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RESEARCH ARTICLE

IMPROVEMENT IN PERFORMANCE OF ACTIVE CLAMP FORWARD CONVERTER WITH FUZZY LOGIC CONTROLLER

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ABSTRACT

This research paper proposes the Fuzzy logic Controller (FLC) for Forward Converter with Active Clamp circuit (ACFC) to improve the performance of the converter Brief review on the fuzzy logic controller and mathematical modeling of Converter is first given. The importance of FLC for forward converter and design procedure is described in detail. And the validity of designing controllers and achievement of desired compensation is verified by the results of implementing Fuzzy PID controller and Fuzzy PD controller to Active Clamp Forward Converter (ACFC). Finally the results are analyzed by applying disturbances at both sides of the converter. And obtained results of Fuzzy Controllers are compared with the results of Discrete-time PID Controller. The ACFC is used in Telecom Power Supply, in Distrubuted Power System Circuits and Improvement in performance of the Converter is achieved by designing the Fuzzy Controllers by simplifying the design process of the controller.

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INTRODUCTION

With the rapid development of the power electronics industry, a primary trend is moving towards high operating frequencies, which help in reducing the size and rating of the magnetic components in Switch Mode power Supplies (SMPS). Among SMPSs used in various applications like Telecommunication Systems, Distributed Power System Servers and Automotive, the single switch forward converter is most promising topology for low output voltage and high current converters up to few hundred watts due to its simplicity and robustness. Since the transformer in a basic forward converter does not inherently reset in each switching cycle, number of reset techniques have been evolved for forward converter. The active clamp reset approach is most attracting one, by improving the efficiency of the converter it solves some problems in conventional forward converter like voltage stress on the switch, core reset, voltage spikes caused by the transformer leakage inductance and low duty cycle. Fig.1. Shows the basic circuit diagram of ACFC with low side clamp circuit. To get the desired performance from any converter, controller is required. There are different types of controllers are available for ACFC. One of the researchers designed a simple voltage mode controller designed and to overcome drawbacks in the voltage mode controller, peak current mode controller is designed for ACFC.

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Further the authors have presented a research paper on the implementation of digital controller for ACFC with the help of small signal discrete time modeling. All these controllers are designed by using a mathematical model of the converter and by using a systematic procedure like frequency response method or by using root locus technique. Due to strong nonlinearity in the components of the converter, linear small signal models restricted the validity of the controller and complexity in the process of design of the controller also increases. One of the solutions to overcome all the drawbacks in linear controllers is to design an FLC for ACFC and complete block diagram representation of the proposed system is shown in Fig.2. Because the design concept of FLC is entirely different, it is able to adopt the nonlinear property of the converter under varying operating points and is able to achieve better response with more robustness. It does not consider how accurate the model is but it considers how effective the linguistic rules. Therefore a perfect FLC simplifies the design of optimal compensation for ACFC. With advances in digital hardware and digital control techniques, it is becoming feasible to implement control schemes such as fuzzy logic controller for power converters. The main objective of this paper is to propose the Fuzzy Logic Controllers for Active Clamp Forward Converter and to verify the validity of the designed controller by comparing with the results of Digital PID Controller. In section 2, an outline of the Mathematical Modeling of the ACFC is presented. The power state design calculations are presented in section 3. Design procedure of the proposed controllers for considered converter and methodology is presented in section 4. In section 5 Simulation Results and discussions are presented and finally, the conclusion about the designed controllers is presented in Section 6.

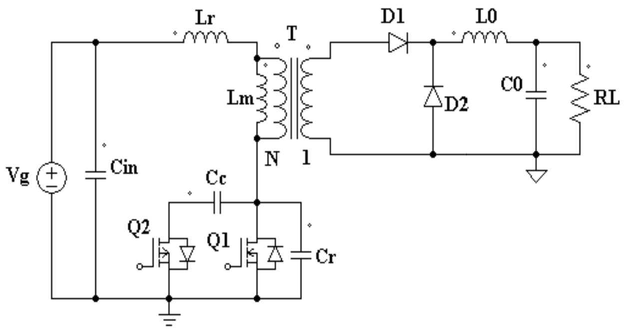

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Fig.1. Forward Converter with Active Clamp Circuit

