Four Leg VSI based Active Filter in Distribution System

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Abstract—A four leg voltage source inverter (VSI) based active filter is implemented for elimination of neutral current, harmonics compensation with load balancing. It is controlled through an algorithm based on learning vector quantization (LVQ) under current fed type nonlinear load. This double stage supervisory control algorithm is used for extraction of reference supply currents. A small rating VSI based active filter is developed using DSP-dSPACE1103 processor to analyze its performance under different loads. Satisfactory performance of the active filter is observed with regulated constant dc link voltage.

Index Terms—Four leg VSI, Harmonic, Neutral current, Sine PWM, Signal estimation, Power Quality.

I. INTRODUCTION

N power filter technology, an active filter is most suitable device for compensation of distortions due to nonlinear characteristics of consumer loads [1]. It is used for reduction of high demand of supply power due to harmonics, neutral current and reactive power using various power electronic based converters [2]. Kneschke [3] has discussed behavior of various type of nonlinear loads such as microprocessor-driven system, rectifiers and power supplies in supply system. A case study of power loss due to various components of harmonics in residential campus is reported in the literature [4]. After connection of an active power filter, it is required to limit harmonic components according to standard guidelines [5]. An active power filter is also used in distributed power generation system because modeling of its control is easy and simple. It application in hybrid power generation is reported in the literature [6]. Tummuru et al. [7] have reported application of VSI based active filter in micro-grid concept. Its control algorithm is described after extraction of symmetrical components of input signal. Some other application of active power filter as power quality conditioner is discussed in wind power, solar power generation under voltage fed type loads [8]. Kumar and Mishra [9] have reported operation of an active filter in voltage control mode in stiff supply system. Naderi et al. [10] have reported performance evaluation of active filter in form of custom power devices such shunt, series, hybrid configuration and STATCOM etc. Topology and control algorithm of both are same. The adaptive nature of control algorithm with respect to internal constants and time delay compensation is the major issues in the selection of control algorithm. These issues are described in the literature [11,12]. Farhoodnea et al. [13] have discussed place location of DSTATCOM using firefly algorithm. In this method, objective function is based on the average total harmonic distortion in the voltage, voltage deviation and total investment cost. Application of heuristic optimization algorithm in the control active filter is reported in the literature [14]. It is based on the bacterial foraging and used for compensation of harmonics. The soft computing is another which is useful in the control of active power filter. In this area, control algorithm depends upon training or learning of input signal, assumption based human being and machine learning etc [15,16]. Prajapati and Sharma [17] have discussed Takagi-Sugeno fuzzy based compensator. In this paper, fuzzy controller is used for tuning of PI controller gains in dc and ac bus. Qasim and Khadikkar [18] have reported comparison of feed forward multi layer neural network and adaptive neutral network control algorithm in the control application of active filter.

The real time implementation of neural network based control algorithm in adaptive nature is reported in the literature [19]. This paper demonstrates function of compensation in four wire system with fixed learning rate. Qasim et al. [20] have reported optimal current harmonic extraction based on adaptive neural network based control algorithm for accurate dynamic response and reduce computation time. Karayiannis [21] has discussed of weighted learning vector quantization (LVQ). It is developed using gradient descent to minimize reformulation functions. Application of learning vector quantization (LVQ) in three wire system is reported in the available text [22].

In this paper, Learning Vector Quantization (LVQ) control algorithm is implemented in shunt connected active filter for weighted value extraction of load active power current components. It is used to obtain the desired performance under double supervisory neural network based control system. In this algorithm, number of winning quantization vectors is changed under feedback system in adaptive nature and selected most suitable weighted value of given input signals. It is simple and efficient for improvement of accuracy in estimated signal in particular class. During training, the output units are adjusted their weighted through supervised training. After training, LVQ neural network define input vector by assigning this as the output unit and it has its weighted vector close to the input vector. It is used in the application of four leg active filter.
for neutral current compensation, harmonic suppression and load balancing with self sustained dc link. Reduced size and weight are the main advantages of used topology compared to any other transformer topology.

II. FOUR LEG ACTIVE FILTER AND CONTROL ALGORITHM

Fig. 1 shows basic circuit diagram of four-leg VSI based active filter feeding to current fed type nonlinear load. Its performance depends upon the accuracy of time varying disturbance detection. Other components of active power filter are ripple filter (Rf and Cf) used for voltage high frequency noise compensation and interfacing inductors (Lf) used for improvement of filter current quality and signal processing circuit. The filter currents (iabc) are injected to cancel neutral current and harmonic components with balanced supply currents.

![Basic circuit diagram of VSC based active filter with three AC supply](Image)

A block diagram of LVQ algorithm is shown in Fig. 2. It is proposed for extraction of reference supply currents through load active power current components. The active filter with proposed control is implemented for power factor correction. Detailed mathematical modeling of algorithm is given below.

