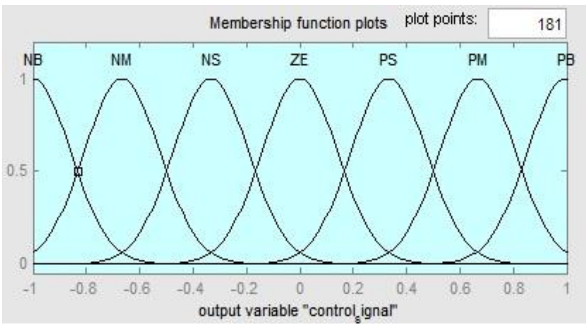


Figure 8: Membership function of the control signal, *du(k)*

In the proposed work, simulation outputs were executed for different line and load conditions. Different line and load conditions are obtained by varying the supply input from 8V to 20V and load resistance from 10 Ω to 100 Ω respectively. Simulation outputs are correlated and tabulated in Table 4 by analyzing the outcomes furnished in Fig. 9 to 18.

Case 1: Minimum Line and Maximum load condition

Variation of output voltage of boost converter with time for both FLC and ATNC in the stipulated settings: V_s= 8V and I_o = 2.5A is demonstrated in Fig. 9 and 10 respectively.Here the effectiveness of ATNC are compared to FLC and is found that for minimum line and maximum load condition, the ATNC controller acts very effectively in reducing the settling time and peak over shoot to 66% and 2.5% respectively as compared with FLC and is tabulated in Table 4.

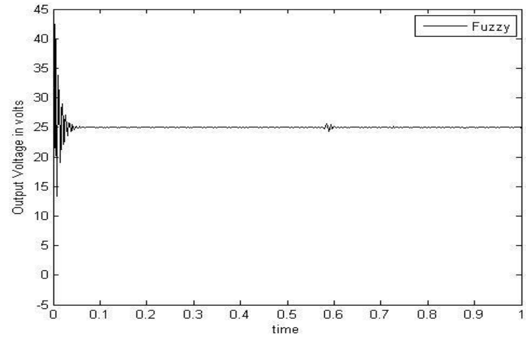


Figure 9: Output Voltage for Minimum Line and Maximum load condition of FLC controlled Boost converter

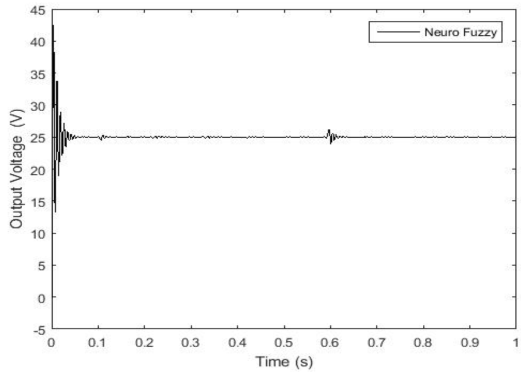


Figure 10: Output Voltage for Minimum Line and Maximum load condition of ATNC controlled Boost converter

Minimum Line and Light load condition

Variation of output voltage of boost converter with time for both FLC and ATNC in the stipulated settings: V_s= 8V and I_o = 0.5A is demonstrated in Fig. 11 and 12 respectively. Here the effectiveness of ATNC is compared to FLC and is found that for minimum line and light load condition, the ATNC controller acts very effectively in reducing the settling time and peak over shoot to 20% and 3.3% respectively as compared with FLC and is tabulated in Table 4.