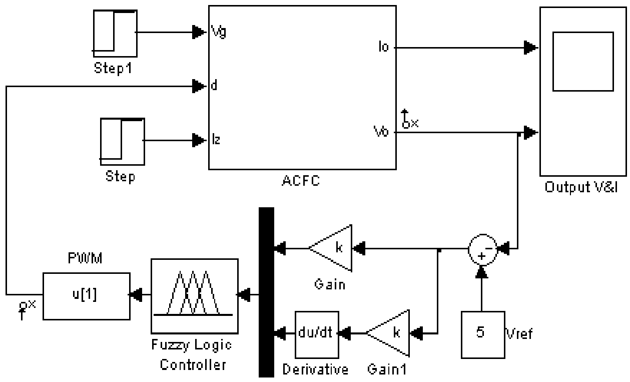

Fig.2. Block diagram representation of ACFC with FLC

Mathematical Modeling of the Converter

Modeling is the representation of physical phenomena by its mathematical equivalent. It is desired to model the important dominant behavior of a system, while neglecting other insignificant phenomena. The resulting simplified model yields physical insight into the system behavior, which helps in designing the system to operate in a specified manner. There are different techniques to model a switching converter like circuit averaging, state space averaging, and switch averaging. If the physical system is Single Input and Single Output (SISO) system, simple transfer function technique is preferable. If the systems are Multi Input Multi Output (MIMO), state space averaging Technique is used. And if systems are having a nonlinear nature, the small signal modeling technique is used to analyze the nonlinear nature of the converter. Determination of the Mathematical model is difficult if the systems are having nonlinear nature and if those are MIMO systems. The most advantage of the proposed controller is there is no necessity of the Mathematical model of the converter to design the FLC. It does not require mathematical model of the converter but it requires only information about the operation of the plant. Therefore, all the difficulties in designing Mathematical model are nullified by FLC. But to evaluate the performance of the converter with FLC by comparing with the results of the Digital PI Controller, Digital PID controller also designed. And to design the Digital PID controller mathematical model of the converter is required. In [10] authors have presented exact design procedure of digital controller with the use of small signal discrete time modeling. Outline of mathematical modeling of ACFC is shown below. Fig.3. Shows the complete small signal model of Forward converter with active clamp circuit.

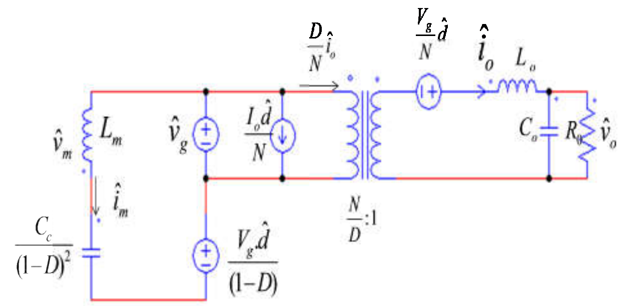

Fig.3. Small signal Model of Forward Converter with Active Clamp Circuit

It is observed from the small signal model shown in Fig.3, the inputs are $\hat{v}_g$, $\hat{d}$ and the outputs are$\hat{v}_o$, $\hat{\imath}_o$ and $\hat{\imath}_m$. The mathematical model of active clamp forward converter that relates the input and output variables can be given by (1), (2) and (3).

$$\hat{v}_o = G_{vg}\hat{v}_g + G_{vd}\hat{d} \quad (1)$$

$$\hat{\imath}_o = G_{ig}\hat{v}_g + G_{id}\hat{d} \quad (2)$$

$$\hat{\imath}_m = G_{img}\hat{v}_g + G_{imd} \quad (3)$$

The transfer functions in (1), (2) and (3) are obtained from Fig. 4. By considering each input at a time while other input is zero. From Figure.4 the transfer functions G_{vg}, G_{ig}, G_{i_mg} are given by (4), (5) and (6) when$\hat{d} = 0$.

