Control algorithms for a three-phase Shunt Compensator – A comparative study

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***Abstract*—A comparison between the performance of the two control algorithms, Adaptive neuro-fuzzy inference system based on least mean square (ANFIS-LMS) and hyperbolic tangent function-based on least mean square (HTF-LMS) control algorithm for three-phase DSTATCOM (Distribution static compensator) is presented in this paper. A Shunt compensator consists of a three leg VSC (voltage source converter) and a zig-zag transformer to eliminate the defects caused by the loads which are nonlinear in nature, in three-phase systems. The ANFIS-LMS-based control algorithm estimates reference supply currents by extracting fundamental components of active and reactive power and the hyperbolic function control algorithm based on LMS enhances the convergence rate with the noise suppression in the power systems. The DSTATCOM prototype is developed in real time and implementation is performed on DSP (Digital signal processor). Simulation is done in MATLAB environment, resulting in the HTF-LMS based control algorithm that is much faster than the ANFIS-LMS based algorithm with a more reduced static error rate.**

Keywords— adaptive neuro-fuzzy inference system (ANFIS); hyperbolic tangent function (HTF); Distribution Static Compensator (DSTATCOM); least mean square (LMS)

I. Introduction

In present world of power systems, reduction of power quality issues such as load unbalancing, high neutral current, presence of harmonics, are the major challenge [1], which are introduced by the presence of numerous loads in the distribution system. Loads can be linear in nature as well as no linear such as air conditioners, geysers, adjustable speed drives, and any other commercially used electronics equipment [2]. Research is being carried out using different devices for improvement in power quality in power systems. In [3], an active filter which performs multi functions is described using theory based on p-q-rmethod. In [4], work is done for the grid connected electric vehicle charging system, using a new application of themulti taskingfilter. Some of the techniques to extract harmonics from distorted load current are also discussed by various researchers. One of such theory is synchronous reference frame theory, in which three phase quantities are converted into their DC parts and for harmonics elimination, low pass filters (LPFs) are realized [5]. The fixed point arithmetic technique is used which is discussed in [6] for improving computation quality.

One such effective device is developed i.e DSTATCOM, which is also considered for reduction of power quality parameters in power generation systems, based on water, wind and sun. Different configurations of DSTATCOM, which is three-phase and four wire are discussed in [7]. The voltage source converter (VSC), which is 3-leg and a transformer (zig-zag) are the main components of three-phase four-wire shunt compensator, which helps in solving problems of harmonics and reactive current. The main criterion for DSTATCOM to achieve desired performance is its internal control. Different control algorithms have been proposed to eliminate the harmonics. These include instantaneous reactive power theory, software phase locked loop extraction, adaptive filtering [8], fuzzy logic controller [9], etc. Adaline technique is also used, which has a good accuracy in extracting harmonic components, noise elimination, etc. Still, some of the techniques suffer from their speed of convergence and stability error [10].

In this paper, two such control algorithms, ANFIS-LMS based and HTF-LMS based are compared. In the first algorithm, there is an use of ANFIS in updating step size parameters and in the later one, learning rate is varied proportionally with mean square error. Both of these algorithms are developed using MATLAB/Simulink, and observations are experimentally verified. The control algorithms are used for the DSTATCOM which is three phase and four wire and has the ability to mitigate various PQ problems such as harmonics elimination, voltage regulation, load balancing and correction of power factor. The performance is achieved under state which is steady and load conditions which are dynamic in nature. It is shown that HTF-LMS based algorithm has fast

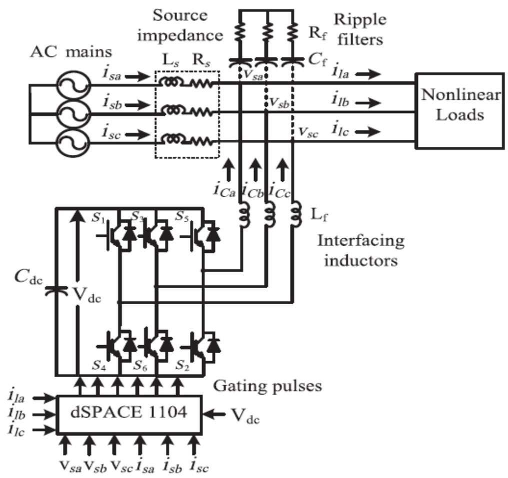

Fig. 1 VSC based three-phase shut compensator

convergence rate, better stability, and less static error as compared to ANFIS-LMS based algorithm.