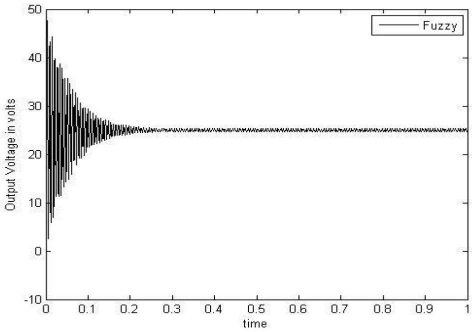


Figure 11: Output Voltage for Minimum Line and Light load condition of FLC controlled Boost converter

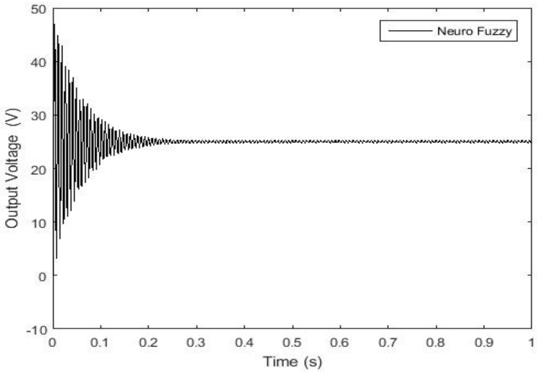


Figure 12: Output Voltage for Minimum Line and Light load condition of ATNC controlled Boost converter

Midrange Line and Midrange Load condition

Variation of output voltage of boost converter with time for both FLC and ATNC in the stipulated settings: V_s= 12V and I_o = 0.9A is demonstrated in Fig. 13 and 14 respectively. Here the effectiveness of ATNC is compared to FLC and is found that for midrange line and midrange load condition, the ATNC controller acts very effectively in reducing the settling time and peak over shoot to 46% and 1.7% respectively as compared with FLC and is tabulated in Table 4.

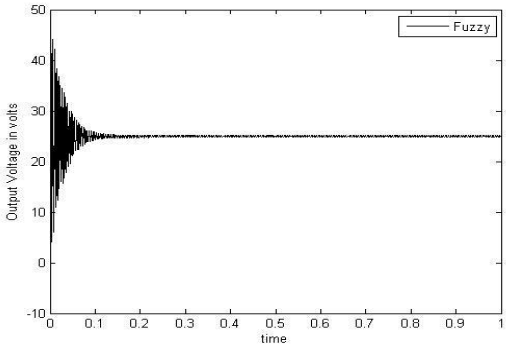


Figure 13: Output Voltage for Midrange Line and Load condition of FLC controlled Boost converter

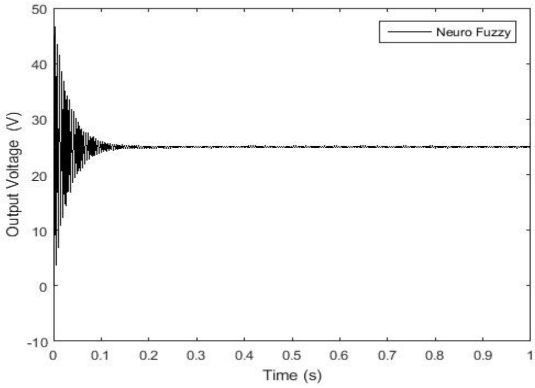


Figure 14: Output Voltage for Midrange Line and Load condition of ATNC controlled Boost converter

Maximum Line and Maximum load condition

Variation of output voltage of boost converter with time for both FLC and ATNC in the stipulated settings: V_s= 20V and I_o = 2A is demonstrated in Fig. 15 and 16 respectively. Here the effectiveness of ATNC is compared to FLC and is found that for maximum line and maximum load condition, the ATNC controller acts very effectively in reducing the settling time and peak over shoot to 66% and 0.7% respectively as compared with FLC and is tabulated in Table 4.

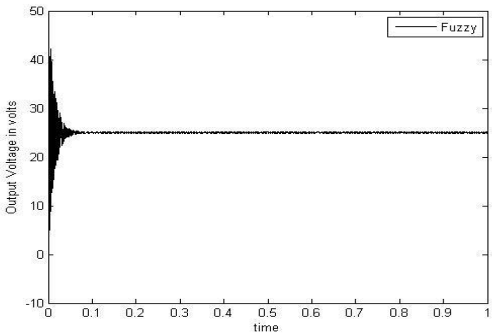


Figure 15: Output Voltage for Maximum Line and Maximum load condition of FLC controlled Boost converter