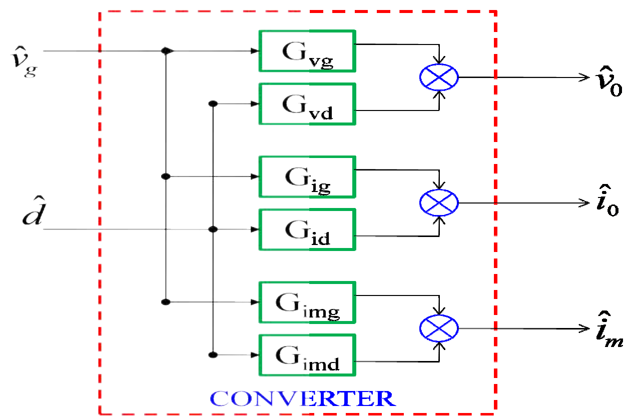

Fig.4. Block diagram representation of ACFC

$$G_{vg}(s) = \frac{D \times R_O}{N(S^2 L_O C_O R_O + S L_O + R_O)} \quad (4)$$

$$G_{ig}(s) = \frac{D(1 + S C_O R_O)}{N(S^2 L_O C_O R_O + S L_O + R_O)} \quad (5)$$

$$G_{img}(s) = \frac{S \times C_C}{s^2 L_m C_C + (1-D)^2} \quad (6)$$

Similarly from the Figure.4 the transfer functions G_{vd}, G_{id}, G_{i_md} are given by (7), (8) and (9) when $\hat{V}_g = 0$

$$G_{vd}(s) = \frac{v_g \times R_0}{N(S^2 L_0 C_0 R_0 + S L_0 + R_0)} \quad (7)$$

$$G_{id}(s) = \frac{v_g(1 + S C_0 R_0)}{N(S^2 L_0 C_0 R_0 + S L_0 + R_0)} \quad (8)$$

$$G_{imd}(s) = \frac{v_g(S \times C_C)}{(1-D)(s^2 L_m C_c + (1-D)^2)} \quad (9)$$

Power Stage Design

A power stage is designed by assuming input and output parameters. Design procedure and results are as follows,

Table 1. Design parameters of ACFC

Parameter	Ratings
Input Voltage	(36-72)V Nominal:48V
Output Voltage	5V
Output power	100W
Switching Frequency	100KHz
High Frequency Transformer	130W,12:3, Lm=100μH.
Output Filter	Lo=8μH,Co=590F

Output Inductor Selection

Assuming a peak-to-peak inductor current ripple equal to 20 percent the maximum output current, L_0 value can be calculated as

$$L_0 = \frac{V_0}{0.2 I_{0(max)} F_s})(1 - D_{min}) = \frac{5}{0.2X20X100X10^3}(1 - 0.35) = 8.125\mu H (8\mu H) \quad (10)$$

Output Capacitor selection

The output capacitor is chosen based upon many application specific variables such as cost, size, functionality and availability. The minimum output capacitance required to limit the output ripple voltage equal to one percent of the regulated output voltage can be calculated and for a load step change from no load to 50 percent of full load and limiting the transient voltage overshoot to 3 percent of the regulated output voltage, C_O is calculated to be 525μF as shown in (11)

$$C_0 = \frac{L_0 I_{STEP}^2}{v_{os}^2} = \frac{8\mu(10^2 - 0^2)}{(5.15^2 - 5^2)} = 525\mu F (590\mu F) \quad (11)$$

Transformer Design

A high frequency transformer is designed based on the guidelines given in "Design of magnetic components for switched mode power converters" by S.R Bhat & L. Umananad. The designed transformer has the following specifications.

Output Power : 130 W.
Core : EE36/11 Ferrite Core.
Turns Ratio : 12:3 (Np:Ns).
Wire gauge : 27 SWG
No. of strands per turn : 3(Primary), 41(Secondary)
Magnetizing Inductance (L_m) : 100 μH.

