Soft Computing Techniques for Control of Active Power Filter

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Abstract: **Soft computing methods are flexible and alternative solutions for the control of shunt active power filter (APF) designed for harmonic current mitigation. In this paper, three soft computing techniques viz; Fuzzy Logic, Neural Network and Genetic Algorithm are used to design alternative control schemes for switching the APF. The models for these control schemes were designed and simulated in MATLAB. The results obtained using these soft computing based schemes were compared with the results obtained using a conventional PI Control scheme and a comparative study is presented.**

KEYWORDS: active power filter, neural network, fuzzy logic, genetic algorithm

I. INTRODUCTION

Soft Computing is a technology to extract information from the process signal by using expert knowledge. It either seeks to replace a human to perform a control task or it borrows ideas from how biological systems solve problems and apply to control processes. The main areas in soft computing notably are fuzzy logic, neural network, genetic algorithm, rough sets etc. Soft Computing has experienced an explosive growth in the last decade partially due to uncertainties and vagueness in the process signal and occurrence of random events, and partially due to non-linearity and complexity of the processes. The conventional controllers such as P, PI, PID, etc. cannot provide the desired solution for an adaptive complex system. Soft Computing is an alternative solution to meet the process and user's requirements simultaneously. The authors in this paper therefore have developed algorithms based on fuzzy logic, neuro-fuzzy, and fuzzy- genetic for controlling the switching of a shunt active power filter configuration. The comparative merits and demerits of these schemes including those of a conventional PI algorithm are discussed.

II. PROBLEM IDENTIFICATION

Most of the load and control equipment today, use embedded system, micro controllers and power electronic devices and converters to get the desired control performance. These devices and controllers draw non-sinusoidal current from the supply resulting in the generation of current and voltage harmonics. Active Power Filters have now become an alternative solution to harmonic filtering technology. An active power filter (APF) is a power electronic converter that is switched to inject equal but opposite distorted current in the power supply line, connected to non-linear load. Its switching, regulated by PWM, generates the harmonics to maintain the mains current sinusoidal and in phase with the mains voltage, irrespective of the load current quality. A number of methods exist for determining the reference switching current for APF [1-2]. In this paper we have considered the control strategy based on regulation of the DC capacitor voltage [3-4].

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III. NON-LINEAR LOAD

A computer consists of drives, mother board, interfacing cards, etc. All these systems are supplied the required voltage from switch mode power supply. Thus, a computer can be represented by a single phase bridge rectifier with RC load[5]. For designing the active power filter, we have considered a full bridge rectifier and (R=430Ω & C = 1000μF) load fed from a 230V, 50Hz supply. The supply voltage and current drawn by this load are shown in Fig. 1(a). The harmonic spectrum is shown in Fig.1 (b), it is evident that the load draws a distorted current from the supply and the total harmonic distortion is found to be 149.7%.

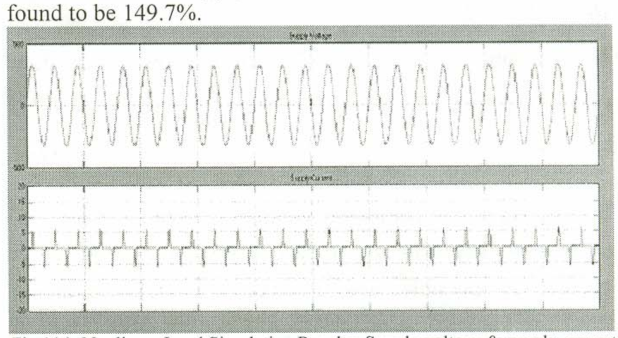

Fig.1(a). Nonlinear Load Simulation Results: Supply voltage & supply current

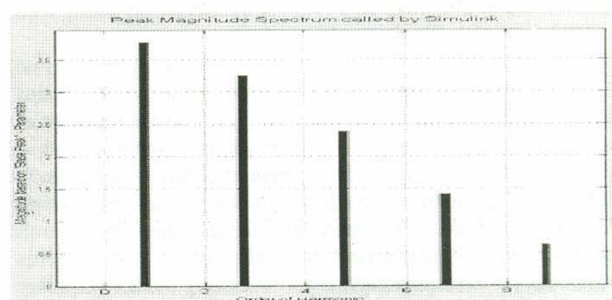

Fig.1(b). Harmonic spectrum of supply current

IV. ACTIVE POWER FILTER

The main objective of the active power filter is to compensate the harmonic currents to the non- linear load. These filters are generally designed around a PWM bridge converter having a capacitor on the DC side. Fig.2 shows the shunt active power filter configuration with generic controller. The switching frequency f_{sw} of the bridge determines the frequency range of harmonic currents that are generated by APF. It is expected to correct up to $f_{sw}/10$ or $f_{sw}/5$. The aim now is to determine how to control this switching so that the voltage source lines, the non linear load and the filter work together. This leads to design the control algorithm which is best suited to compensate the harmonic currents. In the subsequent sections we have presented the study using some intelligent algorithms [6] such as fuzzy logic, neuro-fuzzy and fuzzy-genetic which take into account the uncertainty due to the dynamics in load. From fig.2 of APF, the following equations can be written.