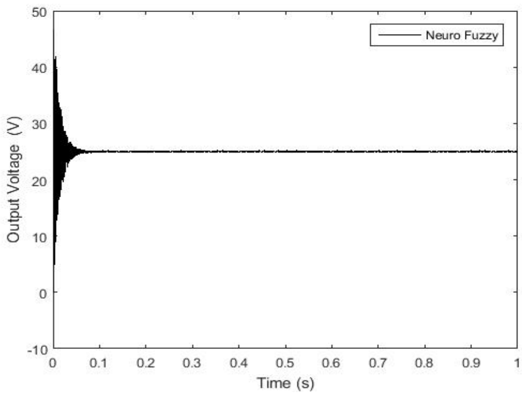


Figure 16: Output Voltage for Maximum Line and Maximum load condition of ATNC controlled Boost converter

Maximum Line and Light Load condition

Variation of output voltage of boost converter with time for both FLC and ATNC in the stipulated settings: V_s= 20V and I_o = 0.5A is demonstrated in Fig. 17 and 18 respectively. Here the effectiveness of ATNC is compared to FLC and is found that for maximum line and light load condition, the ATNC controller acts very effectively in reducing the settling time and peak over shoot to 28% and 2.4% respectively as compared with FLC and is tabulated in Table 4.

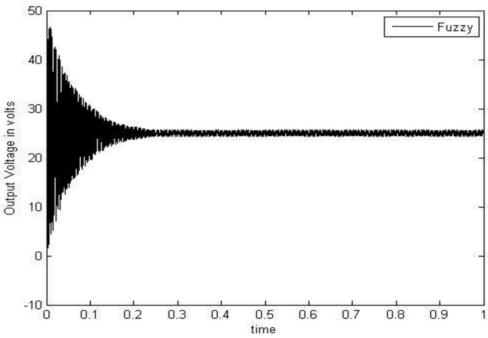


Figure 17: Output Voltage for Maximum Line and Light Load condition of FLC controlled Boost converter

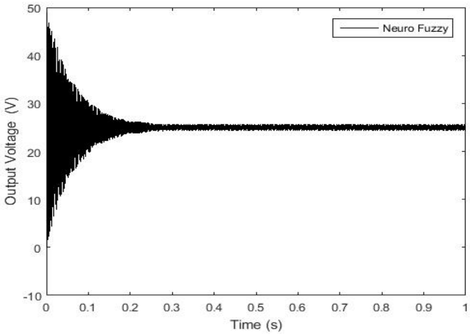


Figure 18: Output Voltage for Maximum Line and Light Load condition of ATNC controlled Boost converter

Superior controlling action of ATNC in Boost converter system is achieved by varying the duty ratio of switch, S. Simulated the duty ratio obtained in different line and load conditions and is illustrated in Fig.19 -23.

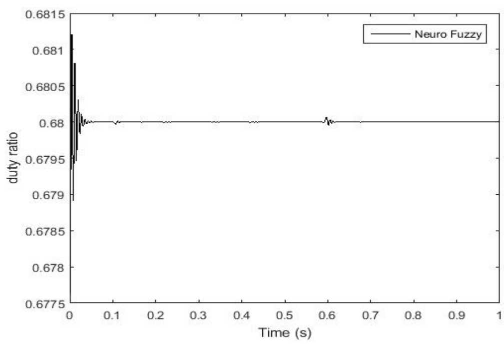


Figure 19: Duty Ratio for Minimum Line and Maximum Load condition of ATNC controlled Boost converter

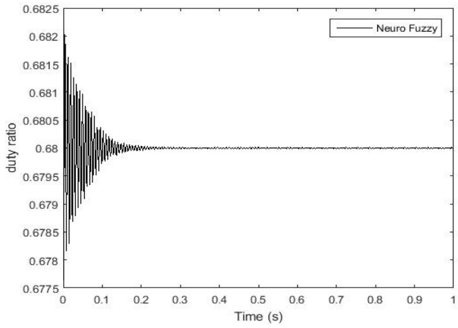


Figure 20: Duty Ratio for Minimum Line and Light Load condition of ATNC controlled Boost converter