Clamp Capacitor Selection

Neglecting the effect of leakage inductance, the transfer function for the low-side clamp can be derived by applying the principle of volt-seconds balance across the transformer magnetizing inductance for one switching cycle. And expressing C_c in terms of known design parameters:

$$C_c > 10X(\frac{(1 - D_{min})^2}{L_m X (2\pi X F_S)^2} > 107 \text{ nF } (100 \text{ nF}) \quad (12)$$

Controller Design

By using designed mathematical model and parameters of the converter, the behavior of the converter is observed with the help of MATLAB software. The closed loop response of the converter without any controller is shown in Fig.5. The simulation result shows that there is a necessity of the controller to achieve the desired performance. There are different types of linear controllers are available to get the desired performance of the converter. But the main drawback to design these types of controllers are mathematical model of the converter is needed. Sometimes it is very difficult to derive a mathematical model of the converters and it takes more time and more iterations are required.

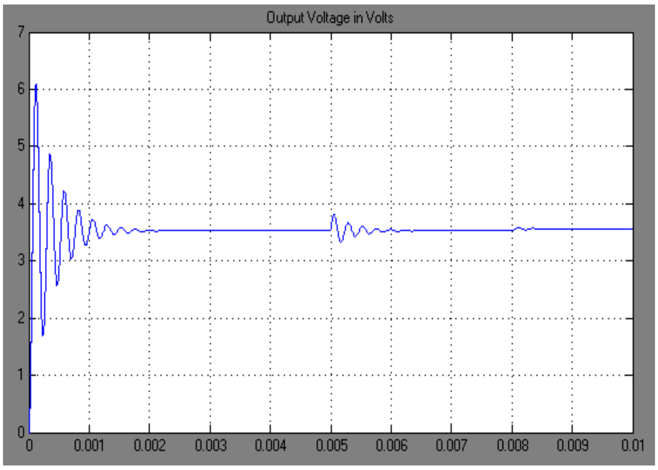

Fig.5. Closed loop response of ACFC without controller

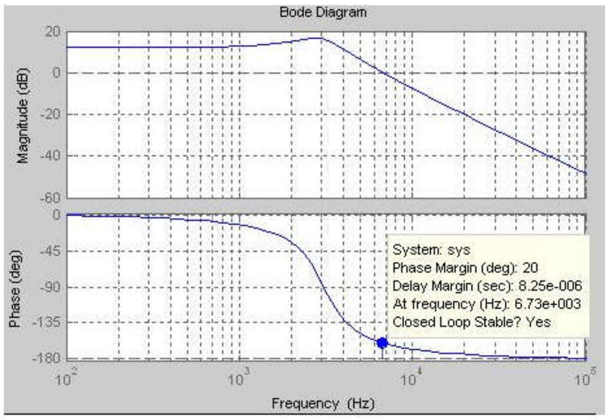

Fig.6. Frequency response of ACFC without any compensator

Discrete-tme PID Controller

With the help of transfer functions from equations (1), (2) and (3) dynamic behavior of the converter is determined by using frequency response analysis. The open loop response of ACFC without controller is shown in Fig.6. The uncompensated system has a crossover frequency of 12.7 kHz, with a phase margin of 9 degrees. It has a poor transient response. It is desired to have a phase margin of 60 degrees with crossover frequency of 20 kHz, which is one tenth of switching frequency. To achieve these requirements a PID controller is designed. The total transfer function of the designed PID compensator is given according to the equation (13).

$$Gc(s) = \frac{8.294e{-}005s^2+3.552s+6773}{2.586e{-}006s^2+s} \quad (13)$$

By using digital redesign technique a digital PID controller is designed for considered converter. The transfer function of discrete time PID Controller is shown in Equation (14). The Simulink Model of ACFC with Discrete-time PID compensator is shown in Fig.7. and Closed loop response of ACFC with Discrete-time PID controller is shown in Fig.8.

