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Design and Development of Neural Fuzzy Controller for Boost Dc - Dc Converters

Neethu Raj.R[1] , P.Sreejaya[2], N.Albert Singh[3]

[1]*Assistant Professor, Dept. of Electronics & Communications, Heera College of Engineering & Technology, Trivandrum, Kerala, India.*

[2]*Professor, Dept. of Electrical Engineering, College of Engineering, Trivandrum, Kerala, India.*

[3]*Executive, Bharat Sanchar Nigam Limited, Nagercoil, Tamil Nadu India.*

Abstract

DC-DC converters are used to attain regulated DC output voltage even though there is variation in load resistance and DC input voltage. The application of DC-DC Boost converters are growing wide in the many areas (eg: HEV, domestic inverter etc). Conventionally, research papers are mainly concentrated on PID controllers in order regulate the output of Boost converter and suffered limitations such as severe system non-linearity, sensitivity to disturbances etc. The practical challenge in regulating the outcome of Boost converter necessitates the design of advanced control strategies to tackle the nonlinearity and stability. For this, it has been implemented in numerous control methods, which include: Fuzzy Logic Controller, Neural Network controller etc.

An intelligent Adaptive TSK-type Neural Fuzzy Controller (ATNC), a fusion of both fuzzy logic and TSK- type neural network is designed in this paper for the control of DC-DC Boost converter. Simulation of the proposed ATNC scheme for Boost converter contributes superior output voltage regulation with slightest overshoot, settling time and smaller error parameters over conventional Fuzzy Logic Controller.

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 [1] 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 devoted to attain regulated DC output voltage even though there is variation in load resistance and DC input voltage. Boost converter in computer are used to step-up the1.5V from individual cell to 5V or more in order to function different 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.

More efficient state space modeling approach [2] is adopted in this paper since small signal model is not efficient in representing a non-linear system. The main role of controller for Boost converter is to govern the voltage output against alterations in supplied input and load resistance (output current). Most of papers have concentrated on design of PID controller [3, 4] and its tuning is performed using Ziegler-Nichols method. An Adaptive TSK-type Neural fuzzy Controller (ATNC) is proposed for the controlling Boost converter and its performance metrics such as settling time and various error parameters is compared with conventional FLC [4-11]. ATNC is a fusion of the humanitarian capability to judge adopted in Fuzzy Inference System and training capability adopted in neural network. The error voltage is calculated by taking the deviation of Boost converter's output voltage and its reference voltage and is devoted to tune the input membership function parameters of ATNC; later feedback the same into the controller. ATNC proposes enhanced computing superiority by exterminating the development of complicated mathematical models, reducing the computational period required. The simulations for various line and load conditions have been included to illustrate the capability of proposed ATNC controller for the Boost DC-DC converter by evaluating its settling time and error parameters. This paper is regimented into the five sections. Succeeding the Introduction, the representation of the frame work of a DC-DC Boost converter and state space modeling is presented in Section II. Section III outlines the design approach of ATNC controller. In section IV, simulation studies are described. Lastly, the conclusions are explained 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.

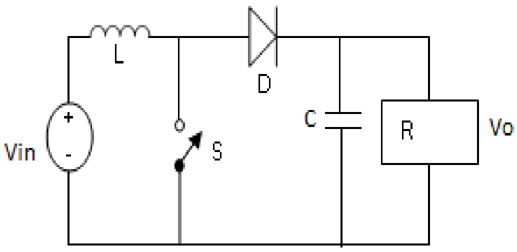

Figure 1: Conventional Boost Converter framework

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).

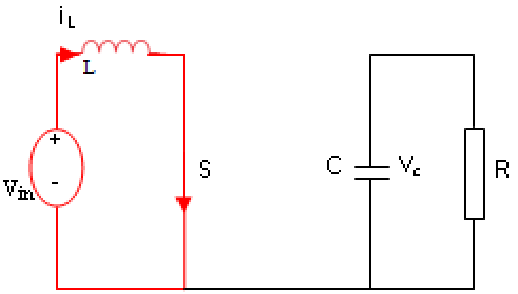

Figure 2(a). Boost Converter circuit during ON state

$$v_{in} - L\, di_L / dt = 0 \qquad (1)$$

$$v_c / R + C\, dv_c / dt = 0 \qquad (2)$$

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)

