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PERFORMANCE COMPARISON OF ANN, FLC and PI CONTROLLER BASED SHUNT ACTIVE POWER FILTER for LOAD COMPENSATION

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***Abstract* – To reduce the power quality issues, it is important to eliminate the harmonics in the power systems. The harmonic elimination through Shunt Active Power Filter (SAPF) provides higher efficiency when compared with other filters.Nonmodel-based controllers have been designed for the control of a SAPFto reduce the distortion which is created by the non-linear loads.An Artificial Neural Network (ANN) is becoming a deterioration technique in many controlapplications due to its parallel operation and high learningcapability. In this paper, the Least Mean Square (LMS) based ADALINEANN is proposed to regulate the DC bus voltage (V_{dc}) to eliminate harmonics and load compensation in the system. The Simulink model of the proposed system is developed using MATLAB/SIMULINK tool. The performance of anANN controller is compared with FLC and conventional PI controller.The proposed method offers a better dynamic response and efficient control in varying load conditions.**

***Index terms:* Power Quality, Harmonic Elimination, Shunt Active Power Filter, Neural Network controller.**

I. INTRODUCTION

Many domestic and industrial non-linear loadsare power electronic switching devices such as television, personal computers, business and office equipment namely copiers, printers, industrial equipment such as Programmable Logic Controllers (PLCs), Adjustable Speed Drives (ASDs), rectifiers, inverters, CNC tools. The power quality issues like interruptions, voltage sag, swell, harmonics, noise and switching transients are occurred in power system and introduces serious power pollution to the utility side. Among these power quality issues, the harmonics are the major contribution for polluting the power grid. Traditionally, passive LC filters have been used to avoid these effects [1]. The resonance, fixed compensation and huge size are the problems arising in passive filters. These problems are overcome by the introduction of active filters which addresses more than one harmonic at a time.

Among the active filters, the SAPF is a power electronic converter that is connected in parallel and cancels the reactive and harmonic currents due to non-linear load [2]. Ideally, the SAPF needs to generate reactive and harmonic current to compensate the non-linear loads in the supply line. The SAPF is Voltage Source Inverter (VSI) with DC side capacitor (C_{dc}) and used to generate the filter current (i_f) and is injected into the utility power grid. This cancels the harmonic components by the non-linear load and keeps the utility line current (i_s) sinusoidal [3]. It has the advantage of carrying the compensation current and small amount of active fundamental current supplied to compensate for system losses.

The V_{dc} is regulated by using PI controller. This improves the system performance effectively. Several techniques are available to generate the switching current for the APF [4]-[6]. Bhim Singh et al proposed PI control algorithm for single phase SAPF [7]. In PI control strategy, reference current is calculated by sensing only line currents [8]. The PI controller requires accurate linear mathematical models, which fails to perform satisfactorily under non-linearity, load disturbances and parameter variations [9].

The conventional control requires mathematical analysis of the system so soft computing is an alternate solution to control the APF. Soft computing is a technology to extract information from the process signal by using expert knowledge. In order to enhance the performance of SAPF, genetic algorithm, bacterial foraging technique, particle swarm optimization, Ant Colony Optimisation (ACO), fuzzy logic controller and ANN technique are employed. The SAPF is optimized by bacterial foraging (BF) technique for load compensation in [4] and Ant colony optimization (ACO) in [5]. The APF is controlled by ANN technology in [10]-[11]. The adaptive neural network compensation algorithm is used to compensate harmonics and reactive power for PQ and DQ strategy [14]-[15]. The Takagi Sugeno-FLC and mamdani FLC are compared in [16]. The FLC with different membership functions are compared in [17]-[18]. The conventional PI, FLC and ANFIS are compared in [12]-[13] based on PQ strategy.

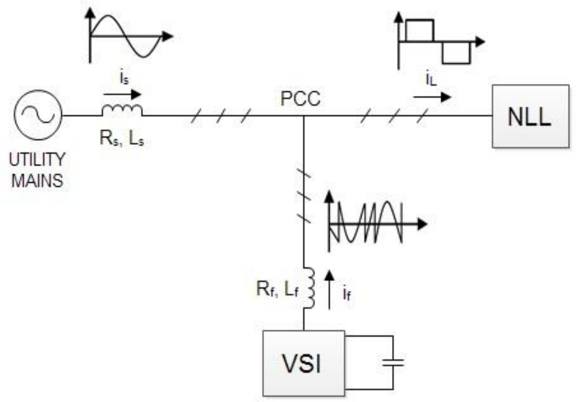

Fig.1 Basic principle of SAPF

In this paper, an ANN is used for controlling SAPF. The performance indices considered are percentage peak overshoot (%Mp), DC link voltage settling time (V_{dc}_Ts) and Total Harmonic Distortion (%THD). The proposed ANN controller offers improved dynamic response by comparing with FLC and conventional PI controller.