$$G_c(z) = \frac{1.3424(z-0.99)(z-0.9717)}{(z-1)(z-0.7214)} \quad (14)$$

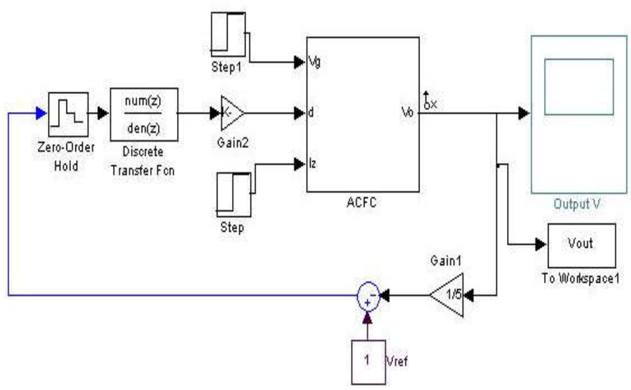

Fig.7. Simulink Model of ACFC with Discrete-time PID compensator

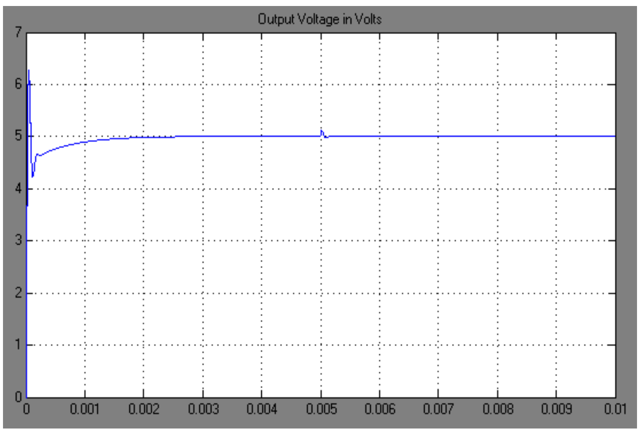

Fig.8. Closed loop response of ACFC with Discrete-time PID Controller

Fuzzy Logic Controller

From the above design Processes it is observed that to design a control by using conventional methods, Mathematical modeling of the converter is necessary. Mainly DC-DC converters are having complexity in the design of mathematical models and having nonlinearity due to some components in the converter. Particularly ACFC has nonlinear characteristic due to the parasitic elements, magnetizing inductance of the transformer and due to switching of the converter. Therefore the simple solution to overcome this drawback is the design of FLC. There is no necessity of the mathematical model of the converter and expert knowledge in the design of the controller is not required to design FLC. It requires only the idea about working of the converter. And Fuzzy control is an attractive control method because of its structure, which consists of fuzzy sets that allow partial membership and "if . . . Then. . ." Rules, resembles the way human intuitive approaches a control problem. This makes the design of controller is very simple, reduces the time to design a controller and the cost of implementation. The general structure of FLC consists of Fuzzifier, Decision making mechanism and Defuzzifier. In which Fuzzifier converts input data into suitable linguistic values, decision making mechanism consists rule base, i.e. control rules and the linguistic variables and the Defuzzifier converts control actions into crisp signals, which can be applied to Physical system. Block diagram representation of the FLC is shown in Fig.9.

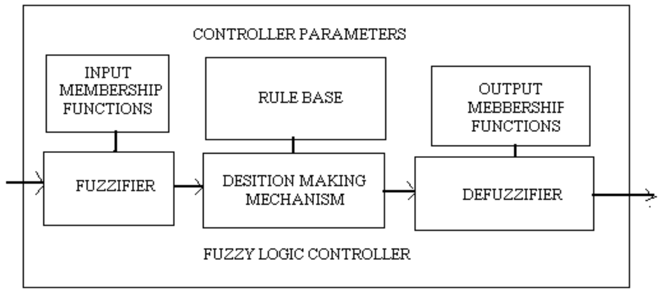

Fig.9. Block diagram representation of FLC

a) Fuzzification

Design of FLC for ACFC is based on the expert knowledge of the Converter instead of a mathematical model. Define membership functions for the inputs are the first step in the design of FLC. There are two inputs for the converter. The first one is error signal and the other one is change in error. Mathematical representation of two inputs is,

$$e[k] = V_{ref} - V_{out} \quad (15)$$

$$ce[k] = e[k] - e[k-1] \quad (16)$$

b) Rule base or Decision making mechanism

Fuzzy control rules are framed by analyzing the behavior of the system. From the output response of the converter error signal is determined and by using a gain block error signal is scaled into accessible limits of the FLC. And level values are defined for various membership functions. For simpler design universal acceptable limits are chosen and the rules are designed by analysis of the converter.

c) Defuzzification

The defuzzification block converts the range values of output variables into corresponding universe disclosure and transforms fuzzy control signals into crisp signals. The levels of crisp signals are calculated based on the performance of the converter. And the centroid method is used to get the output of the Controller.