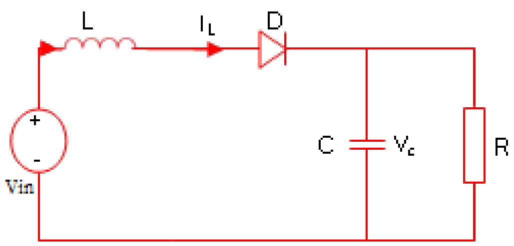

Figure 2(b). Boost Converter circuit during OFF state

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

$$i_L - v_c / R + C\, dv_c / dt = 0 \qquad (4)$$

State space representation is as follows:

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

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

DESIGN PROCEDURE OF ATNC CONTROLLER

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. 3

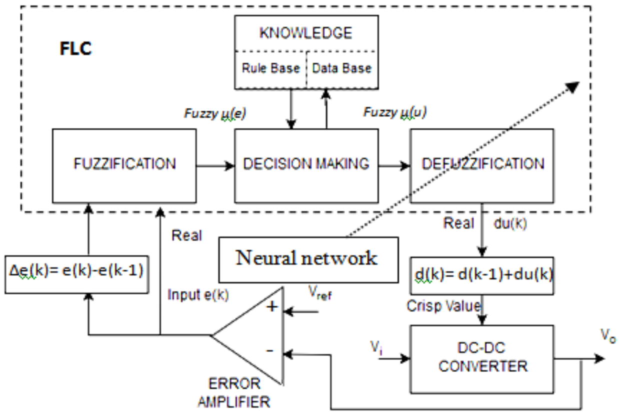

Figure 3: Block diagram of ATNC for Boost converter

Identification Of Inputs And Outputs

The two inputs provided to ATNC controller are as follows:

1) The error '*e(k)*' is the input to the ATNC at k^{th} instant and is the difference between reference voltage (V_{ref})and output voltage (V_o) of Boost converter [14-16] and is depicted by Eq (6),

$$e[k] = V_{ref} - V_o \qquad (6)$$

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 difference between successive errors represented by '$\Delta e[k]$' and depicted by Eq (7)

$$\Delta e[k] = e[k] - e[k-1] \qquad (7)$$

Subsequently both the inputs are then delivered to the ATNC controller. This inputs '*e(k)*' and '$\Delta e[k]$' are handled by ATNC controller and its output is the change of duty cycle '*du(k)*'. Then calculation of the actual duty ratio '*d(k)*', at the k^{th} instant is computed by adding the ATNC controller output '*du(k)*' with the previous sampling period's duty cycle '$d[k-1]$' depicted in Eq (8)

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

Fuzzification

Here, each input to the ATNC controller is segmented into 7 fuzzy subsets: {NB, NM, NS, Z, PS, PM, PB}. 'μ *(e)*' and '$\mu(\Delta e)$' are the membership function of the two inputs to the ATNC and is represented in Gaussian form as displayed in Fig. 4(a) and 4(b).

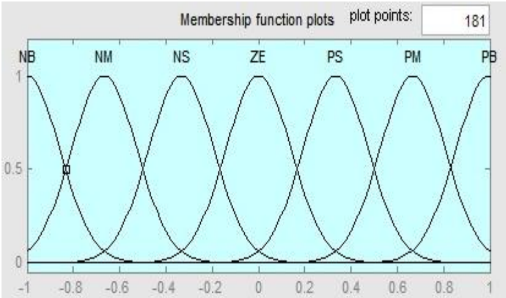

Figure 4(a): Membership function for μ *(e)*

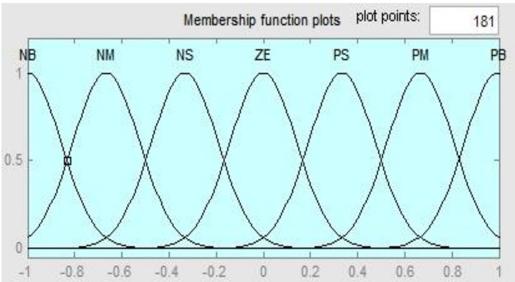

Figure 4(b): Membership function for μ *(*Δ*e)*

Progression of Rule Base

From the actual knowledge of the behavior of boost dc-dc converter, rule base is derived and is modified according to the experimental outcomes. For implementation of boost converter, a 7 × 7 rule base was framed and is generally represented as a set of Fuzzy Linguistic rules. The conclusion session is the linear addition of the crisp inputs for an ATNC controller is as follows:

IF x_1 is $F_{1j}(m_{1j}, \sigma_{1j})$ and x_2 is $F_{2j}(m_{2j}, \sigma_{2j})$

THEN $f_j(x) = w_{0j} + w_{1j}x_1 + w_{2j}x_2$ (9)

Where j= *1,2……J.* From Eq (9), $x_1 = k^{th}$ error signal *e(k)* , $x_2 = k^{th}$ change in error signal $\Delta e(k)$, 'F_{ij}' is a fuzzy subset provided by the input 'x_i' for the j^{th} rule .

Defuzzification

Outcome of each rule is the weighted sum of inputs and a constant term as represented in Eq (9).The control output is acquired by 'defuzzification' of resultant outcome from rule base in order to recast it in to corresponding crisp value[12,13]. The suggested four layered ATNC architecture [18-20] is shown in Fig. 5.

Layer 1 (Input layer): In input layer, each node is provided with crisp input variable and there is no modification of weights in this layer. In the proposed network, error '*e (k)*' and difference between successive errors 'Δe *(k)*' are the inputs.

Layer 2 (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:

$$\mu_{F_{ij}}(x_i) = exp\left(\frac{-(x_i - c_{ij})^2}{2\delta_{ij}}\right) \quad (10)$$

Where the parameters 'c_{ij}', 'δ_{ij}' can be estimated by clustering approach or partition technique. In this paper, fuzzy c-mean (FCM) clustering is adopted.

$$C_{ij} = \frac{\sum_{k=1}^{N} u_{jk} x_{ik}}{\sum_{k=1}^{N} u_{jk}} \quad (11)$$

$$\delta ij = h\frac{\sum_{k=1}^{N} u_{jk}(x_{ik} - C_{ij})^2}{\sum_{k=1}^{N} u_{jk}} \quad (12)$$

Where 'u_{jk}' represents the fuzzy membership of the k^{th} input data. $x_k = [x_{k1}, x_{k2\dots\dots} x_{kd}]^T$ be a segment of j^{th} cluster . Here, '*h*' represents the scale factor which may be altered manually.

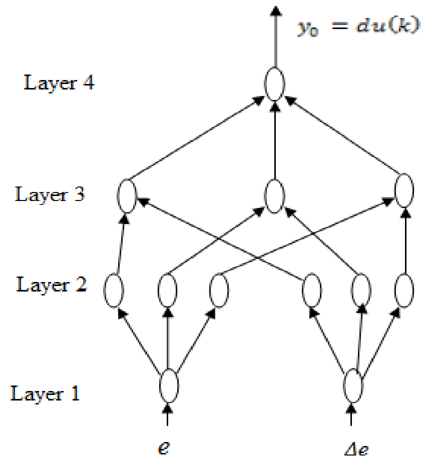

Figure 5: Architecture of four layered Adaptive TSK-type Neural Fuzzy Controller (ATNC)

Layer 3 (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.

$$\mu_j(x) = \prod_{i=1}^{n} \mu_{F_{ij}}(x_i) \quad (13)$$

$$\tilde{\mu}_j(x) = \frac{\mu_j(x)}{\sum_{j'=1}^{J} \mu_{j'}(x)} \quad (14)$$

Where μ_j (x) and $\tilde{\mu}_j(x)$ symbolizes the fuzzy membership function and the normalized fuzzy membership associated with the fuzzy set F_{ij}.

Layer4 (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 *du(k)* and can be represented as:

$$y_0 = du(k) = \sum_{j=1}^{J} \frac{\mu_j(x)}{\sum_{j'=1}^{J} \mu_{j'}(x)} f_j(x)$$

$$= \sum_{j=1}^{J} \tilde{\mu}_j(x) f_j(x) \qquad (15)$$

The duty ratio at the k^{th} instant is represented by '*d(k)*'and is computed by adding the change in duty cycle from ATNC output '*du(k)*' to the past duty cycle at $(k\text{-}1)^{th}$ instant '*d[k-1]*'as in Eq (8). Specification of ATNC structure implemented in the proposed paper is tabulated as in Table1.

Table 1: 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 2016a with a 3MHz processor. The framework of the proposed Boost converter controlled by ATNC is shown in Fig. 6.The specification for the 25V, 50W Boost converter is tabulated in Table 2. 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.

