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# A Comparison of Fuzzy and Brain Emotional Learning-Based Intelligent Control Approaches for a Full Bridge DC-DC Converter

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ABSTRACT

*In this paper, a Brain Emotional Learning-Based Intelligent Controller (BELBIC) and a fuzzy controller were used to control the output voltage of a full bridge DC-DC converter. The converter was presented by its state space averaged model assuming that it operates in a continuous conduction mode (CCM). A comparison was also made between the results. The effectiveness of control approaches was demonstrated by the uncertainty of system parameters and acceptable load variations. The performance of the BEBLIC and fuzzy controller in controlling the output voltage of the full bridge DC-DC converter was satisfactory. Since these controllers are not designed to reduce error to zero, it is not possible to claim that the error rate is precisely zero. Compared to the fuzzy controller, the BELBIC showed negligible overshoots and fluctuations. Both controllers reached stabilization almost at once. It can, therefore, be concluded that the BELBIC outperforms the fuzzy controller Given the uncertainty of the system parameters (including inductance, capacitance, and input voltage and acceptable variations of load).*

**Article Info**

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BELBIC, DC-DC converter, Fuzzy controller, Robustness

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## I. INTRODUCTION

Due to the rapid advancement of power electronics in the recent decays, modern control approaches have needed to be developed accordingly. Since the controller of a linear power supply is in the active mode, its efficiency in high powers is less than 50%. The size of linear power supplies is large owing to the large dimensions of transformers and the need for large heat sinks because of high energy dissipation of switches.

In switched mode power supplies, because the frequency is high, the transformer size can be decreased. In these power supplies, the switches operate in the saturated or threshold point and thus their dissipation is modest. Accordingly, linear power supplies have been replaced by switched-mode power supplies in many applications over time [1]. A full bridge DC-DC converter operates in the switched mode. The performance of this converter and its state space averaged model are discussed in section II.

Based on Brain Emotional Learning-Based Intelligent Controller (BELBIC) there exist a few adjustable parameters to achieve the desired solution. In [2-10], BELBIC was used to control electric drivers or power systems.

In the present study, BELBIC was used to control a full bridge DC-DC converter and the results were compared to the results of a fuzzy controller.

After a brief review of the performance of DC-DC converters and their state space averaged model sectionII, BELBIC and fuzzy controller are described in section III and IV respectively. Section V discusses the results obtained by BELBIC and fuzzy controllers. Moreover, a comparison is also made between the system parameters and load variations of these two controllers under uncertain conditions.

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## II. FULL BRIDGE DC-DC CONVERTER

Fig. 1 shows the circuit diagram of a full bridge DC-DC converter. The circuit is composed of a high frequency step-up transformer (with a ratio of n:1), a diode bridge (D1, D2, D3, and D4), and a LC filter. The command signals of the switches are created by comparing the constant signals $-V_{control}$ and $V_{control}$ with a high-frequency periodic carrier signal. The switching frequency is equal to the carrier signal frequency. When $V_{control}$ is smaller than the periodic signal, the command signal turns T1 and T2 switches on. Otherwise, the command signal is zero and T1 and T2 switches are turned off.

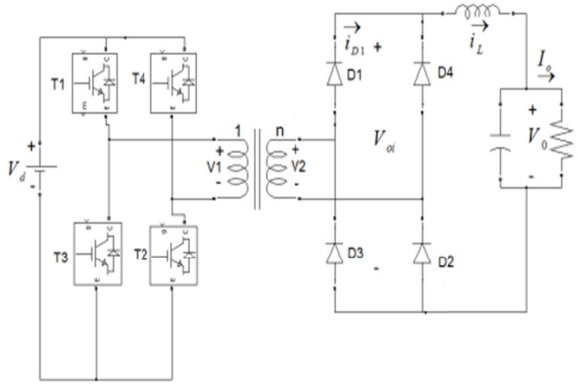



Fig. 1. The circuit schematic of the full bridge DC-DC converter[11]

Moreover, when $-V_{control}$ is larger than the periodic signal, the switches T3 and T4 are on, otherwise they are off. When all four switches are off, load current keeps cycling through rectifiers. The duration of this process is $0.5T_s$-$d.T_s$ .Here $T_s$ is the period of switching and $d$ is the duty cycle. In the first half cycle of the switching period, the switch pair T3 and T4 and in the second half cycle of the switching period, the switch pair T1 and T2 are off respectively [11-12].

The command pulse signals reaching T1, T2, T3 and T4 switches as well as the periodic signal and constant signals $V_{control}$ and $-V_{control}$ are shown in Fig. 2.