A. Weighted Value of Average Active Power Components of Load Currents

A LVQ algorithm is applied for estimation of weighted value of load active power current (ztap, zsbp, zscp) from distorted load currents using feed forward and supervised system. Basic structure and weighted active component of phase a, phase b, phase c at the feed forward block (zap, zbp, zcp) are written as,

\[
\text{zap} = \text{isap} + \text{isbp} + \text{iscp} \quad (2)
\]

\[
\text{zsap} = \text{isap} + \text{isbp} + \text{iscp} \quad (3)
\]

\[
\text{zsap} = \text{isap} + \text{isbp} + \text{iscp} \quad (4)
\]

where \(\text{isap}, \text{isbp}, \text{iscp}\) are the sensed PCC voltage and \(V_{t1}\) is the three phase amplitude of supply voltage.

Extracted values of \(z_{tap}, z_{sbp}\) and \(z_{scp}\) are updated through supervised learning. Its leaning rate \(\beta\) is selected in range of 0 to 1. In first stage, adaptive value of output weighted components \((z_{tap}, z_{sbp}, z_{scp})\) are expressed as [22],

\[
z_{tap} = z_{scp} + \beta (z_{scp} - z_{sbp}) \quad (5)
\]

\[
z_{sbp} = z_{scp} + \beta (z_{scp} - z_{tap}) \quad (6)
\]

\[
z_{scp} = z_{scp} + \beta (z_{scp} - z_{sbp}) \quad (7)
\]

where \(z_{scp}\) is the average value of in phase components of load current.

Computed values of \(z_{tap}^*, z_{sbp}^*\) and \(z_{scp}^*\) are fed as an input of signal hidden layer. The addition of these value (\(z_{sbp}^*\)) is written as,

\[
z_{sbp}^* = z_{scp}^* + \delta (z_{scp}^* - z_{sbp}) \quad (8)
\]

The output of second stage supervised layer (\(z_{sbp}, z_{scp}\)) with feedback factor ‘\(\delta\)’ are written as,

\[
z_{sbp} = z_{scp} + \delta (z_{scp} - z_{sbp}) \quad (9)
\]

\[
z_{scp} = z_{scp} + \delta (z_{scp} - z_{sbp}) \quad (10)
\]

\[
z_{scp} = z_{scp} + \delta (z_{scp} - z_{sbp}) \quad (11)
\]

where \(\delta = \frac{1}{2}\) are the optimized value of three phase weights in second stage feedback system using average weighted value \((v_{sbp})\) of active power current component. In this extraction, ‘\(\delta\)’ is considered as constant factor of feedback. Its value is lying between 0 to 1.

Average weighted active power component \((v_{sbp})\) is calculated from eqn. (9) to eqn. (11). Mathematically, it is described as,

\[
v_{sbp} = \frac{z_{scp}^* + z_{sbp}^* + z_{scp}^*}{3} \quad (12)
\]

A set of low pass filters are connected to eliminate the low frequency oscillations. After eliminating low frequency noise, it is shown as \(z_{sbp}\).

The dc link voltage error \((v_{db})\) is supplied to a proportional-integral (PI) regulator which output signal is used as loss components of VSI of the active filter. At \(k\)th sampling instant, the output components of PI regulator \((z_{sbp})\) at dc link is modelled as,

\[
z_{sbp}(k) = z_{scp}(k-1) + k_{pp} \left( v_{db}(k) - v_{db}(k-1) \right) + k_{ip} v_{db}(k) \quad (13)
\]

where \(k_{pp}\) and \(k_{ip}\) are the proportional and integral gain constants of the dc link PI regulator. \(v_{db}(k)\) and \(v_{db}(k-1)\) are the dc link voltage errors in \(k\)th and \((k-1)\)th sample instant.

Total active power current component of the reference supply current \((z_{scp})\) is the addition of output of dc link PI regulator \((z_{sbp})\) and average magnitude of load active currents \((z_{scp})\) as,

\[
z_{scp} = z_{scp}^* + z_{sbp}^* \quad (14)
\]

The estimation of three phase reference supply currents is totally based on total active power component of load in the active filter. It is expressed as,

\[
\text{i}_{sc} = \text{iszp} \times \text{iszp} \quad (15)
\]

The extracted three phase reference supply currents \((i_{sa}, i_{sb}, i_{sc})\) are used for extraction of error components from sensed supply current \((i_{sa}, i_{sb}, i_{sc})\). The amplified values of current error components are supplied to ±0.2 bandwidth hysteresis current controller to generate the switching pulses for three leg of four leg VSI.

The gating pulses for fourth leg of VSI are generated after addition of sensed three phase supply currents \((i_{sa}, i_{sb}, i_{sc})\). It can be considered as supply neutral current \((i_{sn})\) as,

\[
i_{sn} = i_{sa} + i_{sb} + i_{sc} \quad (16)
\]
Estimated supply neutral current \(i_{sn}\) is compared from reference supply neutral current \(i_{sn}^0 = 0\) which is considered as zero for ideal condition. After that estimated current error component is fed to hysteresis current controller to generate switching pulses of VSI of forth-leg for load neutral current compensation.