II. REFERENCE SOURCE CURRENT ESTIMATION METHOD

Due to non-linear load, the harmonic distortion occurs in the supply system and in other loads which are connected from the same supply. Hence the SAPF is connected across the main supply system at Point of Common Coupling (PCC). Fig.1 shows the basic principle of SAPF. It controls and cancels the current harmonics on the utility side by supplying a compensating current which makes the source current in phase with the source voltage [3].

From Fig.1, the instantaneous current is given by Eq. (1):

$$i_s(t) = i_L(t) - i_c(t) \qquad (1)$$

The utility source voltage is given in Eq. (2):

$$v_s(t) = V_m sin\omega t \qquad (2)$$

If a non-linear load is applied, then the load current will have a fundamental component and harmonic components, which can be expressed as in Eq. (3):

$$i_L(t) = I_1 \sin(\omega t + \varphi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \varphi_n) \quad (3)$$

The instantaneous load power can be given in Eq.(4):

$$p_L(t) = v_s(t) * i_L(t)$$

$$p_L(t) = V_m I_1 sin^2\omega t * cos\varphi_1 + V_m I_1 sin\omega t * cos\omega t * sin\varphi_1 + V_m \sin\omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \varphi_n) \qquad (4)$$

$$p_L(t) = p_f(t) + p_r(t) + p_h \qquad (5)$$

From Eq. (4) and (5), the real power drawn by the load is given by:

$$p_f(t) = V_m I_1 sin^2\omega t * cos\varphi_1 = v_s(t) * i_s(t) \qquad (6)$$

From Eq. (6), the current supplied by the source, after compensation is

$$i_s(t) = \frac{p_f(t)}{v_s(t)} = I_1 cos\varphi_1 * sin\omega t = I_{sm} sin\omega t$$

where

$$I_{sm} = I_1 cos\varphi_1$$

There are also some switching losses in the PWM converter and so the utility must supply a small overhead for the capacitor leakage and converter switching losses accumulated with real power of the load.

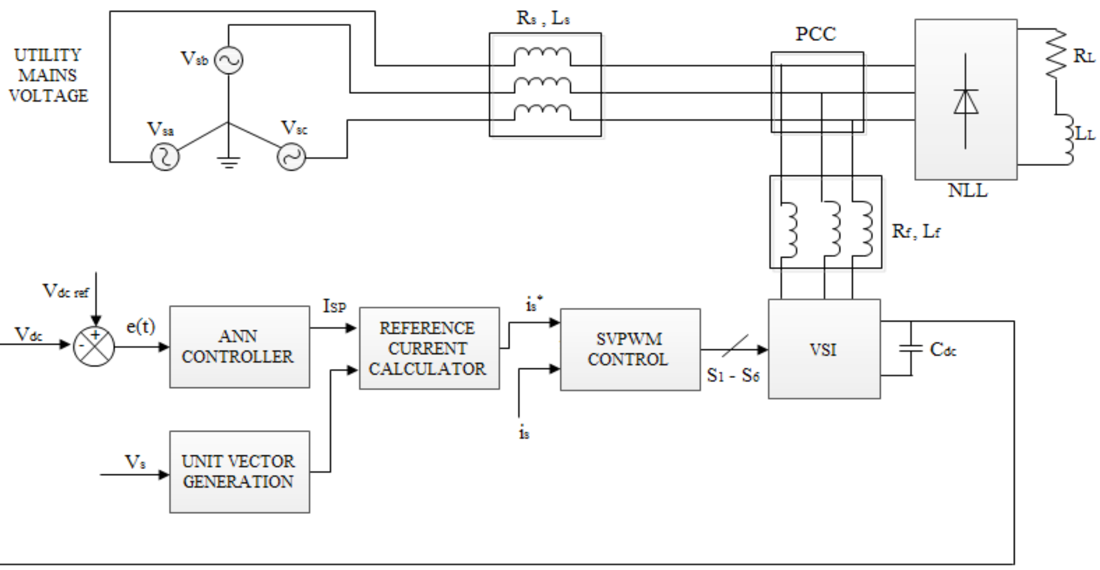

Fig.2. Schematic diagram of ANN controller based SAPF

The total peak current supplied by the source (I_{sp}) is given by Eq. (7)