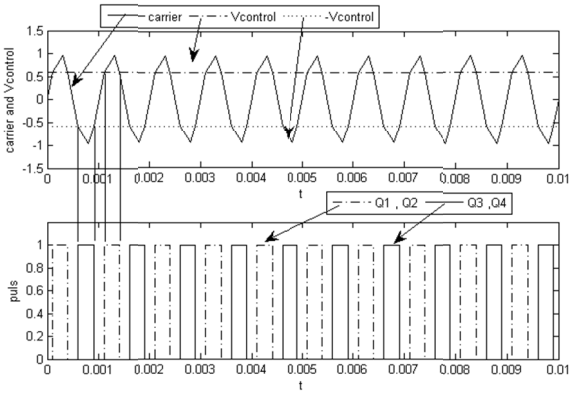



Fig. 2. The command signals, periodic signals and constant signals for controlling the switches [11]

## III. FULL BRIDGE DC-DC CONVERTER STATE SPACE AVERAGED MODEL

It is assumed that:

1. the converter operates in the Continuous Conduction Mode (CCM).
2. the transformer, diodes, and switches are ideal.

In each duty half-cycle, the converter can be shown in two modes:

*Duty Mode 1:*

During the time T1 and T2 switches are on and power is transferred to the load via the transformer and two diodes. The circuit schematic of this mode is depicted in Fig. 3. In this mode, with KVL and KCL shown in Eq.(1) and (2), the converter state space equations can be obtained as Eq.(3).

$$nV_d = L\dot{x}_1 + x_2 \tag{1}$$

$$x_1 = C\dot{x}_2 + \frac{x_2}{R} \tag{2}$$

$$\dot{X} = A_1.X + B_1.V_d \tag{3}$$

where:

$$X = [x_1 \quad x_2]^T$$

$$A_1 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, B_1 = \begin{bmatrix} \frac{n}{L} \\ 0 \end{bmatrix}$$

In which $x_1$ denotes the current of the inductor L and $x_2$ is the voltage of the capacitor C.

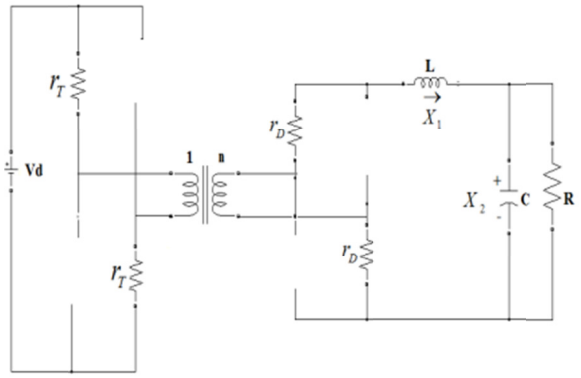



Fig. 3. The circuit schematic for duty mode 1

*Duty Mode 2:*

In this mode, all switches are off and the load current keeps cycling via rectifiers. The circuit schematic for this mode is shown in Fig. 4. In this mode, with KVL and KCL shown in Eq.(4) and (5), the converter state space equations can be obtained as Eq.(6).

$$0 = L\dot{x}_1 + x_2 \tag{4}$$

$$x_1 = C\dot{x}_2 + \frac{x_2}{R} \tag{5}$$

$$\dot{X} = A_2.X + B_2.V_d \tag{6}$$

where:

$$A_2 = A_1, B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

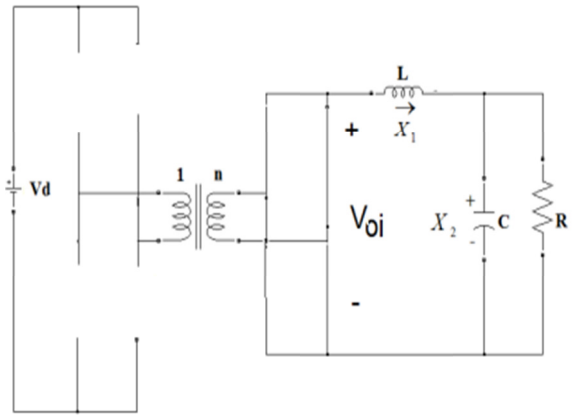



Fig. 4. The circuit of duty mode 2

Since the second half-cycle is similar to the first half-cycle, $A_1$ and $B_1$ can be used for the period $2dT_s$ and $A_2$ and $B_2$ for the period $(1\text{-}2d)T_s$. According to the state space averaged model of the converter described in [12] and [13], the final full bridge DC-DC converter state space averaged model can be obtained as follows:

$$\dot{X} = A.X + B.V_d \quad (7)$$
$$V_o = C.X \quad (8)$$

where:

$$A = A_1.2d + A_2.(1-2d) = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}$$

$$B = B_1.2d + B_2.(1-2d) = \begin{bmatrix} \frac{2dn}{L} \\ 0 \end{bmatrix}$$

## IV. BRAIN EMOTIONAL LEARNING COMPUTATIONAL MODEL

The Brain Emotional Learning-Based Intelligent Controller (BELBIC) is a control algorithm based on the emotional learning computational model of the mammals brains. This model includes an amygdala, a sensory cortex, an orbitofrontal, and thalamus shown in Fig. 5 [14].