II. Structure of Shunt Compensator

Fig.1 shows the structure of DSTATCOM (VSC based), which is three-phase and four-wire configuration. The input variables at point of common coupling voltages (v_a,$v_b$and v_c) of supply current, load current and DC load voltage (V_{dc}) of Voltage source converter are sensed. To reduce ripples in current, inductors (L_f) are connected to the output of VSC and for noise suppression, R-C shunt ripple factor is connected at PCC. The compensating currents (i_{ca},i_{cb}, and i_{cc}) for DSTATCOM are injected to reduce harmonics and power components which are reactive, of load current.

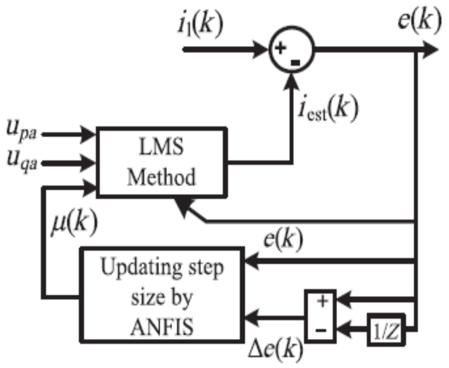

Fig. 2 Minimization of error by ANFIS-LMS

III. Control Algorithms

Detailed description of the two algorithms, which has been compared is presented in the following sections.

A. *ANFIS-LMS Based control algorithms*

A step size parameter is used, which is updated by using adaptive neuro-fuzzy system. Based on this, a control algorithm is developed. LMS method is shown in Fig.2 and ANFIS structure is depicted in Fig.3. The detailed diagram of ANFIS based on LMS control algorithm is shown in Fig.4.

Mathematical analysis

Amplitude of point of common coupling voltage(V_n) is calculated in Eq. 1,

$$V_n = \sqrt{2(v_{ma}^2 + v_{mb}^2 + v_{mc}^2)/3} \tag{1}$$

Therefore, point of common coupling voltages:v_{pca}, v_{pcb}, v_{pcc} are derived as Eq. 2,

$$v_{pca} = {v_{ma}}/{v_n}, v_{pcb} = {v_{mb}}/{v_n}, v_{pcc} = {v_{mc}}/{v_n} \tag{2}$$

DC link voltage and reference link voltage difference is calculated and it is passed through an integral controller. The output of proportional integral controller is depicted in Eq. 3,

$$p_{oloss}(n) = [p_{loss}(n-1) + n_{pd}\{v_{de}(n) - v_{de}(n-1)\} + n_{id}\{v_{de}(n)\}]$$

(3)

where, p_{oloss}= PI output
n_{pd}= PI proportional gain
n_{id}= PI integral gain

The next step is to find out the non-sinusoidal load current and is expressed as $i_l(n)$[1]. Harmonics and fundamental components of load current are further divided as in [1]. The load current which is estimated is computed and expressed as Eq. 4,

$$i_{lest}(n) = W^T X(n) \tag{4}$$

where,input vector

$$X(n) = [sin\omega k, cos\omega k, sin5\omega k, cos5\omega k, \dots\dots\dots]^T$$

The difference between actual load current and estimated load current is then computed and termed as final error as shown in Eq.5,

$$F_e(n) = i_l(n) - i_{lest}(n) \tag{5}$$

To minimize the mean error, the weights are optimized by the LMS method, which are computed as Eq. 6,