$$I_{sp} = I_{sm} + I_{sl} \qquad (7)$$

where, I_{sl} is the peak value of the loss current

If the active filter provides the total reactive and harmonic power, then it will be in phase with the utility voltage and purely sinusoidal. At this time, the active filter must provide the compensating current as in Eq. (8):

$$i_f(t) = i_L(t) - i_s(t) \qquad (8)$$

Thus, for accurate and instantaneous compensation of reactive and harmonic power, it is necessary to estimate $i_s(t)$ (i.e., the fundamental component of the load current as the reference current). The peak value of the reference current can be estimated by controlling the DC side capacitor voltage. Ideal compensation requires the main current to be sinusoidal and in phase with the source voltage, irrespective of the load current nature. The desired source currents, after compensation, can be given as in Eq. (9):

$i_{sa}^{*} = I_{sp} \sin \omega t$
$i_{sa}^{*} = I_{sp} \sin(\omega t - 120)$(9)
$i_{sa}^{*} = I_{sp} \sin(\omega t + 120)$

where I_{sp} is the amplitude of the desired source current, while the phase angle can be obtained from the source voltages.

Hence the I_{sp} needs to be determined. The peak value of the reference current has been estimated by regulating the C_{dc} voltage of the PWM converter. The capacitor voltage is compared with a reference value and the error is processed in ANN controller. The output of the ANN controller has been considered as the amplitude of the desired source current and the reference currents are predicted by multiplying this peak value with the unit sine vectors in phase with the source voltages. The detailed schematic diagram of ANN controller based SAPF is shown in Fig.2. The modified Space Vector Pulse Width Modulation (SVPWM) current control scheme [19] is used to generate switching pulse of SAPF. In this paper, the performance of proposed ANN controller is compared with FLC and conventional PI controller of SAPF.

III. DESIGN OF ANN CONTROLLER

An ANN is implemented to control the C_{dc} voltage based on processing of the V_{dc} error i(n) is used to improve the dynamic of SAPF. An ANN consists of a large number of strongly connected elements. The artificial neurons represent a biological neuron conceptconceded in a computer program. The artificial neuron model is shown in Fig.3.

Inputs i(n) enter into the processing element from the left. The first step is to multiply each of these inputs by their respective weighting factor w(j). These modified inputs are then fed into the summing function Σ(w(j)*i(n)and the information flow to the output through a transfer function which may be the threshold function, sigmoid function, tangential function, Gaussian function, hyperbolic function, linear function or pure linear function. [20]

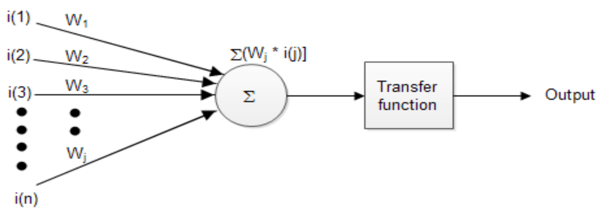

Fig.3.Artificial Neuron model

Inputs i(n) enter into the processing element from the left. The first step is to multiply each of these inputs by their respective weighting factor w(j). These modified inputs are then fed into the summing function Σ(w(j)*i(n)and the information flow to the output through a transfer function which may be the threshold function, sigmoid function, tangential function, Gaussian function, hyperbolic function, linear function or pure linear function. [20]

A. *Adaline Based Control Algorithm*

The basic concept of proposed ANN is based on the LMS algorithm and it is trained through ADALINE tracks the unit vector templates to maintain minimum error. The initial weight is set to zero whereas the learning rate is the coefficient of convergence and its value lies between 0 and 1. It is used as 0.001 in the LMS algorithm. The LMS based ADALINE control algorithm is shown in Fig.4.The initial output pattern is compared with the current output and the weights are updatedusing LMS algorithm until the error becomes small.