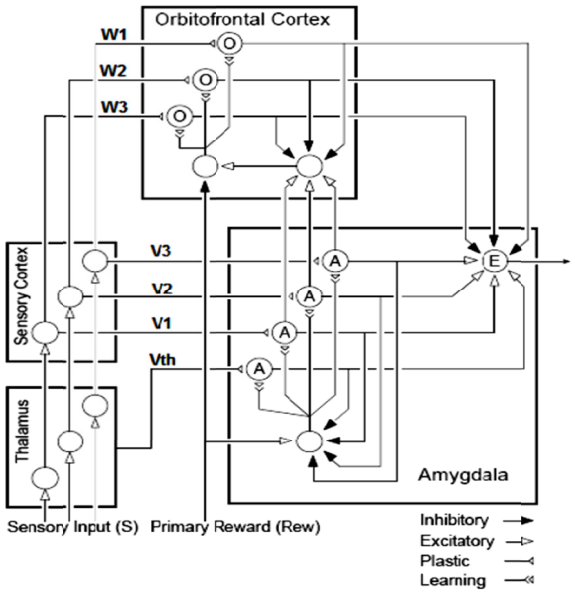



Fig. 5. The brain emotional learning computational model [14]

The amygdala and orbitofrontal cortex have a grid structure in the computational model. There is a node in the amygdala and orbitofrontal context for sensory stimulus. There is also a node in the amygdala for thalamus stimulus. The input to these nodes is equal to the maximum amount of inputs [15].

The outputs of the nodes in the amygdala and orbitofrontal cortex are obtained by Eq. (9) and (10):

$$A_j = V_j.S_j \quad (9)$$
$$O_j = W_j.S_j \quad (10)$$

where, $V$ and $W$ are the weights of nodes, and $S_j$ is the sensory input. Variations of $V$ and $W$ in the learning process are calculated by Eq. (10) and (11), where $\alpha$ and $\beta$ are the learning coefficients of the amygdala and orbitofrontal cortex and $R$ is the sensory signal.

$$\Delta V_j = \alpha.S_j.\max(0, R - \sum_i A_j) \quad (11)$$
$$\Delta W_j = \beta.S_j.(\sum_i A_j - \sum_i O_j - R) \quad (12)$$

As seen, it is not possible to reduce the values of $A_j$. That is to say, learned information is not forgotten through the amygdala. In fact, forgetting or prevention is carried out in the orbitofrontal cortex. The output of the node in the amygdala is a stimulus originating from the thalamus. It is obtained by Eq. (13). Finally, the model output is calculated by Eq.(14) [14]:

$$A_{th} = \max(S_j) \quad (13)$$
$$E = \sum_i A_j - \sum_i O_j + A_{th} \quad (14)$$

Fig. 6 shows the system control block diagram using BELBIC. The functions of emotional signal R and sensory inputs S are as presented in Eq. (15) and (16), respectively.

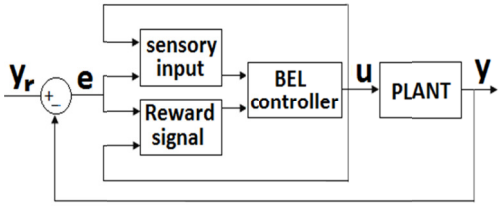


Fig. 6. The system control block diagram using BELBIC [14]

$$R = f(e, y, u) \quad (15)$$

$$S = g(e, y, u) \quad (16)$$

where $e$, $y$, and $u$ are the system error, system output and controller output, respectively. In this paper, the sensory input and emotional signal are defined as below: [14]

$$R = K_1.|\,y\,| + K_2.\int e.dt + K_3.\mathrm{e} + K_4.|\,\mathrm{u}\,| \quad (17)$$

$$S = K_5.\int e.dt + K_6.\mathrm{e} \quad (18)$$

The control of gains $K_3$ and $K_6$ as well as $K_2$ and $K_5$ is similar to a conventional PI controller. $K_3$ and $K_6$ are determined for the settling time adjustment and $K_1$ is responsible for smoothing the system response. Also, $K_2$, $K_4$ and $K_5$ gains affect the steady-state error [16].