### III. PERFORMANCE AND DISCUSSION

A four-leg VSI based active filter is developed with the proposed control algorithm in real-time application. Hall Effect current sensors (LEM make LA55) and Hall Effect voltage sensors (LV25) are used for sensing PCC voltages, dc link voltage and current signals according to DSP-dSPACE-1103 ADC port requirement. Proposed control algorithm is implemented for the control of DSTATCOM using a DSP-dSPACE1103 Processor. The 2N2222 transistor and opto-coupler IC 6N136 with other auxiliary components are used for optical isolation with amplification of gating signal received from DSP-dSPACE processor after signal processing. Experimental setup data related to design are given in Appendix.

#### A. Performances of Active Filter for Neutral Current, Harmonic Suppression and Load Balancing

Performances of active filter for neutral current and harmonic compensation are discussed with load balancing features. Figs. 3(a-c) shows the waveforms of load neutral current \(i_{ln}\), filter neutral current \(i_{fn}\) and compensated supply neutral current \(i_{sn}\). From these figures, it is seen that after compensation, supply neutral current is very less. The waveform of phase ‘a’ supply current \(i_{sa}\), compensation current \(i_{fa}\) and load current \(i_{la}\) are displayed in Figs. 3(d-f). It is observed that after compensation, supply current and voltage harmonics are 3.9% and 3.1% respectively. Test results illustrate the function of active filter for power quality enhancement.

Figs. 4(a-c) and (d-f) show the waveforms of three phase load currents \(i_{la}, i_{lb}, i_{lc}\) and supply currents \(i_{sa}, i_{sb}, i_{sc}\) under unbalanced nonlinear load. These waveforms are recorded with reference of PCC line voltage \(v_{ab}\). During unbalance, harmonic spectra in supply current \(i_{sa}\), supply voltage \(v_{ab}\) and load current \(i_{la}\) are presented in Figs. 4(g-i). After observation, it is found that level of harmonics, THD in respective quantity are 3.9%, 3.1% and 3.4%. The performance of neutral current compensation is illustrated in Figs. 4(j-l), where waveform of load neutral current \(i_{ln}\), compensator neutral current \(i_{fn}\) and compensated supply neutral current \(i_{sn}\) are shown. These results show the function of four leg active filter and their control algorithm in compensation technology.
B. Dynamic Performance of Active Filter

The variation in ac main voltage \(v_{ab}\) and dc bus voltage \(v_{dc}\) with supply current \(i_{sa}\), compensating current \(i_{fa}\) and load current \(i_{la}\) are presented in Figs. 5(a, b). It shows the response of control algorithm after load injection. Fig. 5 (c) demonstrates the function of neutral current compensation during load unbalancing where amplitude of compensator neutral current \(i_{fn}\) and load neutral current \(i_{ln}\) are equal and opposite phase. These waveforms include supply current \(i_{sa}\), compensator neutral current \(i_{fn}\) and load neutral current \(i_{ln}\) with PCC voltage \(v_{ab}\). These results demonstrate acceptable performance of topology and control algorithm of active filter under balanced and unbalanced nonlinear loads.

IV. CONCLUSION

A four leg active filter has been tested for compensation of harmonic current, neutral current and load current balancing using LVQ control algorithm. The control algorithm based on LQV has been used for extraction active power components of load current. It is the major components of reference supply currents to generate the gating pulses VSC based active filter. Various functions of active filter such as harmonic elimination, neutral current compensation and load balancing have been demonstrated with self sustained dc link of VSC. From recorded results, it is concluded that four leg active filter and its control algorithm is easily and efficiently tested in real time for compensation of power quality problem. Used VSI rating is also varying and this depends upon type of power quality problem.
APPENDIX

AC mains: 3Phase, 225 V (phase to phase), 50 Hz; Nonlinear loads: Three single phase diode based rectifier with R= 28 Ω and L=100 mH; dc link capacitance: 2350 μF; dc link voltage: 400 V; Interfacing inductor in neutral branch (L_a)=4 mH; Interfacing inductor in phase a, phas b and phase c (L_a,L_b,L_c)=4 mH;  Interfacing inductor  in neutral branch (L n)=5mH, Ripple filter: R_f =5 Ω, C_f = 10 μF; Learning rate (β) = 0.5; Feedback factor(δ) = 0.25; PI regulator for constant dc link: k_pp= 0.7, k_pp= 0.1; low pass filter cut off frequency used in dc link = 10 Hz; Sampling time (t_s) = 65µs.

Fig. 5. Dynamic performance of active filter during removal of phase ‘a’ in nonlinear loads (a) v_ab isa, ifa and i_La (b) vdc isa, i_La and ifa (c) v_ab, isa, ifn and i_sn (d) v_ab, isa, isb and i_sc.

REFERENCES