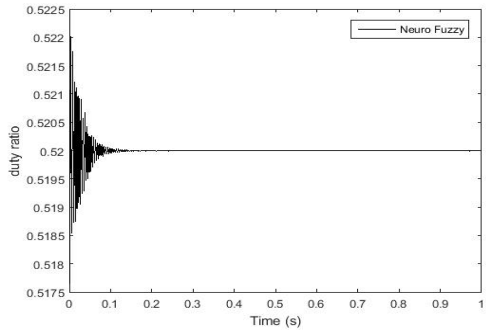


Figure 21: Duty Ratio for Midrange Line and Load condition of ATNC controlled Boost converter

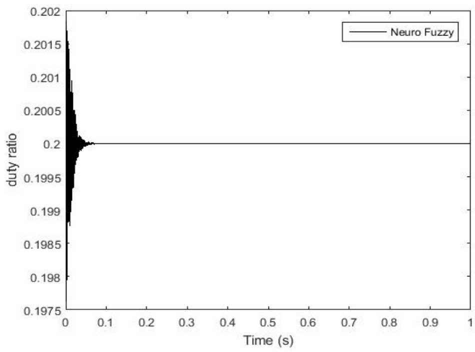


Figure 22: Duty Ratio for Maximum Line and Maximum load condition of ATNC controlled Boost converter

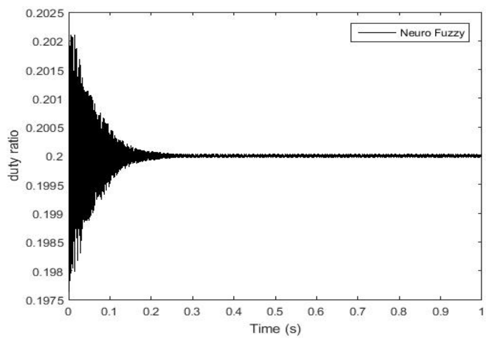


Figure 23: Duty Ratio for Minimum Line and Light Load condition of ATNC controlled Boost converter

Simulation results for both FLC and ATNC for different line and load conditions are summarized as shown in Table 4.The simulation outcomes of proposed FLC and ATNC is compared and testified that the settling time and percentage peak overshoot of ATNC is declined to a maximum of 66% and 3.3% respectively than that for Fuzzy controllers. The proposed system by fusing humanitarian capability to judge adopted in fuzzy inference system and training capability adopted in neural network operates efficiently as related to conventional systems. From the simulation under different line and load conditions, there is an oscillation in the converter's output voltage and is under damped in the proposed ATNC system.

Table 4: Simulation Results for Various Line and Load Settings

Cases	**Damping Ratio(δ)/ Damping Type**	**FLC**		**ATNC**	
		Peak Overshoot (%)	**Settling Time Ts (s)**	**Peak Overshoot (%)**	**Settling Time Ts (s)**
Minimum Line and Maximum load condition	0.103 (Under Damped)	43.7	0.15	42.49	0.05
Minimum Line and Light load condition	0.026 (Under Damped)	48.5	0.25	46.98	0.20
Midrange Line and Load condition	0.087 (Under Damped)	47.3	0.15	46.70	0.13
Maximum Line and Maximum load condition	0.121 (Under Damped)	47.5	0.15	46.63	0.08
Maximum Line and Light Load condition	0.04 (Under Damped)	49	0.27	48.40	0.2

CONCLUSION

In the proposed work, a Fuzzy Logic Controller(FLC) and Adaptive TSK-type Neural fuzzy Controller (ATNC) is devised to control the DC-DC Boost converter and simulation results are executed to empower its performance comparison. The proposed ATNC controller made the entire system less oscillatory even in increasing the load and results superior performance in all operating conditions. Simulation results demonstrate that Boost converter controlled using ATNC is more effective in lessening the impact of exterior disturbances like variation of input voltage and load resistance. The ATNC gives smaller overshoot and settling time at the time of parameter variation and has superior performance compared to FLC.

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