$$w(n+1) = w(n) + 2\mu F_e(n) X(n) \tag{6}$$

whereμ= step size parameter

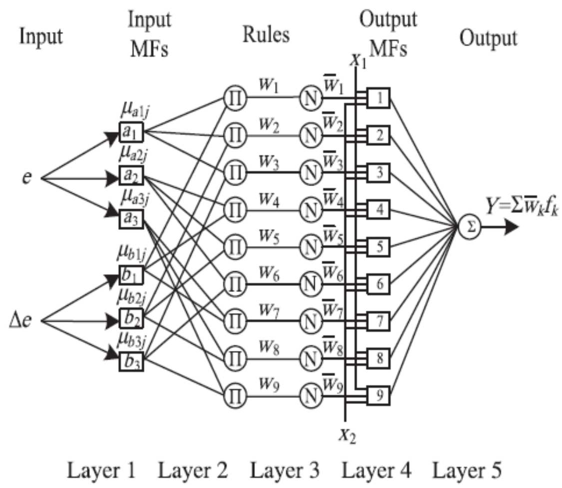

Fig. 3 ANFIS Structure

When, “μ” is fixed, LMS algorithm cannot achieve minimum static error with fast rate of convergence. Therefore, to sort out the problem and the contradictory response in steady state error and convergence rate, ANFIS based “μ” is developed and proposed in this paper [1].

There are two inputs, nine rules and three membership functions in structure of ANFIS [26], [27]. Square and circular nodes are represented in this proposed structure. Five layers named as layer1, layer2, layer3, layer4 and layer5, respectively, have different functions in ANFIS, as shown in Table I.

Table I. Description of layer representation

Layer representation	Name	Nodes	Function
I	Fuzzification layer	2 inputs	One i/p is error between actual and estimated values of load currents and another is change in error
II	Implication layer	Fixed nodes	Output is multiplication of its input signals
III	Normalizing layer	Fixed nodes	Output is normalization of its input signals and called normalized firing strength
IV	Defuzzifying layer	Adaptive nodes	Output are consequence parameters
V	Summative layer	Single node	Output is summation of all input signals

This layering ANFIS structure is used to compute the step size parameter, μ(n). Further, it can be used to find LMS algorithm weight vector. The Proportional integral controller is used for regulation of voltage at PCC. In this proposed structure, first active and power components which are reactive in nature,of reference supply currents are estimated to get the final supply current and then the switching pulses are generated.

Table II. Comparison between control algorithm

Control algorithm	Voltage (PCC), THD%	Current (Supply), THD%	Current (Load), THD%
HTF-LMS	219.5V, 1.96%	23.12A, 1.99%	24.14A, 18.95%
ANFIS-LMS	338.8V, 2.39%	40.72A, 2.57%	39.76A, 26.66%

B. Hyperbolic- Tangent function based algorithm

The block diagram of HTF LMS control algorithm is shown in Fig. 5.

Mathematical Analysis

The estimated weight vector equation from steepest descent method is given below [2] in Eq. 7,

$$W_{vt}(k+1) = W_{vt}(k) + \frac{1}{2}\gamma[-\nabla(E\{e^2(k)\})] \quad (7)$$

Where, γ= learning rate, $e^2(k)$= error (men square) between the current (load) and reference supply current

The gradient vector is expressed as Eq. 8,

$$\nabla(E\{e^2(k)\}) = -2c + 2CW_{vt}(k) \quad (8)$$

Where, “c” and “C” are the covariance matrices, and can be expressed as Eq. 9 and Eq. 10,

$$C(k) = x_v(k)x_v^h(k) \quad (9)$$
$$c(k) = i_L(k)x_v(k) \quad (10)$$

Therefore, the formula of weighted vector is calculated as [2], Eq. 11,

$$W_{vt}(k+1) = W_{vt}(k) + \gamma(k) * x_v(k)\left[i_L(k) - \left(W_{vt}(k) * x_v(k)\right)\right] = W_{vt}(k) + \{\gamma(k) * e(k) * x_v(k)\} \quad (11)$$

Weighted components can be calculated for the load balancing in three-phase system as given below in Eq. 12,

$$W_{vt}(k) = \{W_{va}(k) + W_{vb}(k) + W_{vc}(k)\}/3 \quad (12)$$

Where,$W_{va}(k)$,W_{vb}(k) and W_{vc}(k) are the weighted components of all the three phases.