d) Methodology to design a fuzzy logic controller

The below flow chart represents the design procedure to design a controller to PWM based switching Converters,

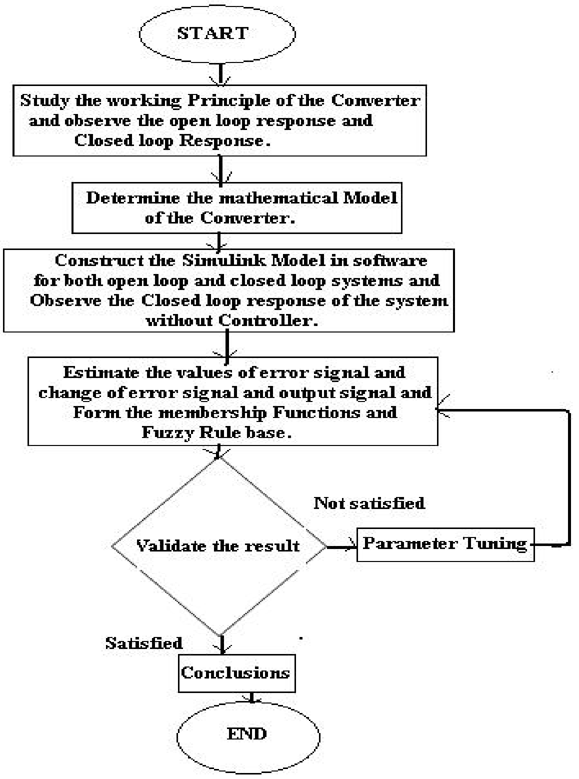

Fig.10. Methodology to design FLC

4.2.1 Fuzzy like PID Controller

With the help of above methodology a Fuzzy like PID controller is designed by considering three linguistic rule base and the output signal is the sum of Defuzzified outputs of the Proportional, Integral and derivative Fuzzy Inference Mechanism. The rule base of the system is shown in Table.2 and the Membership functions for both Input and Output is shown in Fig.11.

Table 2. Rule Base for Fuzzy PID

Proportional	Integral	Derivative
If e(k)=Negative then Y=Negative	If e(k)=Negative then Y=Negative	If e(k)=Negative then Y=Negative
If e(k)=Zero then Y= Zero	If e(k)=Zero then Y= Zero	If e(k)=Zero then Y= Zero
If e(k)=Positive then Y= Positive	If e(k)=Positive then Y= Positive	If e(k)=Positive then Y= Positive

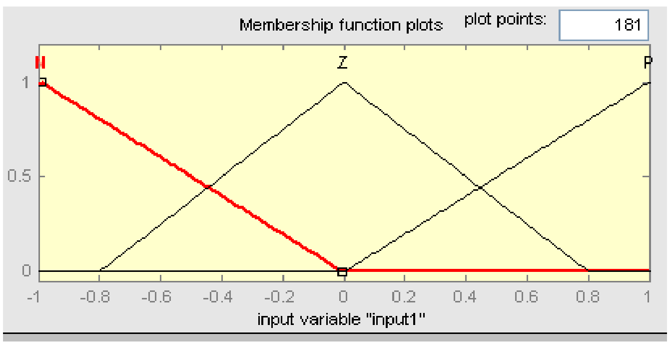

Fig.11. Membership functions for Input and Output variables

The Simulink model of the ACFC with Fuzzy PID and corresponding output wave forms are shown in Fig.1 and in Fig.13.