## V. FUZZY CONTROLLER

In practical systems, important information originates from two sources. One of the sources is the experts, who define their knowledge of the system using the natural language. The other consists of measurements and mathematical models derived from physical laws. Hence, what matters is how to incorporate these types of information into the design of systems. The question is that how it is possible to formulate human knowledge within a framework similar to mathematical models. In other words, the main question is "How is it possible to convert human knowledge to a mathematical formula?"

Basically, the main function of a fuzzy system is to make such a conversion possible. Fuzzy systems are based on knowledge or rules. The core of a fuzzy system is a knowledge base following the IF-THEN fuzzy rules. If a fuzzy system is used by a controller, the controller is called "fuzzy controller".

The fuzzy controller designed for the full bridge DC-DC converter takes two inputs: error ($e$) and error variations ($\Delta e$). The membership input functions for this controller are in the range of -5 and 5. Membership functions for each of the two input components of error and error variations are shown in Fig.7. Seven membership functions are used here for the input [17]-[18]: negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive big (PB), positive medium (PM), and positive small (PS).

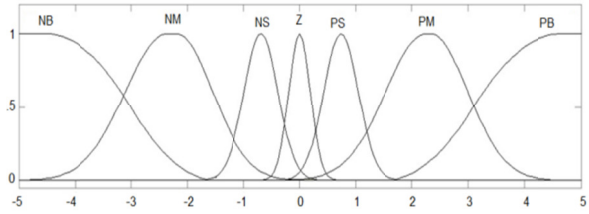


Fig. 7. The membership functions for e and $\Delta_e$

The controller output is assumed to be equal to the duty cycle, which varies between 0 and 0.5. Fig. 8 displays the controller output functions.

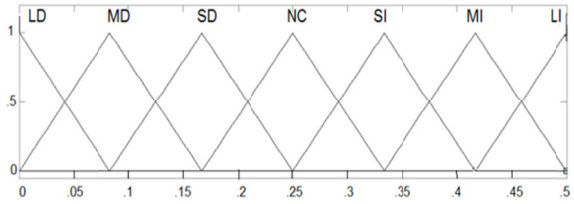


Fig. 8. The output membership functions

LI, MI, SI, NC, SD, MD and LD stand for large increase, medium increase, small increase, no changes, small decrease, medium decrease and large decrease in the half of the maximum duty cycle (i.e. 0.25). The fuzzy rules are presented in Table 1.

TABLE I
THE FUZZY RULES [17]

| e / Δe | NB | NM | NS | Z | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| NB | LD | LD | LD | MD | MD | SI | LI |
| NM | LD | LD | MD | SD | MD | MI | LI |
| NS | LD | LD | MD | SD | SD | MI | LI |
| Z | LD | MD | SD | NC | Si | MI | LI |
| PS | LD | MD | SI | SI | MI | LI | LI |
| PM | LD | MD | MI | SI | MI | LI | LI |
| PB | MD | SD | MI | MI | LI | LI | LI |

## VI. SIMULATION RESULTS

The parameters of the full bridge DC-DC converter used in this paper are presented in the Appendix. It is assumed that the converter operates in the CCM mode. Simulations were carried out using Matlab/Simulink®.

### A. *Effectiveness of BELBIC for the full bridge DC-DC converter*

The reference signal increases linear from a voltage of zero to 250V, and then it stops growing. The coefficients of the controller obtained by trial and error for the system with this input, are shown in Table 2. As seen in Fig. 9, at t=0.01s the output voltage is stabilized with a slight overshoot.

BELBIC is a model-independent controller. Consequently, the system remains stabilized in spite of variations in the values of $L$, $C$, load, input voltage and reference voltage (Figs. 10 - 13).

In Fig. 10, the reference voltage changes from 250V to 350V. In Fig. 11, the values of $L$ and $C$ are changed from ($330\mu f$, $7mH$) to ($700\mu f$, $4mH$), ($200\mu f$, $5mH$), and ($700\mu f$,

10mH) respectively.

Fig. 12 shows the result of an increase in load from 12.5Ω to 20Ω (at t=0.05s). Fig. 13 displays the result of an increase in the input voltage from 40V to 50V.