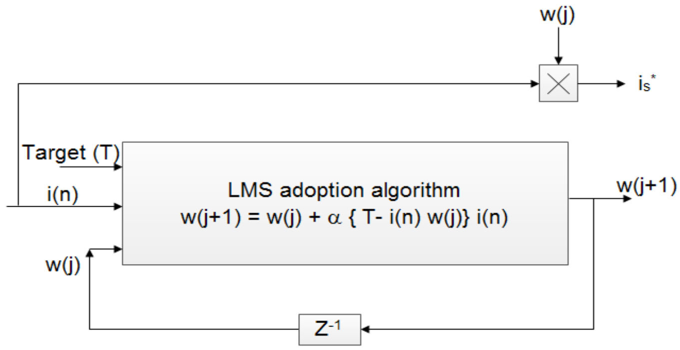

Fig.4.LMS based ADALINE control algorithm

The amplitude of the desired source current is estimated by ANN is given in Eq. (10)

$$Y = \sum_{n=1}^{j} i_n w_j \qquad (10)$$

The updated weighted equation is given in Eq. (11)

$$w(j+1)=w(j)+\alpha e(n)i(n) \qquad (11)$$

where Y is the amplitude of the desired source current, α is learning rate, e(n) iserror between output equation and target value, i(n) isinput values and w(j) is weights of the ADALINE network.

An ADALINE is used to extract the amplitude of desired source is shown in Fig.5. The input of the ANN block i(n) is the errorsignal by comparing the capacitor voltage and reference value.The desired peak value of source current is estimated by using LMS based ADALINE ANN.

The reference currents are estimated by multiplying this desired peak value with the unit sine vectors in phase with the source voltages. The modified SVPWM current control scheme is used to generate switching pulse of SAPF by comparing actual source current and desired source current which is estimated by ANN.

IV. DESIGN OF FUZZY LOGIC CONTROLLER

In order to keep C_{dc} voltage constant [20], the active power flowing into the filter needs to be controlled. If the active power flowing into the filter can be controlled, losses inside the filter get compensated. Then, the V_{dc} can be maintained at the desired value. The FLC is implemented to control the C_{dc} voltage based on processing of the V_{dc} error e(t) and its derivative Δe(t) is used to improve the dynamic of SAPF.

The input variables are given in Eq. [12] & [13],

$$e(t) = V_{dc\,ref} - V_{dc} \qquad (12)$$
$$\Delta e(t) = e(t) - e(t-1) \qquad (13)$$

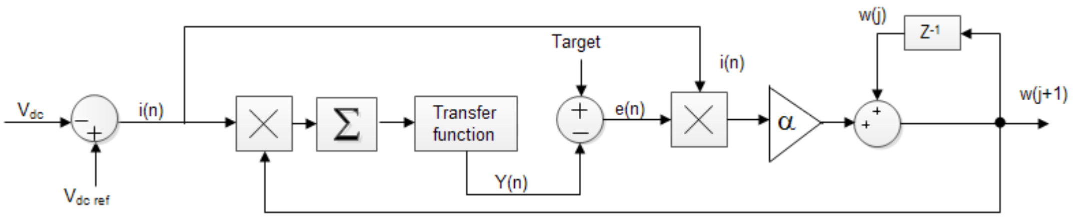

Fig.5. ADALINE is used to extract the amplitude of desired source current

A FLC consists of four stages:

(i) Fuzzification
(ii) Knowledge base
(iii) Inference mechanisms
(iv) Defuzzification

The knowledge base is composed of a data base and rule base, and is deliberated to obtain good dynamic response under improbability in process parameters and peripheralturbulences. The data base, consisting of input and output membership functions, provides information for the suitablefuzzification operations, the inference technique and defuzzification.

The inference technique uses a collection of linguistic rules to transform the input conditions into a fuzzified output. Finally, defuzzification is used to transform the fuzzy outputs into control signals [12]. Fig.6 shows a block diagram of the FLC for DC voltage control of SAPF.

A.Design of Control Rule

To propose the control rules of FLC, the formulation of rule set plays a key role in improvement of the system performance. In the case of the fuzzy logic based DC voltage control, the capacitor voltage deviation (e(t)) and its derivative (Δe(t)) are considered as the inputs of the FLC and the requirement for voltage regulation is taken as the output of the FLC. The input and output variables are transformed into linguistic variables as given in [17].

In this case, the knowledge of the systems behavior is put in the form of rules of inference. The rule table which is shown in Table I contains 49 rules. To convert crisp variables into fuzzy sets, the seven fuzzy sets are NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive large) have been chosen. Normalized triangular membership functions are used for the input and output variables used here are shown in Fig.7.