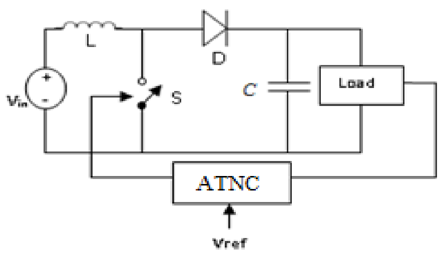

Figure 6: ATNC for controlling Boost Converters

Table 2: 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. Examination of output voltage versus time simulation graph as in Fig. 9 to 13 is executed to summaries the Table 3.The following performance metrics [21] is compared:

i) Integral Squared Error , ISE= $\int_{t=0}^{\alpha} |e|^2 dt$

ii) Integral Absolute Error , IAE= $\int_{t=0}^{\alpha} |e(t)| dt$

iii) Integral of Time multiplied by the Squared Error, ITSE= $\int_{t=0}^{\alpha} t|e|^2 dt$

iv) Integral Time-weighted Absolute Error (ITAE), ITAE= $\int_{t=0}^{\alpha} t|e(t)| dt$

v) Peak Overshoot

vi) 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.

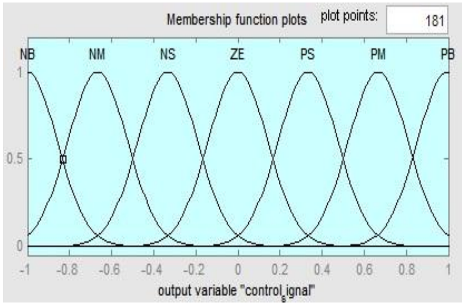

Figure 8: Membership function of the control signal, *du(k)*

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 3 by analyzing the outcomes furnished in Fig. 9 to 13.

Minimum Line and Maximum load condition

Variation of output voltage of boost converter with time in the stipulated settings: V_s= 8V and I_o = 2.5A is demonstrated in Fig. 9.Here the effectiveness of ATNC are compared to FLC [17] with respect to six different parameters. It 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 3. The error parameters such as ISE, IAE, ITSE and IATE for this condition are also tabulated in Table 3.

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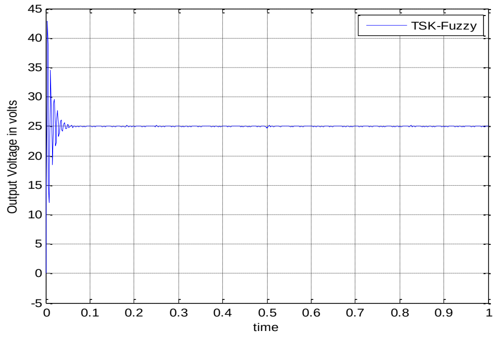

Figure 9: Output Voltage for Minimum Line and Maximum load condition

Minimum Line and Light load condition

Variation of output voltage of boost converter with time in the stipulated settings: V_s= 8V and I_o = 0.5A is demonstrated in Fig. 10. Here the effectiveness of ATNC is compared to FLC [17] with respect to six different parameters. It 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 3. The error parameters such as ISE, IAE, ITSE and IATE for this condition are also tabulated in Table 3.

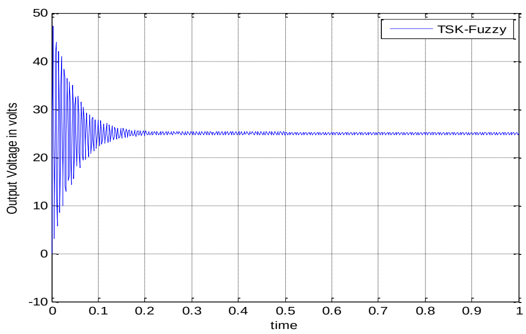

Figure 10: Output Voltage for Minimum Line and Light load condition

Midrange Line and Midrange Load condition

Variation of output voltage of boost converter with time in the stipulated settings: V_s= 12V and I_o = 0.9A is demonstrated in Fig. 11. Here the effectiveness of ATNC is compared to FLC [17] with respect to six different parameters. It 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 3. The error parameters such as ISE, IAE, ITSE and IATE for this condition are also tabulated in Table 3.