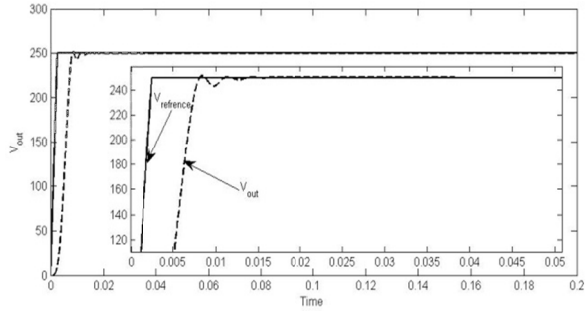



Fig. 9. The output voltage of the full bridge converter

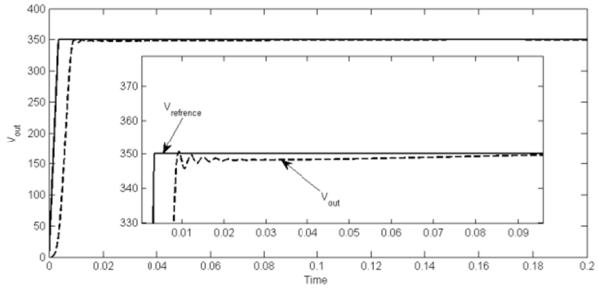



Fig. 10. The output voltage as a result of changes in the reference voltage

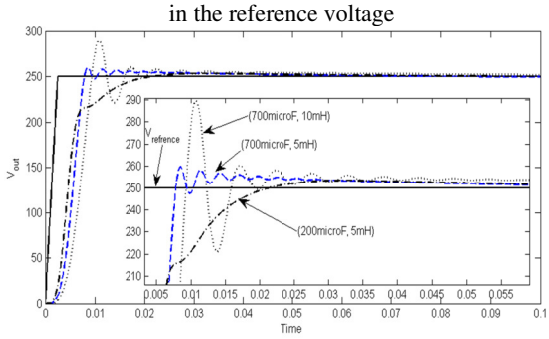



Fig. 11. The output voltage as a result of changes in the values of L and C

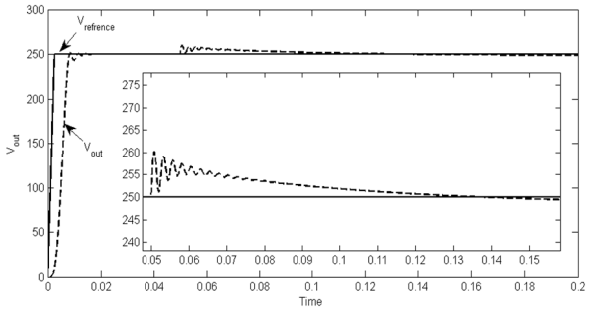



Fig. 12. The output voltage as a result of changes in the load

*B. Comparison of BELBIC with fuzzy controller*

Fig. 14 shows the system output voltage after the application of the fuzzy and BELBIC controllers. As seen in this figure, the BELBIC has a slight overshoot while the fuzzy controller has a considerable overshoot (the initial overshoot is 35 V).

The time required for stabilization is almost the same in both cases. It is therefore concluded that the BELBIC outperforms the fuzzy controller.

Figs. 15 and 16 show a comparison of output voltages values obtained from the two controller types described earlier. As seen in these figures, the capacitance of *C*, which is initially equal to 330*μf,* reduces by 10% and 12% and reaches 297*μf* and 290*μf*, respectively. In addition, a 10% decrease in the capacity of the capacitor using the fuzzy controller leads to higher growth in the range of fluctuations and an overshoot of the output voltage compared to the BELBIC. Hence, the BELBIC demonstrates better performance. When the capacitance of *C* reduces by 12%, the output voltage obtained from the BELBIC shows a higher delay in reaching stabilization compared to the fuzzy controller. Moreover, the range of fluctuations and overshoot of the output voltage are higher with the fuzzy controller.

Fig. 17 depicts a comparison of output voltage values obtained using the aforementioned two controllers. In this figure, the initial capacitance of *C* (330*μf*) increases by 20% and reaches 396*μf*. Obviously the range of fluctuations and overshoot of the output voltage using the fuzzy controller surpass those of the BELBIC controller. Hence, the BELBIC demonstrates a better performance.