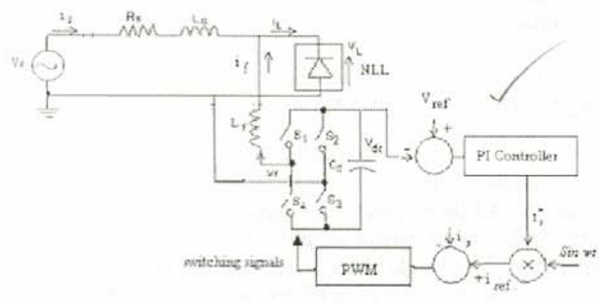

Fig.2. Configuration of Active Power Filter

$$i_s = i_l + i_f \text{ , and} \tag{i}$$

$$\frac{di_f}{dt} = \frac{V_s}{L_f} + \frac{v_f}{L_f} \tag{ii}$$

The filter output voltage v_f can be controlled only by the duty cycle of bridge u_f. Therefore, we obtain

$$v_f = u_f . V_{dc} \tag{iii}$$

The problem of soft computing control algorithm is, therefore, to determine duty cycle u_f in such a way that V_{dc} remains as constant as possible and produce the right harmonic compensated current. The active power filter consists of a single-phase voltage source inverter with an energy storage capacitor C_d at DC bus. This APF is connected in shunt with the load through a filtering inductor L_f.

The average voltage of the capacitor can supply the real power information and the desired amplitude of the mains current can be obtained by using a voltage regulation circuit of the DC capacitor. The DC bus voltage is compared with a reference setting voltage. The compared result is fed to a PI controller to generate the desired amplitude of mains current. The output of the PI controller is multiplied by a unit amplitude sine wave derived from the mains voltage. This constitutes the reference current for switching the active power filter. This is then compared with the actual supply current and fixed frequency PWM is used to generate the switching signals for the inverter. The switch control applies $+V_f$ or $-V_f$ on the ac side, forcing the compensation current to track the reference current. For proper operation of the filter the DC bus voltage V_{dc} (t) is maintained greater than the peak of the supply voltage V_S (t). The filter current i_f can be forced to increase or decrease if $V_f > |V_S|$.

V. PI ALGORITHM

The generic controller shown in fig.2 is replaced with PI controller. In this controller, the control action is determined according to:

$$u(t) = k_p\{V_e(t) + (1/\tau_e)\int V_e(t)\,dt\} \tag{iv}$$

Here, error $V_e(t)$ is the difference between reference voltage(400 V) and dc capacitor voltage V_{dc}, sensed using a voltage sensor. k_p is the gain of the controller and τ_e is the time constant. Under transient conditions, the rate at which u(t) changes is given by:

$$du(t) / dt = k_p\{dV_e(t) / dt + V_e(t) / \tau_e\} \tag{v}$$

At steady state derivatives of u(t) and $V_e(t)$ will be zero. Therefore, $V_e(t)$ also becomes zero. In discrete form we may write these equations as below:

$$V_e(t) = V_{ref}(n) - V_{DC}(n) \tag{vi}$$

$$V_0(n) - V_0(n-1) = K_p\{V_e(n) - V_e(n-1)\} + K_i V_e(n) \text{ or}$$

$$V_0(n) = V_0(n-1) + K_p\{V_e(n) - V_e(n-1)\} + K_i V_e(n) \tag{vii}$$

where k_p and K_i are proportional and integral gain constants. $V_0(n-1)$ and $V_e(n-1)$ are the output of the controller and voltage error at the $(n-1)^{th}$ sampling instant. The output voltage $V_0(n)$ of the controller is limited to a safe permissible value and limited to peak value of supply current I_s^*. Similarly, the expression for capacitor voltage taking into account the ripple due to the compensating current is written as:

$$\frac{dV_{DC}}{dt} = u\frac{i_f}{C_{dc}} \tag{viii}$$

B. Simulation Results

The scheme was modeled and simulated in MATLAB and the results are shown in Fig.3. The load current remains unchanged but the supply current after compensation is seen to be sinusoidal and in phase with the supply voltage. Transient behavior of the APF system may be observed from Fig.3 for addition and removal of load at 0.1ms and 0.3ms. The supply current is found to settle to the new steady state value within one cycle. There is an energy imbalance when load changes and the dc bus voltage fluctuates. It is observed that the dc capacitor voltage settles smoothly to its steady state value within two cycles. There is substantial reduction in the harmonic contents of supply current as is evident from Fig. 3(g) and the reduction in percentage THD is found to be 97%.Though the response to step change in load is quite satisfactory it has been observed that there is a tendency to over shoot Fig. 3(f).

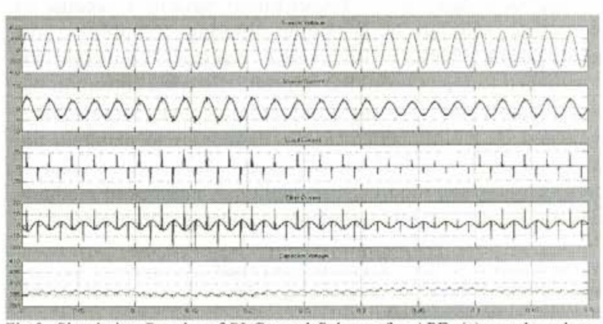

Fig.3. Simulation Results of PI Control Scheme for APF; (a) supply voltage, (b) compensated supply current, (c) load current, (d) filter current, (e) voltage across dc capacitor.