In the hyperbolic tangent algorithm, where “γ” is very small, algorithm converges at a very slow rate and there is a large value of “μ” which led to convergence at a faster rate. The maximum value for “γ” is based on several iterations and is expressed as Eq. 13,

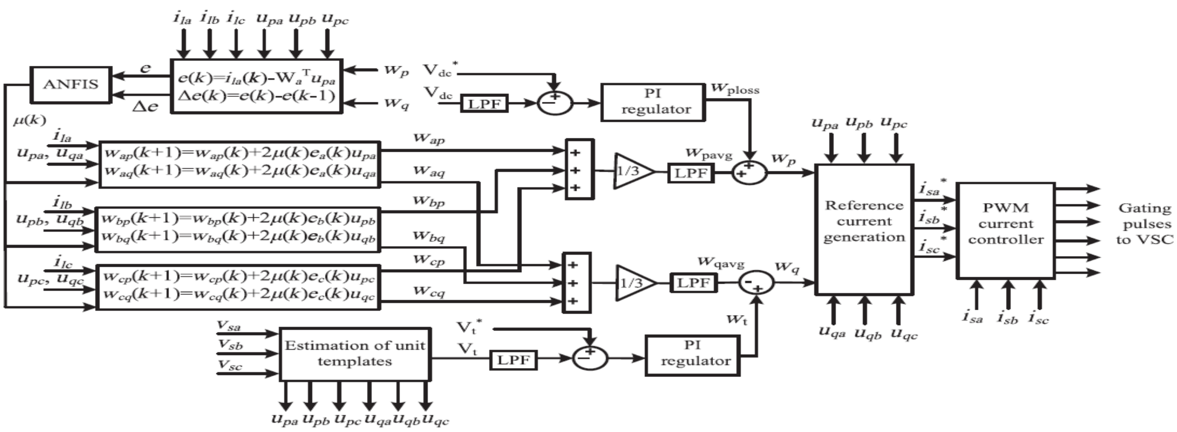

Fig. 4 ANFIS LMS based control algorithm block diagram for shunt compensator

$$\gamma <= \frac{1}{3\ trac\ (C)} \quad (13)$$

IV. EXPERIMENTAL RESULTS

Fig. 6 shows the performance of ANFIS control algorithm based on LMS for the three-phase DSTATCOM under state (steady). Fig. 6(a)-(c) show waveforms of the phase "a" of supply current, load current, and shunt compensator current, along with voltage on point of common coupling. Fig. 6(c) shows that there is a harmonic compensation by the shunt compensator. Fig. 6(d)-(f) shows total harmonic distortion of supply current and PCC voltage. The result shows that THDs lie within the specified limits of IEEE-519 standards, that is, 5%. Reading and evaluation is done under non-linear loads. Above comparison is based on non-linear loads which shows satisfactory performance of ANFIS-LMS based control algorithm for DSTATCOM. Performance of three-phase shunt compensator under dynamic loads is also taken, which shoes how effective the three-phase DSTATCOM is in compensating distorted load currents and maintaining supply currents. Dynamic performance of DSTATCOM is studied in oscilloscope.

Performance of DSTATCOM in hyperbolic tangent function based algorithm is also simulated under distorted PCC voltages. Fig. 7(a) and (b) shows the waveform of three-phase PCC voltages, V_{pcc}, with three-phase supply currents, i_s, load currents, neutral current, compensating currents, and DC bus voltage, under non-linear loads. Performance of DSTATCOM under linear loads is also noted with the dynamic performance, which concludes that the hyperbolic tangent function based control algorithm is simple to implement and gives satisfactory response.

As from the observations, performance of hyperbolic tangent function based on LMS control algorithm is better in terms of convergence and harmonics compensation. The THD is also, 1.96% which is less than the THD in ANFIS-LMS based control algorithm. A study of harmonics analysis and current for both of the control algorithm is shown in Table II.

V. CONCLUSION

The ANFIS based on LMS and HTF-LMS based control algorithm is verified for the control of three-phase Shunt compensator. The performance and results of both the algorithm is noted on the basis of mitigation of certain power quality parameters like reactive power compensation, balancing of loads and elimination of harmonics. The THD in supply current is reduced to 2.39%, when there is THD of 26.66% in load current, in ANFIS-LMS- based control algorithm, whereas, the THD in HTF based control algorithm is reduced to 1.96%, when there is THD of 18.995% in load current. By observing these parameters, HTF based control algorithm is very simple to implement, fast convergence performance, fast in response and gives good results than ANFIS-LMS based technique. Also, static error is less and there is a fast learning of step size parameter.