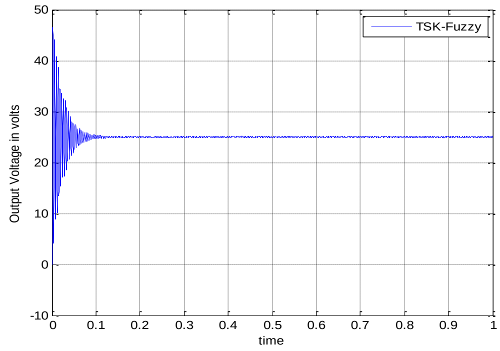

Figure 11: Output Voltage for Midrange Line and Load condition

Maximum Line and Maximum load condition

Variation of output voltage of boost converter with time in the stipulated settings: V_s= 20V and I_o = 2A is demonstrated in Fig. 12. Here the effectiveness of ATNC is compared to FLC [17] with respect to six different parameters. It 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 3. The error parameters such as ISE, IAE, ITSE and IATE for this condition are also tabulated in Table 3.

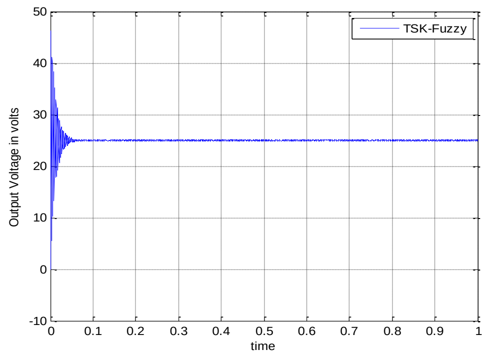

Figure 12: Output Voltage for Maximum Line and Maximum load condition

Maximum Line and Light Load condition

Variation of output voltage of boost converter with time in the stipulated settings: V_s= 20V and I_o = 0.5A is demonstrated in Fig. 13. Here the effectiveness of ATNC is compared to FLC [17] with respect to six different parameters. It 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 3. The error parameters such as ISE, IAE, ITSE and IATE for this condition are also tabulated in Table 3.

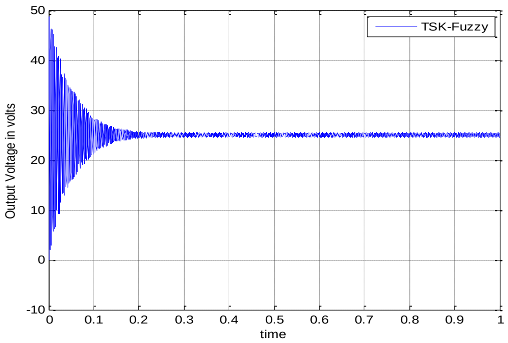

Figure 13: Output Voltage for Maximum Line and Light Load condition

Simulation results for both FLC and ATNC for different line and load conditions are summarized as shown in Table 3.The simulation outcomes of proposed ATNC is compared with that of conventional Fuzzy controllers [17] 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. Among the different conditions tabulated, lower settling time (0.05ms) is for the maximum line and maximum load condition.

Table 3: Simulation Results for Various Line and Load Settings

Cases	Damping Ratio(δ)/ Damping Type	ATNC					
		Settling Time Ts (ms)	ISE	IAE	ITSE	IATE	Peak Overshoot (%)
Minimum Line and Maximum load condition	0.103 (Under Damped)	0.05	216875	8675	1.0140×10^5	4.0561×10^3	42.4899
Minimum Line and Light load condition	0.026 (Under Damped)	0.2	295625	11825	1.3064×10^5	5.2257×10^3	46.9839
Midrange Line and Load condition	0.087 (Under Damped)	0.13	404375	16175	1.8635×10^5	7.4542×10^3	46.7037
Maximum Line and Maximum load condition	0.121 (Under Damped)	0.08	615625	24625	2.9404×10^5	1.1761×10^4	46.6253
Maximum Line and Light Load condition	0.04 (Under Damped)	0.2	726875	29075	3.3261×10^5	1.3304×10^4	48.4039

CONCLUSION

In the proposed work, an Adaptive TSK-type Neural fuzzy Controller (ATNC) is devised to control the DC-DC Boost converter. The simulation results are executed to empower the robustness of the proposed control system. The proposed 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, settling time and error performance metrics at the time of parameter variation and has superior performance compared to FLC.

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