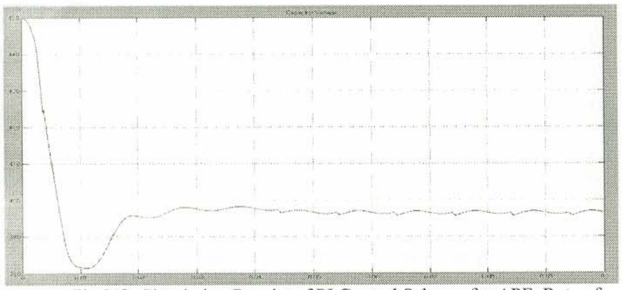

Fig.3(f). Simulation Results of PI Control Scheme for APF: Rate of compensation for an error of 50V

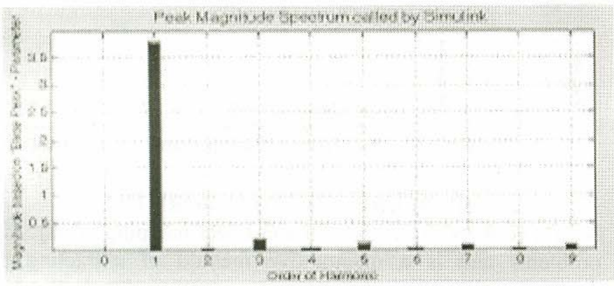

Fig.3 (g). Harmonic spectrum of compensated supply current

VI. FUZZY CONTROL ALGORITHM

Fuzzy logic [7] is a multi level logic system in which the fuzzy logic set has a degree of membership associated with each variable. Basically, a fuzzy set has three principal components: (i) A degree of membership measured along the vertical axis (Y), (ii) the possible domain values for the set along the horizontal axis (X) and (iii) the set membership function (a continuous curve that connects the domain values to the degree of membership in the set). A large class of fuzzy sets represents approximate members of one type or other. Some of these fuzzy sets are explicitly fuzzified numbers whereas others simply represent fuzzy numeric interval over the domain of a particular variable. Fuzzy numbers, hence, can take many shapes triangular, trapezoidal, sigmoid and bell shape etc. The fuzzy set principally attributes two fuzzy numbers; a center value and a degree of spread. The degree of spread is also called as the expectancy (E) of the fuzzy number when the fuzzy number is a single point it is called single tone. As the expectancy increases the number becomes fuzzier. This results in an increase in information and entropy. Triangular fuzzy membership shape is commonly employed in control applications due to primarily low computational costs of creating and integrating triangular fuzzy sets. However, they are less robust. The sigmoid function and bell shaped fuzzy numbers are better in robustness since their center value is not a single point. The trapezoidal number is slightly different from the triangular and sigmoid number shapes because the set does not pivot around a single central number. In the present study, we have considered triangular membership functions only. Fig.4. shows the structure of fuzzy controller for APF.

A. Fuzzy Control Scheme for APF

In order to develop the fuzzy logic control algorithm for APF [8], we have considered two inputs: (i) The voltage error (e) (reference voltage minus actual capacitive voltage), (ii) the change of capacitive voltage (ce) (previous error minus current error) over one sample period.. The two inputs are represented by sets of seven membership functions and the output by a set of nine membership functions as shown in fig.5.