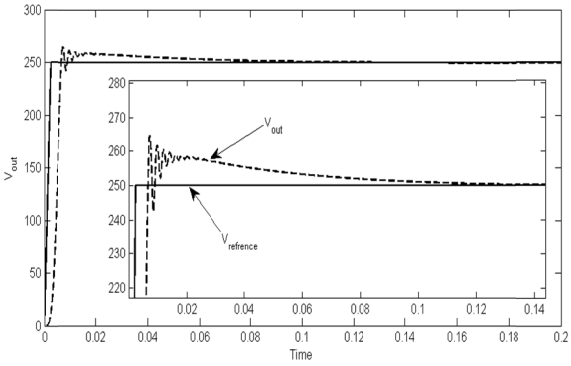



Fig. 13. The output voltage as a result of changes in the input voltage

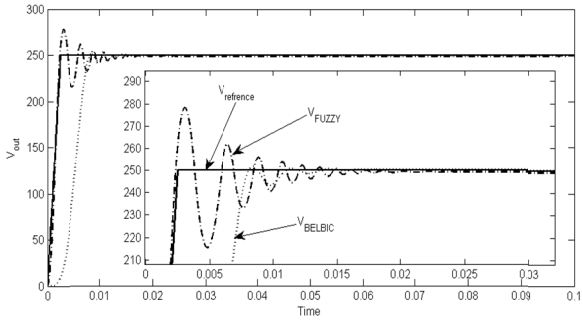



Fig. 14. The comparison of the fuzzy controller with the BELBIC

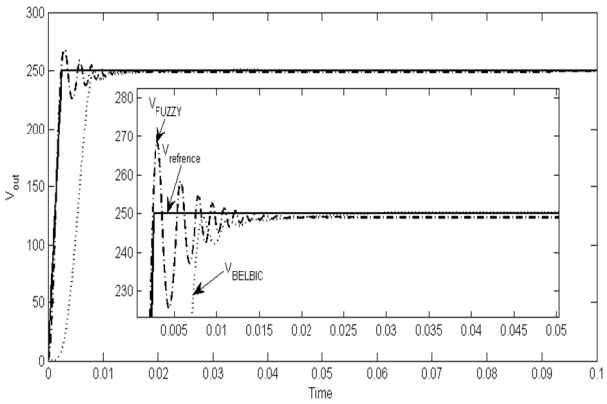



Fig. 15. The comparison of the BELBIC controller and fuzzy controller with a 10% reduction in C.

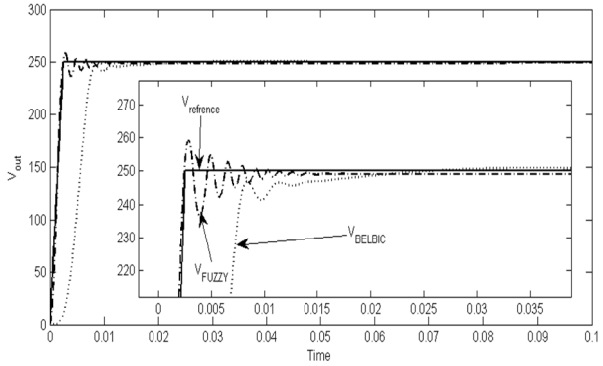



Fig. 16. The comparison of the BELBIC controller and fuzzy controller with a 12% reduction in capacity.

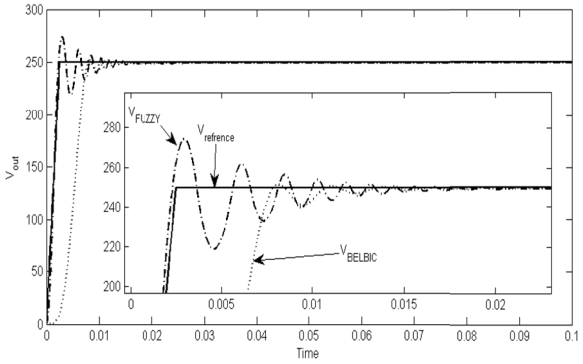



Fig.17. The comparison of the fuzzy controller and BELBIC with a 20% increase in capacitance of *C*

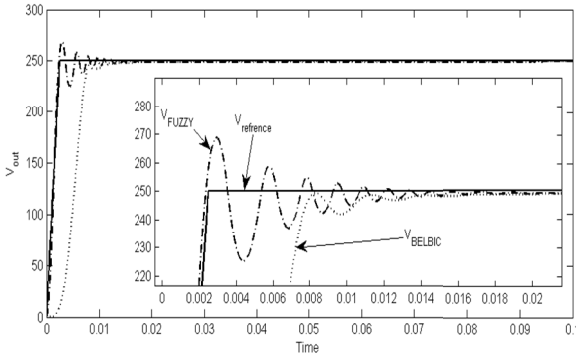



Fig.18. The comparison of the BELBIC and fuzzy controllers with a 10% reduction in inductance

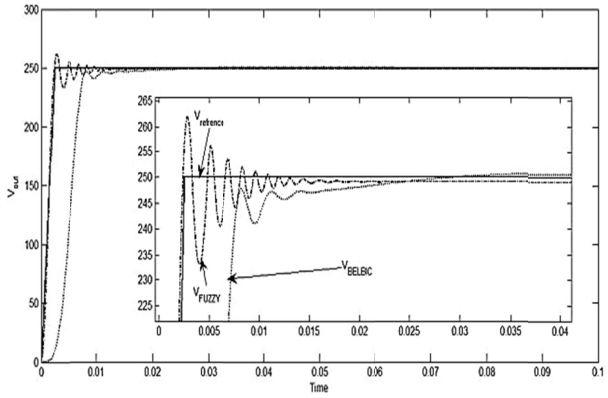



Fig.19. The comparison of the BELBIC and fuzzy controllers with a 12% reduction in inductance