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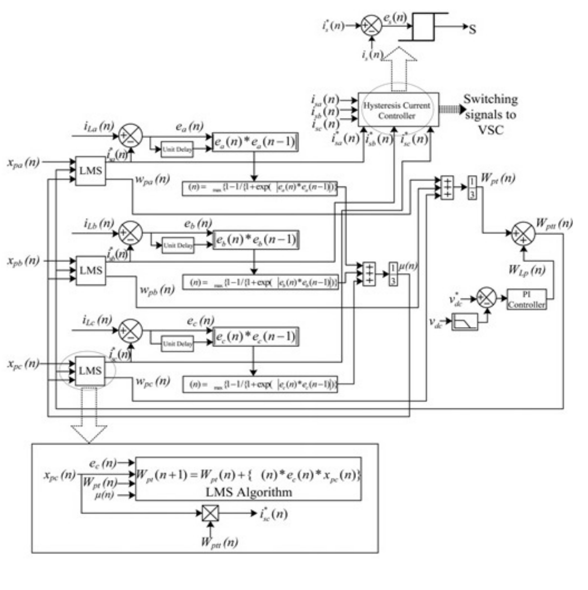

Fig. 5 HTF-LMS Control algorithm

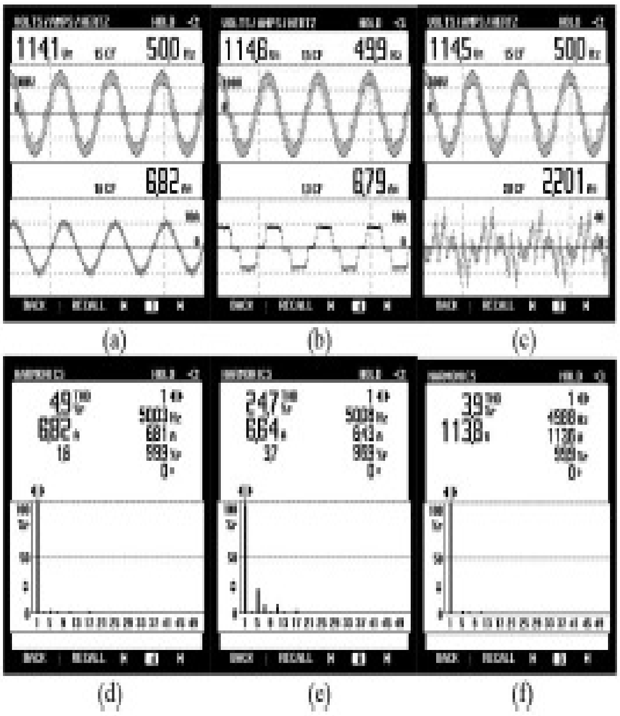

Fig. 6 Performance of shut compensator undernon linear conditions in AFIS-LMS control algorithm

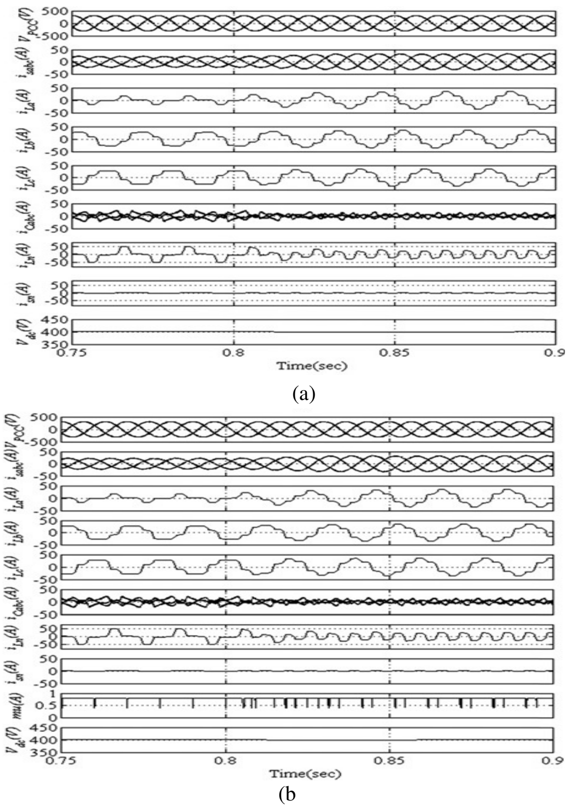

Fig. 7 Performance of DSTATCOM under non linear loads in HTF-LMS based algorithm