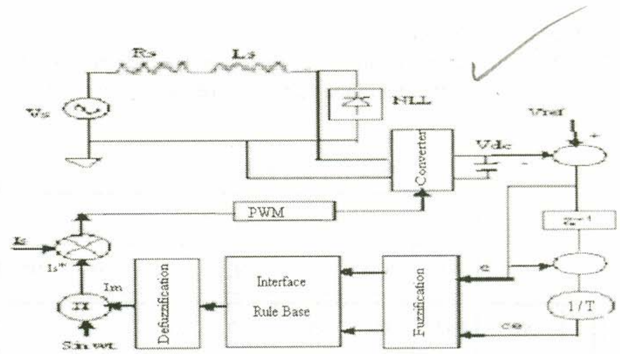

Fig.4. Structure of fuzzy controller for APF

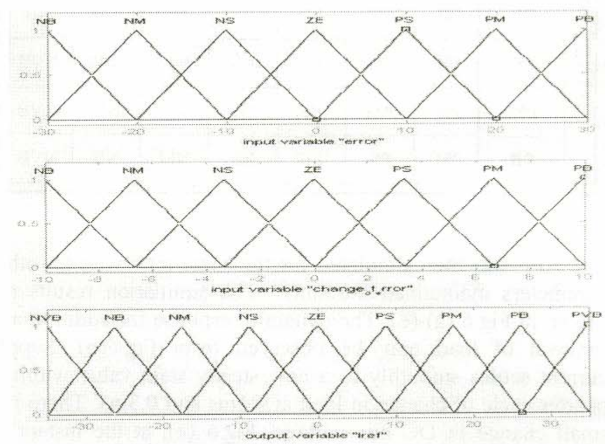

Fig.5. Membership functions for the Fuzzy PI Scheme for control of APF

The range for the 'error' input was set as [-30 30] and that for 'change of error' was set as [-10 10]. A limiting block was introduced before the fuzzy block in order to truncate values beyond these ranges before supplying them to the fuzzy logic controller. The output was represented by a set of 9 membership functions whose shape was taken similar to the shape of the input membership functions. The range of output was set to [-35 35]. Thus, fuzzy control algorithm for regulation of DC capacitor voltage implements a 49 rule Fuzzy Inference System (FIS) that can replace the PI controller block in the control scheme of APF. The 49 rule FIS accepts error and change of error in the capacitor voltage as inputs and gives the required magnitude of supply current I_m. Centroid method was used for the de-fuzzification. The de-fuzzified output (I_m) of the fuzzy controller was then multiplied by a unit sine wave in order to bring it in phase with the supply voltage. The error between the reference generated by the fuzzy logic controller $I_s^*$and the sensed supply current I_s is fed directly to the PWM generator, which uses it to generate the APF switching signals

The 49 fuzzy if-then weighted rule base was designed using the pendulum analogy. The rule matrix so designed is shown in Table I. The AND method used during interpretation of the if-then rules was 'min' and the OR method used 'max'. Also ‘min’ was used as the implication method whereas ‘max’ method was used for aggregation.

B. Simulation Results

The PI controller block in the control scheme of APF, Fig. 1, was replaced by the designed fuzzy inference system (FIS).

Table I: Fuzzy Rule Base

CHANGE OF ERROR	ERROR: NB	NM	NS	ZE	PS	PM	PB
NB	PVB	PB	PM	PS	ZE	NS	NM
NM	PVB	PB	PM	PS	NS	NM	NB
NS	PVB	PB	PM	PS	NS	NM	NB
ZE	PB	PM	PS	ZE	NS	NM	NB
PS	PB	PM	PS	NS	NM	NB	NVB
PM	PB	PM	PS	NS	NM	NB	NVB
PB	PM	PS	ZE	NS	NM	NB	NVB

The APF was then simulated for the same load with all other parameters maintained the same. The simulation results are shown in Fig.6 (a)-(e). The dynamic response for addition and removal of load may be observed from Fig.6(b). Supply current settles smoothly to a new steady state value within a quarter cycle of change in load at 0.1ms and 0.3ms. There is a small change in DC bus voltage, Fig.6 (e), at the instant of disturbance in load to balance extra energy due to increased or decreased level of compensation. DC bus voltage settles to its steady state value within a few cycles. Also with a large deviation the capacitor voltage is found to reach steady state without overshooting the set value as is evident from Fig.6(f). Harmonic spectrum of the compensated supply current is shown in Fig. 6(g). It was observed that the supply current after compensation becomes sinusoidal with a 97.88% reduction in total harmonic current distortion. The FIS controlled APF is found to give a better and robust performance under transient and varying load conditions.

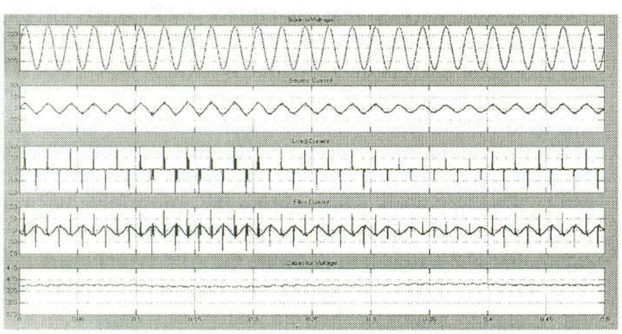

Fig.6. Simulation Results of fuzzy Control Scheme for APF; (a) supply voltage, (b) compensated supply current, (c) load current, (d) filter current, (e) voltage across dc capacitor

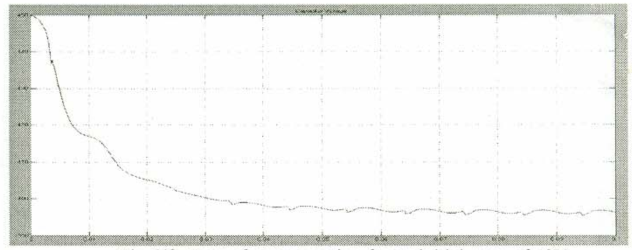

Fig.6(f). Rate of compensation for an initial error of 50V

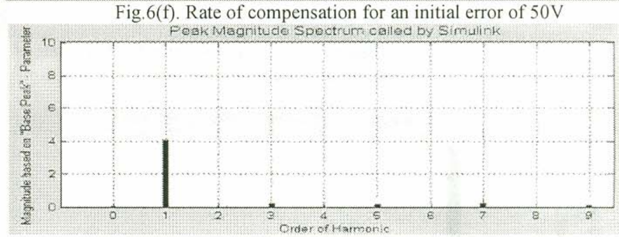

Fig.6(g). Harmonic spectrum of compensated supply current

VII. NEURO- FUZZY ALGORITHM

Neural network [9] deals with non-linear mapping of objective problems and is a quantitative method of extracting the required information from the raw process signal. Fig.7.(a) represents an artificial neuron model.