Figs. 18 and 19 show a comparison of output voltages values obtained from the two controllers described earlier. The results of decreasing the value of inductance by 10% to 6.3mH the results are shown in Fig. 18. The results of decreasing the value of inductance by 12% to 6.3mH are shown in Fig. 19. As seen in these figures, with a 10% decrease in inductance, the range of fluctuations and overshoot of the output voltage obtained using the fuzzy controller exceed those of the BELBIC. Hence, the BELBIC shows a better performance. When inductance is reduced by 12%, the output voltage obtained by using the BELBIC controller reaches stabilization in a longer time. Moreover, the fluctuations and overshoot of the output voltage obtained using the fuzzy controller, are higher than those derived from the BELBIC controller.Figs. 20 and 21 show a comparison of the output voltages obtained using the aforementioned two controllers. In these figures,the initial load (12.5Ω) is increased by 20% and is decreased by 20% to reach 15 and 10 ohms, respectively. As seen in the figures, when the fuzzy controller is used, a higher range of fluctuations and overshoot are gained for the output voltage than when the BELBIC is used. Therefore, the BELBIC functions better.The range of fluctuations and overshoot of the output voltage are higher by using the fuzzy controller with a decrease and an increase in the input voltage to 39V and 41V, respectively. Hence, the system yields a more satisfactory output when the BELBIC is used (Figs. 22 and 23). When the voltage decreases and increases to 38V and 42V, the BELBIC demonstrates a higher delay in reaching stabilization. In addition, the range of fluctuations and overshoot of output voltage obtained through the fuzzy controller are higher (Figs. 24 and 25).

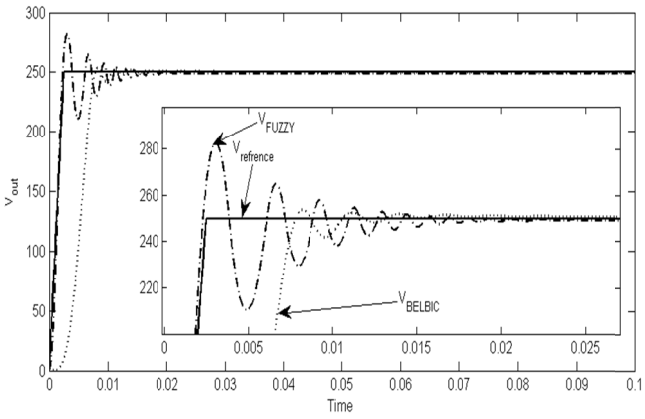



Fig. 20. The comparison of the fuzzy controller and BELBIC with a 20% increase in load

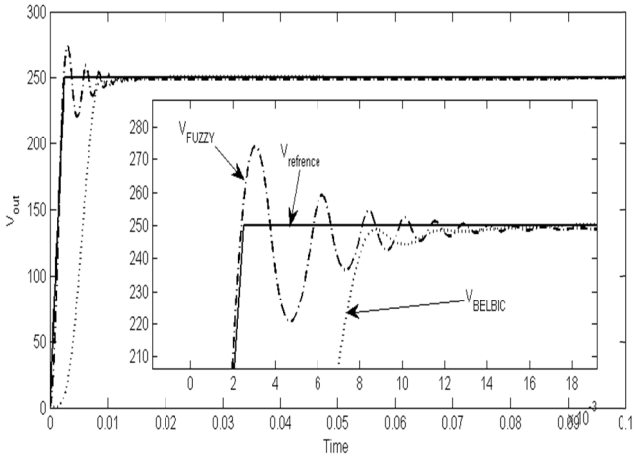



Fig. 21. The comparison of the fuzzy controller and BELBIC with a 20% decrease in load

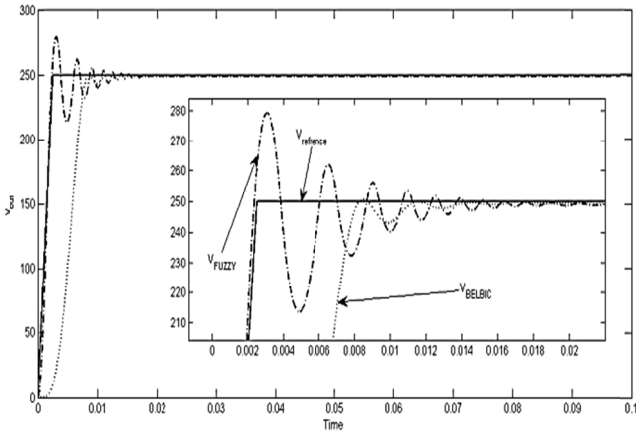



Fig. 22. The comparison of the fuzzy controller and BELBIC with a decrease in the input voltage ($V_d$=39V)