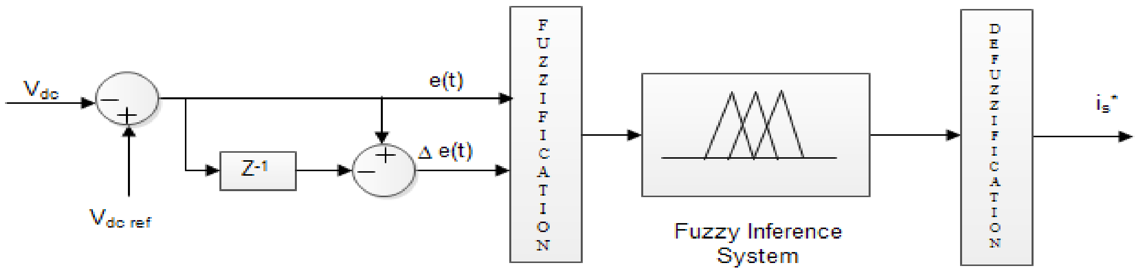

Fig.6. FLC for DC voltage control

TABLE I
RULE SET OF FUZZY SYSTEM

ΔE E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

The FLC of SAPF is characterized as follows:

(i) Seven fuzzy MFs for each input and output.
(ii) Fuzzification using continuous universe of discourse.
(iii) Implication using Mamdani's 'min' operator.
(iv) Aggregation using Mamdani's 'max' operator.
(v) De-fuzzification using the 'centroid of area' method.

V. CONVENTIONAL PI CONTROLLER PARAMETERS

By using conventional PI controller, the performance of the proposed ANN controller of SAPF is evaluated. The SAPF system parameters are presented in Table II. Parameters of the conventional PI controller are designed based on the model in [2]. The values of conventional PI controller proportional gain and integral gain are selected as 0.57 and 10.3 respectively.

TABLE II

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SAPF System Parameters	
V_s – AC supply voltage	100V(peak)
R_s – Source resistance	0.1 Ω
L_s – Source inductance	0.15 mH
V_{dco} – Steady state operating point on V_{dc}	220V
C_{dc} – DC side capacitor	2000 μF
I_{fo} – Steady state operating point of I_f	23.57 A
L_f – Filter inductance	0.66 mH
R_f – Filter resistance	0.1 Ω
R_L – Load resistance	6.7 Ω
L_L – Load inductance	20 mH
$V_{dc\ ref}$ – Reference DC link voltage	220V

VI. SIMULATION RESULTS AND DISCUSSION

The Simulink model was developed using MATLAB SimPower Systems toolbox. The FLC and ANN are designed by using MATLAB fuzzy and neural toolbox. The performance of the FLC and ANN are detailed below.

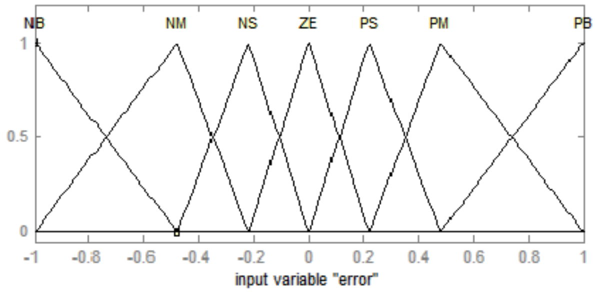
A. *Dynamic Performance of SAPF*

The balanced and sinusoidal three-phase input source voltages are considered. The diode bridge rectifier is considered as load for the system. The Total Harmonic Distortion (THD) before SAPF is 28.01%. The performance of SAPF with the proposed FLC, ANN controller and conventional PI controller has been analyzed for the following three cases.

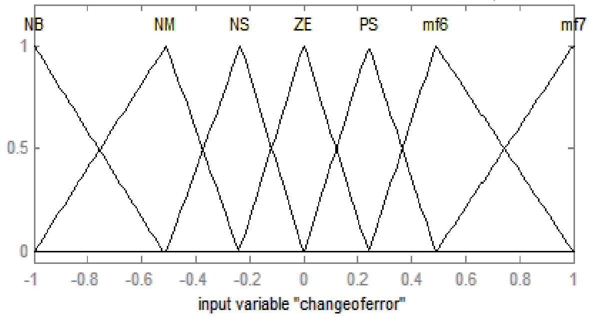
1. Switch-on response

The SAPF is switched on at t=50ms. The concert of DC capacitor voltage of conventional PI controller and FLC controller is given in Fig. 8. The performance of SAPF in terms of V_{dc}_T_s, %Mp and %THD are listed in Table.III. The supply voltage (V_{sa}), supply current (I_{sa}), load current (I_{La}), filter current (I_{ca}) and V_{dc} related to phase-A of conventional PI controller ANN and FLC controller are shown in Fig. 9 to Fig. 11 respectively.