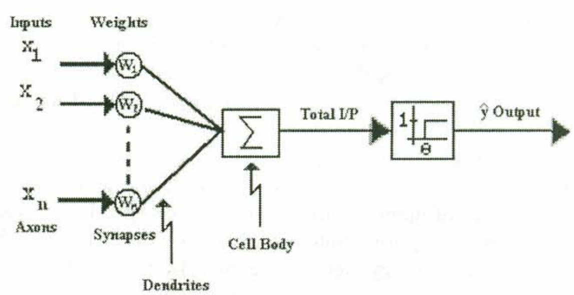

Fig.7. (a) Artificial Neuron Model

The output $\hat{Y}$ is given by the equation

$$\hat{Y} = 1; \ \sum w_i x_i \geq \theta$$
$$= 0; \ \sum w_i x_i < \theta$$

Here w_i are the connection weights and no set guidelines or rules are present to select these weights. In our present study we have computed these weights with fuzzy logic tool, using Hybrid method for training the neural network. The hybrid approach deals with linguistic variables and numerical variables. In this type of model, condition part uses linguistic variables and conclusion part is represented by numerical value. Fig.7(b). shows the general fuzzy neural net model. In this scheme instead of choosing the membership function parameters based on the system behavior the artificial neural network was trained to choose membership parameters automatically. The system is modeled using the Sugeno type FIS, which is ideal for implementing neuro- adaptive learning techniques. In a Sugeno type system the output membership functions are either linear or constant. A typical rule in a Sugeno fuzzy model is given as;

If input1 = x and input 2 = y, then output z = ax + by + c

The output level 'z_i' of each rule is weighted by the firing strength w_i of the rule. For an AND rule in the above case the firing strength is

$$w_i = \text{AND Method } [F_1(x), F_2(y)]$$

where F(.) are the membership functions for inputs 1 & 2. The final output of the system is the weighted average of all rule outputs computed as

$$\text{Final output} \quad \hat{Y} = \sum w_i z_i / \sum w_i$$

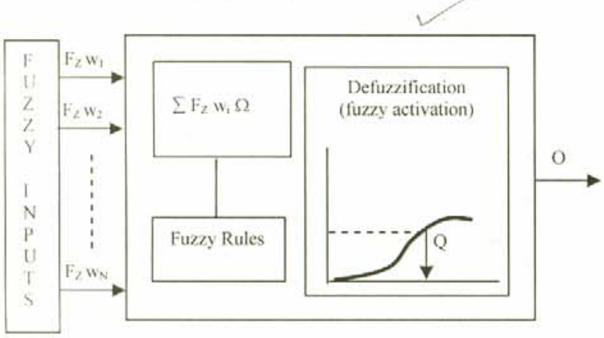

Fig.7(b). Fuzzy-Neural Net Model

Fig.8. shows how the Sugeno rule operates. The Sugeno system is computationally efficient and compact and hence was chosen to construct the fuzzy models.

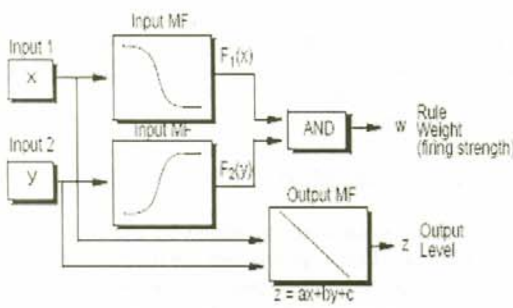

Fig.8. Sugeno Inference Method

A. Neuro-Fuzzy Control Scheme for APF

Neural Network has been used to generate the switching signals directly for control of APF [10]. The computation involved increases the response time considerably. The authors in this paper have instead used neural network to customize the membership functions so that the fuzzy system best models the control data. In a fuzzy neural system, the neural network essentially implements the functions of a fuzzy system. The first network fuzzifies the crisp input data and the second or hidden network layer implements the fuzzy rules. Finally defuzzification of the fuzzy output is done by the third network to provide the crisp data output. In the proposed scheme of developing a Artificial Neural Network based Fuzzy Inference System (ANFIS) for control of the active power filter the following steps were used:

1. Error and change of error values generated by the Mamdani type FIS with 49 rules and triangular MF's were provided to the ANFIS as training data.
2. Output generated by the above specified Mamdani type FIS was provided as checking data.
3. A 25 rule, Sugeno FIS was selected with 5 input triangular membership functions and constant MF's were selected for output.
4. Back propagation and Hybrid methods were selected to train the FIS generated with training limited to 1000 epochs and error tolerance limit set to zero.

The input membership functions so generated are shown in Fig.9 and the fuzzy inference system is shown in Fig.10. The variation of the generated output with the training data provided to the neuro-fuzzy system is shown in Fig.11. It also depicts the training error for every iteration, to guard against over fitting of the training data set.