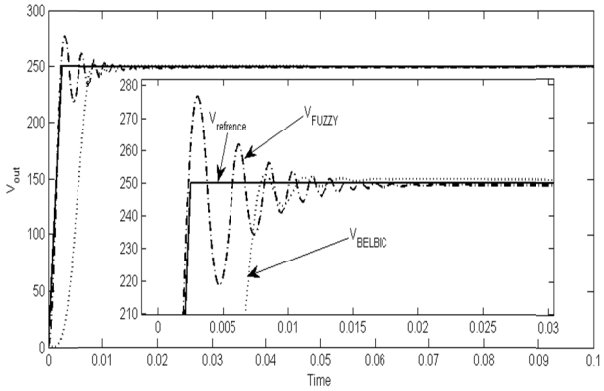



Fig. 23. The comparison of the fuzzy controller and BELBIC with an increase in the input voltage ($V_d$=41V)

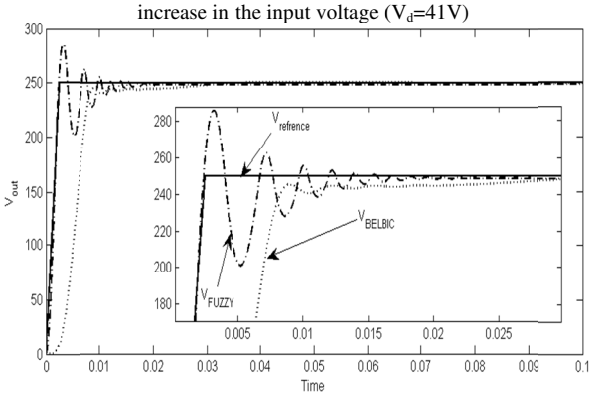



Fig. 24. The comparison of the fuzzy controller and BELBIC with a decrease in the input voltage ($V_d$=38V)

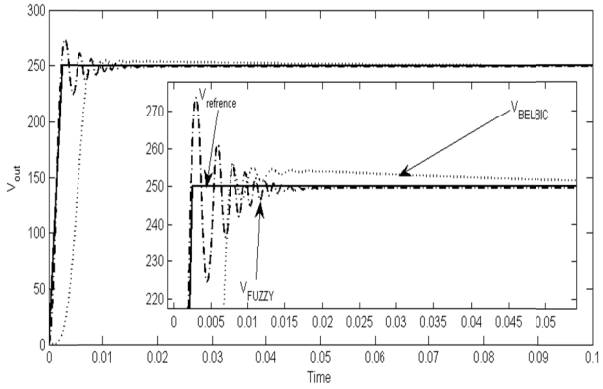



Fig. 25. The comparison of the fuzzy controller and BELBIC with an increase in the input voltage ($V_d$=42V)

## VII. CONCLUSION

The performance of the BEBLIC and fuzzy controller in controlling the output voltage of the full bridge DC-DC converter was satisfactory. Since these controllers are not designed to reduce error to zero, it is not possible to claim that the error rate is precisely zero. Compared to the fuzzy controller, the BELBIC shows negligible overshoots and fluctuations. Both controllers reach stabilization almost at once.

It is, therefore, concluded that the BELBIC outperforms the fuzzy controller. Considering the uncertainty of system parameters (including inductance, capacitance, and input

voltage and acceptable variations of load), the BELBIC presentss better performance than the fuzzy controller. Although fuzzy control is a robust and effective method for a large number of engineering systems, but its design (and consequently its performance) is almost depend on the experience and tact of the designer. Furthermore, after design and installation, its performance is not improved, and in other word, it is not a learning-based or intelligent controller. It can be stated that a Learning Based Intelligent Control which 'may' in the first step, act not as satisfying as any another modern controller, any straight-forward-designed controller after a few iterations thanks to its learning automata feature. Based on this deduction, we felt no need to emphasize the comparison of these controllers after setting optimization.

## APPENDIX

Specifications of the full bridge DC-DC converter

| | | | |
|---|---|---|---|
| Switching frequency (Hz) | 2000 | Switches and diodes resistance (Ω) | 0 |
| Filter inductance(mH) | 7 | Load resistance(Ω) | 12.5 |
| Filter capacitor(μf) | 330 | Input voltage(V) | 40 |
| Transformer rating (KVA) | 9 | Transformer ration | 1:10 |

BELBIC CONTROLLER COEFFICIENTS

| | | | |
|---|---|---|---|
| $K_1$ | 0.00045 | $K_5$ | 50 |
| $K_2$ | 0.21 | $K_6$ | 2 |
| $K_3$ | 0.000002 | α | 0.000039 |
| $K_4$ | 0.0007 | β | 0.0000008 |

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