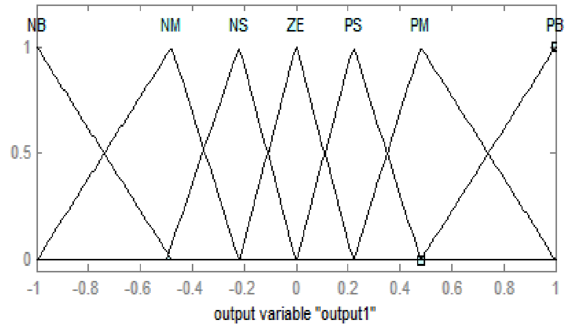
The capacitor voltage of ANN settles at 6ms and FLC settles at 10ms. ANN settles faster compared to conventional PI method takes 310ms. In all the cases, %THD is within the limit of IEEE 519-1992 standard.



(a)



(b)



(c)

Fig.7. Normalized triangular membership function of FLC for: (a) input variable (e(t)), (b) input variable (Δe(t)) (c) output variable (I_{ref})

2.Transient response

To execute the transient analysis, the load resistance is increased from 6.7 Ω to 10 Ω at t=0.3s. The supply voltage (V_{sa}), supply current (I_{sa}), load current (I_{La}), filter current (I_{ca}) and V_{dc} related to conventional PI controller, ANN and FLC controller are shown in Fig. 12 to Fig. 14 respectively. The performance indices are listed in Table.III.

When compared to conventional PI with FLC and ANN, rise or dip in V_{dc} is larger in conventional PI and takes more cycles to settle down. In conventional method, the %THD in source current settles after 3-4 cycles. The FLC takes 10ms and ANN takes 6ms to settle down at V_{dc}

TABLE III
PERFORMANCE ANALYSES OF SAPF BASED ON CONVENTIONAL PI, ANN AND FLC CONTROLLERS

Parameters	**Conventional PI Controller**		**FLC**		**ANN**	
	Switch_on response	**Transient response**	**Switch_on response**	**Transient response**	**Switch_on response**	**Transient response**
Settling time (ms)	310	310	10	10	6	6
%THD	3.88	4.3	3.7	3.9	3.65	3.8
Peak overshoot (%)	0	0	0	0.5	1.3	1.8