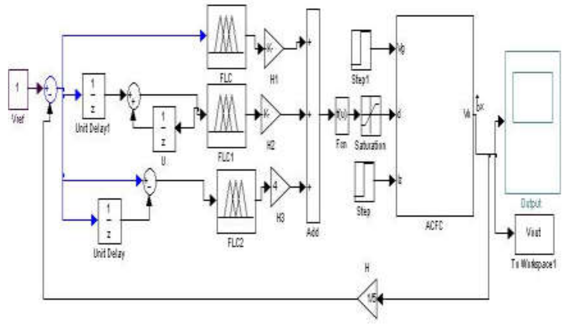

Fig.12. Simulink Model of ACFC with Fuzzy like PID Controller

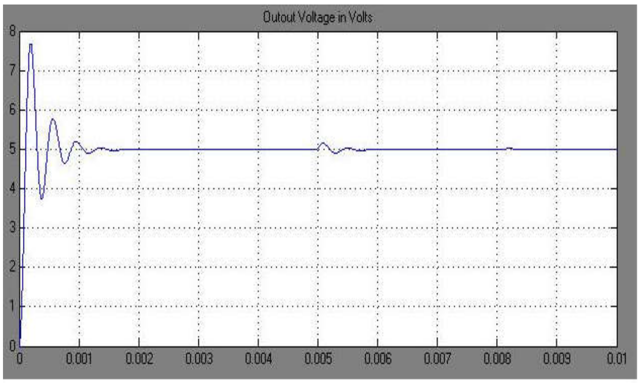

Fig.13. Closed loop response of ACFC with Fuzzy like PID Controller

Fuzzy Logic Controller

To get the better performance to improve stability limits a fuzzy PD controller is designed. Seven levels or sets are chosen and defined by the following library of fuzzy set values for the error e and the change in error ce. Those are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero Error (ZE), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). The degree of input resolution depends upon the number of fuzzy levels. In this paper triangular membership function is chosen due to its simplicity and trapezoidal Membership functions are chosen at the end points to consider variations in input and output variables. Fig.14 and Fig.15 shows the membership functions for input variables and output variable of the Fuzzy Logic Controller. Based on the performance of the conversion rules are designed and the designed rules are sown in Table.3.

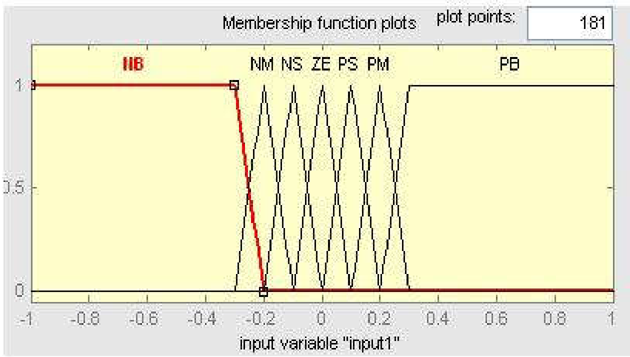

Fig.14. Membership functions for e & ce

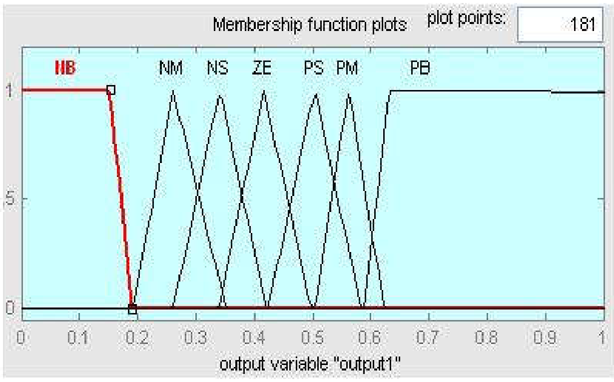

Fig.15. Membership functions for output variable

Table 3. Membership Rules

E\CE	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	ZE
NM	PB	PM	PM	PS	PS	ZE	NS
NS	PM	PM	PS	PS	ZE	NS	NS
ZE	PM	PS	PS	ZE	NS	NS	NM
PS	PS	PS	ZE	NS	NS	NM	NM
PM	PS	ZE	NS	NS	NM	NM	NB
PB	ZE	NS	NS	NM	NM	NB	NB

With the help of designing rules considered converter is simulated with the Fuzzy Logic controller. The Simulink Model of the converter is shown in Fig.16 and the corresponding results are shown in Fig.17.