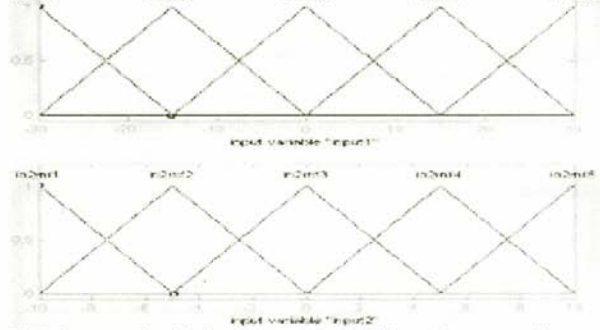

Fig.9. Input membership functions generated by Neuro-Fuzzy controller

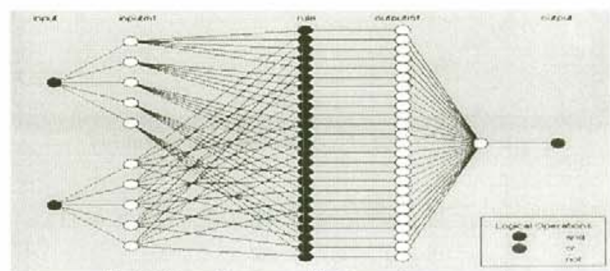

Fig.10 FIS model generated by Neuro-Fuzzy controller

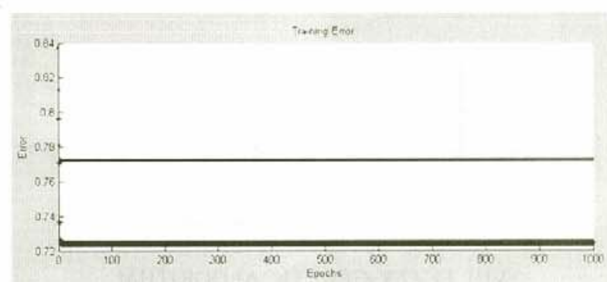

Fig.11. Variation in Training Error with Epoch no.

B. Simulation Results

The proposed scheme was simulated using the MATLAB ANFIS editor to design the tuned Sugeno type FIS, which was then used to control the APF by incorporating them in the fuzzy logic controller block. The system was tested for fixed as well as variable load and the results are shown in Fig.12. It was observed that the neuro-fuzzy system emulated the fuzzy performance satisfactorily and was computationally more efficient and faster. It was observed that the supply current after compensation becomes sinusoidal with a 98.46% reduction in total harmonic current distortion. The transient response under varying load conditions was found to be same as that achieved by the fuzzy control system.

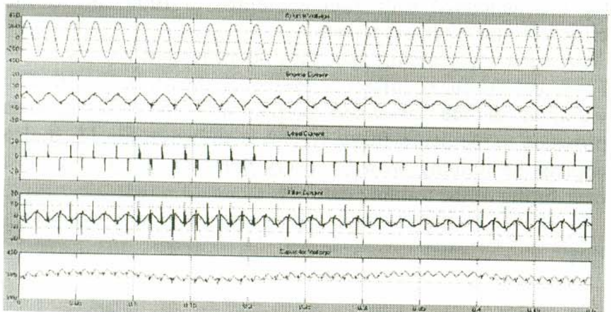

Fig.12. Simulation Results of Neuro-Fuzzy Control Scheme for APF; (a) supply voltage, (b) compensated supply current, (c) load current, (d) filter current, (e) voltage across dc capacitor