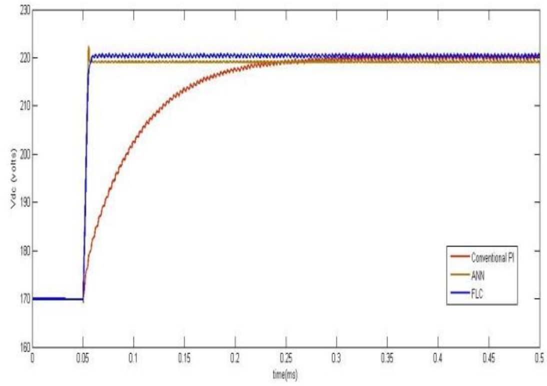


Fig.8. $V_{dc}$of conventional PI, ANN and FLC controller

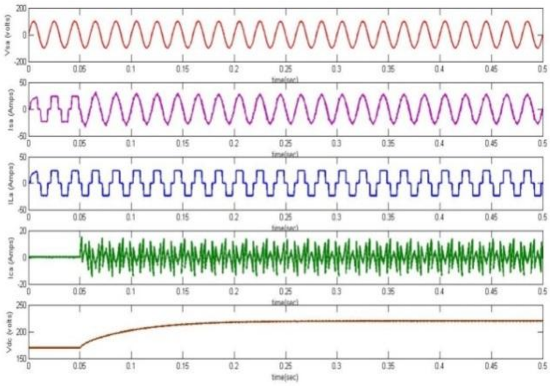


Fig.9.V_{sa}, I_{sa}, I_{La}, I_{ca} and V_{dc}ofConventional PI controller

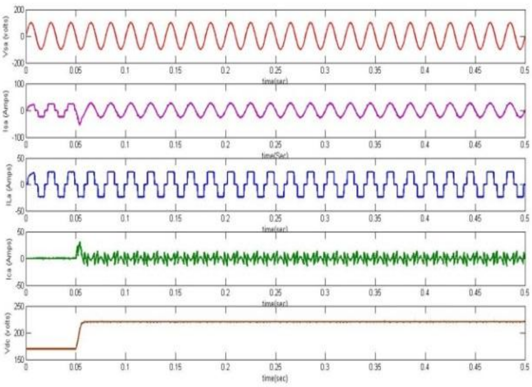


Fig.10. V_{sa}, I_{sa}, I_{La}, I_{ca} and $V_{dc}$of FLC

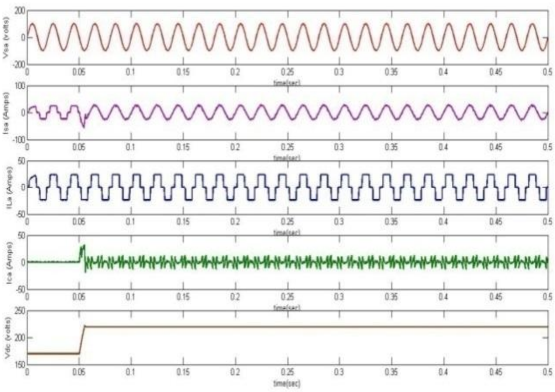


Fig.11. V_{sa}, I_{sa}, I_{La}, I_{ca} and V_{dc} of ANN

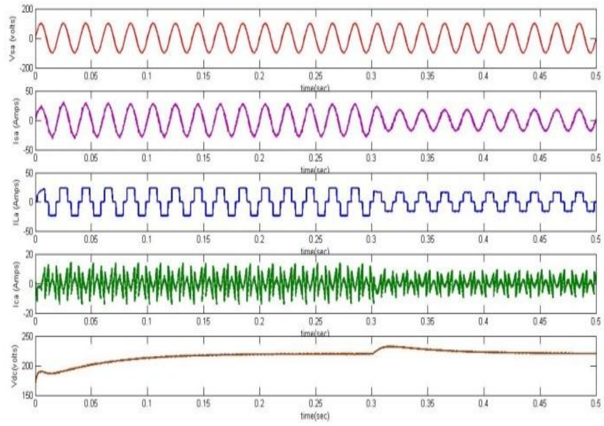


Fig.12. V_{sa}, I_{sa}, I_{La}, I_{ca} and V_{dc} of Conventional PI controller for varying R_L (6.7Ω to 10Ω)

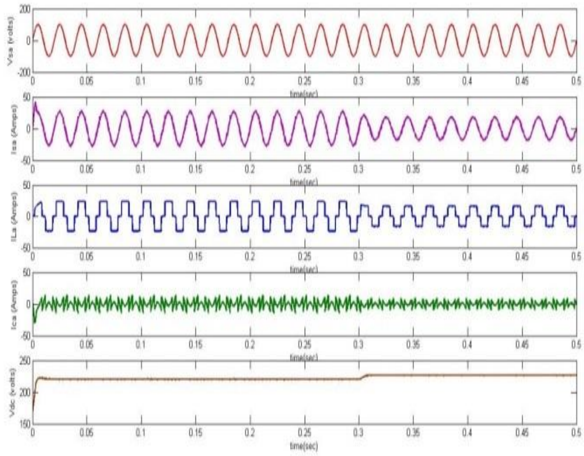


Fig.13. V_{sa}, I_{sa}, I_{La}, I_{ca} and V_{dc}ofFLC for varying R_L (6.7Ω to 10Ω)

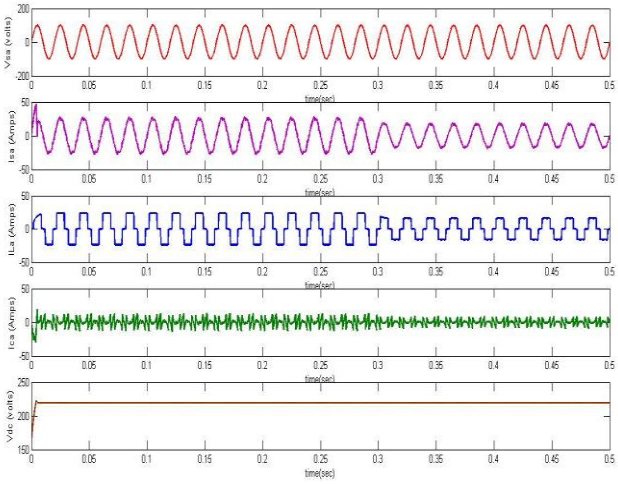


Fig.14. V_{sa}, I_{sa}, I_{La}, I_{ca} and $V_{dc}$of ANN for varying R_L (6.7Ω to 10Ω)