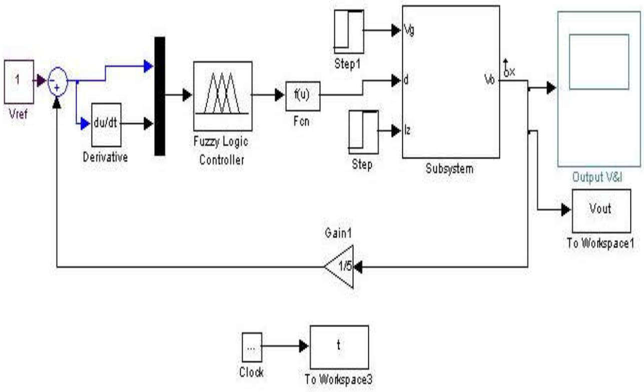

Fig.16. Simulink Model of ACFC with Fuzzy Logic Controller

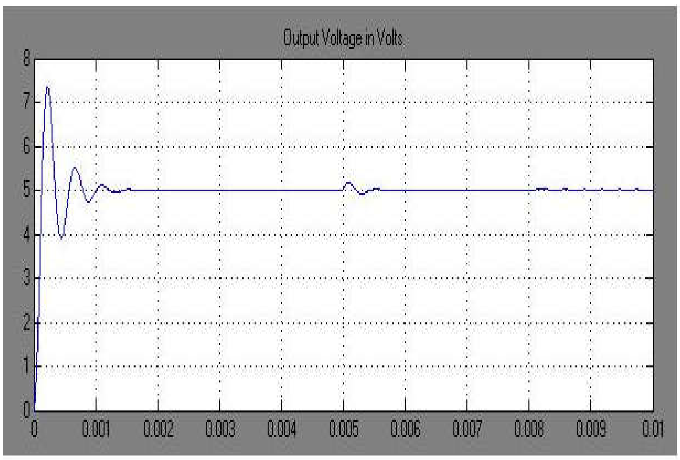

Fig.17. Closed loop response of ACFC with Fuzzy Logic Controller

RESULTS AND DISCUSSION

To evaluate the steady state and dynamic behavior of the designed controllers a line and load step changes are given at simulation time 0.005 Sec with load step change of 2A and at simulation time of 0.008 Sec line step change of 2V. The obtained results for ACFC with all types of controllers are shown in Fig. (8), in Fig.(13) and in Fig.(17). Performance comparision of various types of designed controllers is shown in Table.4.

Table 4. Performace comparision of various types of Designed Controllers

S.No	Type of Controller	Rise Time (Tr)in Sec	Peak Time (Tp) in Sec	Settling Time (Ts) in Sec	Steady State Error (Ess)	% Peak Over Shoot (%Mp)
1	Discrete Time PID Controller	0.0001	0.0001	0.0026	0	26
2	Fuzzy like PID Controllers	0.0002	0.0003	0.0018	0	52
3	Fuzzy Logic Controller	0.0002	0.0002	0.0015	0	44

And the results show that zero volt regulation is achieved by the performance of the designed Fuzzy Logic Controllers as well as discrete-time PID Controller. But the steady state behavior of the designed Fuzzy Logic controller is very good and more robust as compared to the Fuzzy like PID and Discrete-time PID Controllers. Because in the case of Discrete-time PID Controller peak overshoot is reduced, but the settling time is increased as compared to the designed Fuzzy Logic Controller. And the design of Discrete-time PID controller is difficult as compared to the design of the Fuzzy Logic controller. Because to design Discrete-time PID Controller expert knowledge in the design of the controller and mathematical model of the ACFC is required. But expert knowledge in behavior of the converter is sufficient to design Fuzzy Logic Controller. There is no necessity of mathematical model of the converter.

Conclusion

A step by step design procedure of Fuzzy Logic Controller is presented in this research article. The difference between a design procedure of linear controllers and nonlinear controller is presented clearly. The validity of designing models and achievement of desired compensation form designed controller is confirmed by the results of designing Fuzzy Logic Controllers for ACFC. The performance by designing controllers is compared by applying line and load step changes for 48V input ACFC. By analyzing obtained results of the converter, it is observed that Zero Volt Regulation is achieved by the designed controllers. But in the view of the design of the controller, the performance of the converter and implementation of designing controller, Fuzzy Logic Controller has more advantages as compared to other linear controllers. Final results are presented for ACFC with Fuzzy Logic Controllers and with Discrete-time PID Controller by analyzing in different aspects.

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