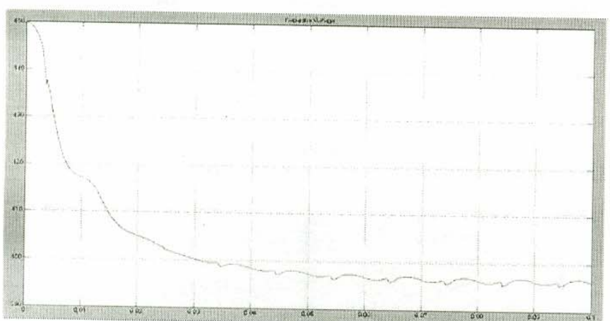

Fig.12 (f). Rate of compensation for an error of 50V

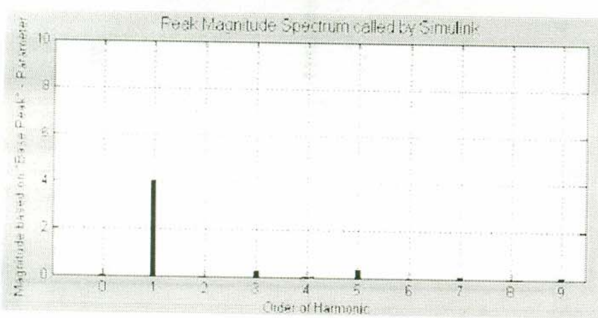

Fig.12(g). Harmonic spectrum of compensated supply current

VIII. FUZZY-GENETIC ALGORITHM

Genetic Algorithm (GA) is essentially a search algorithm inspired by the process of natural evolution. It is a method for solving optimization problem through a search procedure. The major components of genetic algorithm are encoding schemes, fitness evaluation, parent selection, crossover operators and mutation operators. Switching signals for APF have been derived directly using GA [11]-[13] but the method is found to be best suited offline due to the computational delay involved. In this paper a fuzzy- genetic approach has been proposed to control the APF. A fuzzy-genetic algorithm is a directed random search over all fuzzy subsets of an interval. The optimization abilities of GA are used to develop the best set of rules to be used by a fuzzy system and to generate a custom membership function [14]-[18]. The training data and randomly generated rules are combined to create the initial population giving it a better starting point for reproduction. Finally a fitness function measures the strength of the rules, optimizing quality and diversity of population. A typical fuzzy genetic scheme is as shown in figure 13.

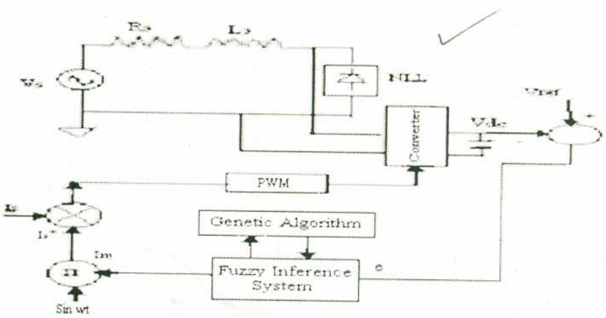

Fig. 13. Structure of fuzzy-genetic controller for APF

A. Fuzzy-Genetic Control Scheme for APF

The fuzzy-genetic approach to generate switching signals for the APF involves using GA to design a custom membership function shape so as to produce a 25 rule [5×5] FIS which can give results at par with those obtained using the weighted triangular MF's presented earlier in the fuzzy control scheme for APF. A custom membership function was defined and one interval of the membership function was divided into 11 equal sections by 10 points. These points denote the value of the 'Y' co-ordinate of the membership function. The 12-bit string so formed is given below;

[start, p1, p2,p3,p4, p5,p6,p7,p8,p9,p10,end]

The intermediate values are calculated by linear interpolation between any two of these points and the membership function value before 'start' and after 'end' is taken as zero. A fitness function was designed which accepts 10 inputs and fitness of FIS was calculated. All input membership functions (MF) of a predefined 25 rules triangular MF FIS were replaced by the new custom MF. The new FIS was then evaluated for all input values from an evaluation data file. The results so obtained were then compared with the results obtained using the weighted 49 rule triangular membership functions. The fitness value was calculated so as to minimize the error between the results obtained by the two FIS.

B. Simulation Results

This scheme was implemented by designing custom input MFs All weights were considered to be 1. The GA settings used in implementing the Fuzzy-Genetic control are as follows:
Population Size: 40,Type: double, Creation: Uniform
Fitness Scaling: Rank
Selection: Tournament; Size 4
Reproduction: Elite Count: 4, Crossover fraction: 0.8
Mutation: Uniform, Rate: 0.2
Crossover: Scattered
Migration: Interval: 10 generations, Fraction: 0.2

Stopping Criteria: Generation = 150, Fitness = 0,
Stall Generations = 50, Stall time = Inf

Fig.14. shows the optimized input membership function shapes generated by GA and Fig.15 shows the fitness value achieved in each generation. Standard triangular MF's were used for output. The FIS generated by implementing this scheme was then incorporated into the fuzzy logic controller in the basic fuzzy model of APF controller and simulated for fixed and variable load. Rate of compensation was also observed. Simulation results for the active power filter controlled with a fuzzy-genetic control scheme are shown in Fig.16 (a)-(e). An excellent dynamic response for addition and removal of load may be observed from Fig.16(b). Supply current settles smoothly to a new steady state value within a quarter cycle of change in load at 0.1ms and 0.3ms. It was observed that the supply current after compensation becomes sinusoidal with a 98.46% reduction in THD. The system response to load change was found to be at par with the fuzzy control scheme.

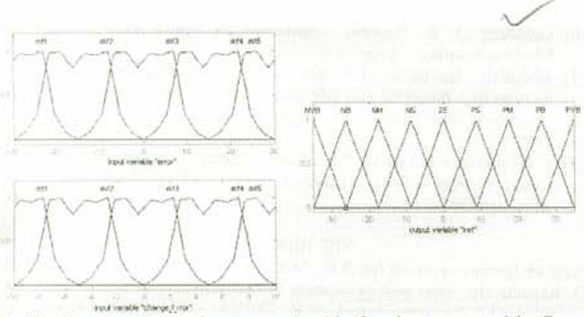

Fig.14. Custom Input & Output membership functions generated by Fuzzy-Genetic Control Scheme for APF