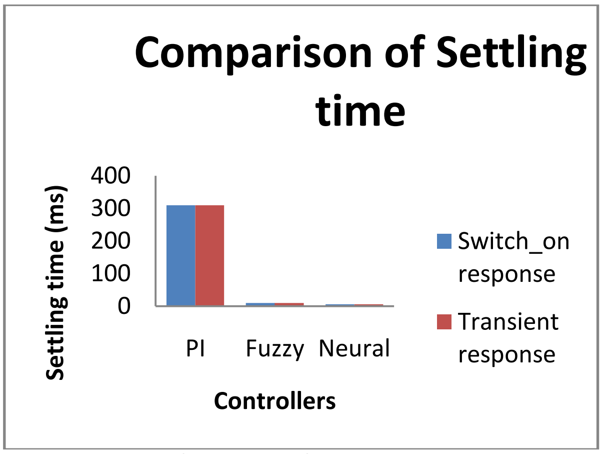


Fig.15. Comparison of settling time for Conventional PI, FLC and ANN controllers

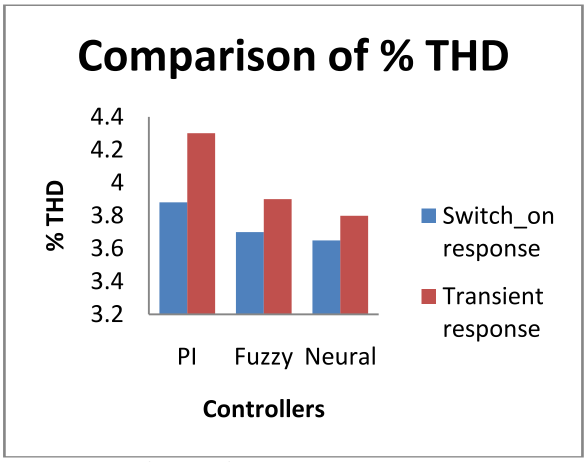


Fig.16. Comparison of %THD for Conventional PI, FLC and ANN controllers

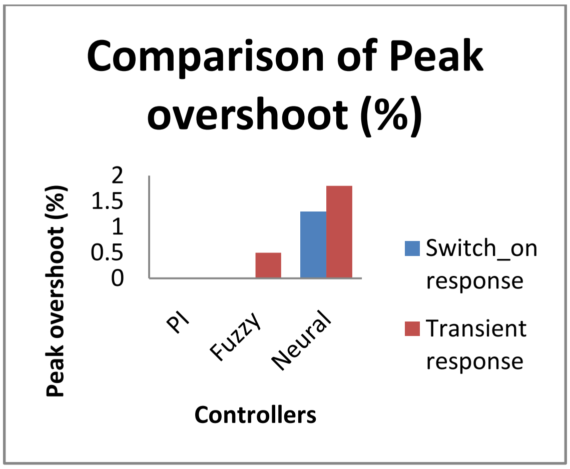


Fig.17. Comparison of peak overshoot for Conventional PI, FLC and ANN controller

The comparison of settling time, %THD and peak overshoot for Conventional PI, FLC and ANN controllers is shown in Fig.15 to Fig.17. The ANN controller settles at 6ms compared to FLC and Conventional PI controllers. The %THD is reduced in ANN compared to FLC and Conventional PI controllers. But the peak overshoot produced in ANN is larger compared to FLC and Conventional PI. Thus, the dynamic performance of ANN is compared with FLC and conventional PI controller. The performance of ANN is improved than FLC and conventional PI controller. The ANN has a settling time of 6ms, which is much better than the FLC and conventional PI controller.

VII. CONCLUSION

In this paper, the Nonmodel-based controllers are designed to achieve better utilization and reactive current compensation. The soft computing techniques were applied to control the switching of the SAPF. The LMS based ADALINE network is trained online to extract the fundamental load active current magnitude. The performance such as settling time, %THD of the ANN-based SAPF controller is better than FLC and conventional PI controllers and it is found to provide much better response under dynamic conditions.

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