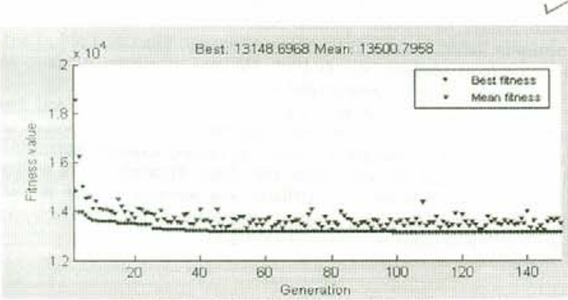

Fig.15. Variation of fitness function with generation

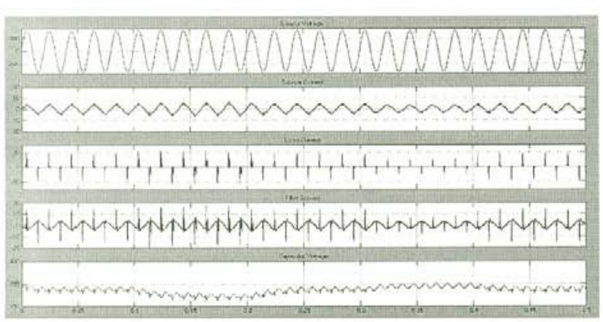

Fig.16. Simulation Results of Fuzzy-Genetic Control Scheme for APF; (a) supply voltage, (b) compensated supply current, (c) load current, (d) filter current, (e) voltage across dc capacitor

IX. DISCUSSION

The conventional PI algorithm for regulating the DC bus to generate the reference supply current was found to lack the capacity to adjust satisfactorily to large fluctuations. Though the response to step change in load was quite satisfactory it was observed that there is a tendency to over shoot. Also the fine-tuning of the PI parameters has to be done by trial and error and is time consuming.

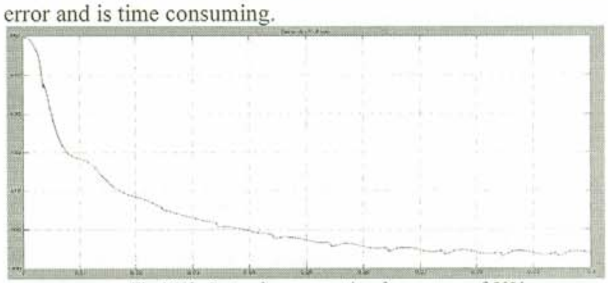

Fig.16(f). Rate of compensation for an error of 50V

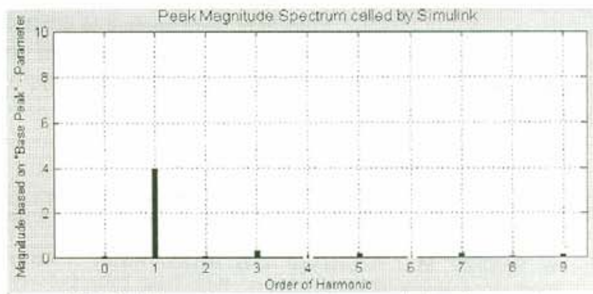

Fig.16(g). Harmonic spectrum of compensated supply current

The fuzzy control algorithm for regulation of the DC capacitor voltage was designed to implement a 49 rule Fuzzy Inference System (FIS) that can replace the PI controller block in the control scheme of APF. It is observed that the filter responds to the changed load conditions within a quarter of a cycle. From the transient response it is clear that the fuzzy alternative to the conventional PI control provides better and fast dynamic response. Though versatile, the fuzzy alternative to conventional PI control was seen to be slow and computationally intense as 49 rules were involved.

Neural Network has the advantage that it can manage with less information than that needed by fuzzy logic. This fact was used to design a neuro-fuzzy controller for controlling the APF. In a fuzzy-neural system, a neural network can be trained to discover relationship and patterns in data and can be used to generate a fuzzy inference system. It was observed that the neuro-fuzzy system emulated the fuzzy PI controller satisfactorily with less number of rules. Also de-fuzzification was avoided by using the Sugeno type FIS. The system designed with just 25 rules, as compared to the 49 rule based Fuzzy control provided good harmonic current compensation and was much faster in generating the FIS.

The performance of fuzzy control and consequently neuro-fuzzy control is limited by the use of standard membership functions. Genetic Algorithm was used to overcome this limitation. The fuzzy-genetic approach involved using GA to design a custom membership function shape. In the fuzzy-genetic controller, the genetic tuner optimized the architecture of the fuzzy model by creating a population of new process parameters. The fuzzy tuned FIS was observed to give results on par with those obtained using the 49 rule triangular MFs. The approach resulted in a reduced rule set (25 rules) with unit weights assigned to the rules. The complexity of assigning weights to the rules was eliminated and the optimized membership shape was found to give the best harmonic compensation over the other schemes. It was observed that though GA was applied to build custom input, output and both input/output MFs, its application to only input MFs yielded the desired compensation performance.

X. CONCLUSION

The overall aim of this work was to study the methods of achieving better utilization and control of Active Power Filters dealing with harmonic current compensation. Alternative schemes based on soft computing techniques have been proposed. The control schemes based on soft computing methods do not require the mathematical model. Fuzzy logic, neural network and Genetic Algorithm were applied to control the switching of the active power filter and were found to provide much better response under varying load and supply conditions.

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XIII. BIOGRAPHIES

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