Spectral Analysis of Harmonic Measurement Using Wavelet Transformation in IEEE -13 Bus System

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Abstract - **An efficient compensation method and design for sizing the three phase four wire shunt Active Power Filter (APF) based on wavelet transformation is presented in this paper. The compensation currents injected by shunt active power filter are determined to eliminate harmonic currents of the non linear loads as well as to compensate reactive power and maintain the source currents as sinusoidal. In this paper Fast Fourier Transforms (FFTs) is used for APF to calculate reference compensation current. Proposed APF has the capability to operate in balanced, unbalanced and variable load conditions. The proposed auto tuned filter meet the IEEE – 519 harmonic current limits and other constraints like power factor improvement and reactive power compensation. The proposed methodology is tested for different loads with good dynamic behavior of APF using wavelet controllers. The results obtained by simulations with MATLAB/Simulink shows that the proposed approach is very effective and simple for compensating harmonic currents generated by the nonlinear loads with an optimal size of the shunt active power filter.**

Keyword: **Active Power Filter, IEEE-519, Wavelet Transform Controller, Matlab/Simulink, Reactive Power Compensation, THD**

I. Introduction

Due to sudden increase of number of non linear loads in modern electrical distribution system, the harmonic distortion of the currents and voltages increases [1]. The loads at this level are mostly single phase and these are distributed in a unbalanced way in three phase supply system. All non linear loads such as Switched Mode Power Supplies (SMPS), Electronic fluorescent lighting ballasts, Uninterruptable power supplies (UPS), domestic appliances and Adjustable Speed Drives (ASDs) produced harmonic load currents. Harmonic currents cause problems both on the supply system and within the installation. The effects and solutions are very different and need to be addressed separately. The measures that are appropriate to controlling the effects of harmonics within the installation may not necessarily reduce the distortion caused on supply side and vice versa. Due to harmonics, distorted voltage, overheating of equipment, excessive neutral currents, malfunction in system protection, light flicker and malfunctioning of power flow metering. All these effects causes Power Quality problems.

To mitigate harmonic problems Active Power Filters (APFs) are caused since 1970's [2&3]. For eliminating harmonic currents and voltages APF appears to be a viable solution. APFs injects equal and opposite distortion and absorbs (or) generates reactive power, thereby harmonics and compensating reactive power of the load is controlled. In [4], Akagi *et al.* proposed the theory of instantaneous reactive power in the α – β reference frame which inspires Active Power Filters. APF control is the most strategic method on the elimination of harmonic currents generated by the non linear load with sinusoidal source voltages. Recent years it is a trend to develop shunt APF which can be used under non sinusoidal supply voltages, where the voltages at the Point of Common Coupling(PCC) of the APF are harmonics contaminated and are caused by other non linear loads in APF application [5&6].

II. APF Control Strategy

A. Control system description for Shunt APF

The control system for shunt APF could be divided into two main stages. In the first stage the reference compensating current has to be determined, while in the second stage the derivation of the switching function for the filter inverter circuit is computed [7].

B. Reference Compensation Current Calculation

By knowing the information about measured load current harmonic content and the fundamental value, the reference compensation current is determined. For reference compensation current computation several methods have been proposed in the literature [8&9]. Those methods depend on either time domain or frequency domain analysis. In this paper the method utilized for reference compensation current calculation depends on Fast Fourier Transform (FFT), sort of frequency domain analysis. FFT is used to extract the magnitude of the fundamental component of the load current from which the reference compensation current will be computed [10].

$$i_{load} = i_{loadfund} \underset{\text{III.}}{+} i_{harmonics} \rightarrow (1)$$

$$i_{loadfund} = \left| i_{loadfund} \right| \sin \omega t \rightarrow (2)$$

$$i_{load} = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left[a_n \cos(n\omega t) + b_n \sin(n\omega t) \right]$$

$$a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} i_{load}(t)dt$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} i_{load}(t)\cos(nt)dt$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} i_{load}(t)\sin(nt)dt$$

The above equations describe the procedure used for reference compensation current calculation.

Thus, the fundamental component magnitude of load current

$$i_{loadfund} = \sqrt{(a_n^2 + b_n^2)}$$

The amplitude of the reference supply current is given by

$$= (i_{loadfund} + i_{dc}) \sin \omega t \rightarrow$$

Where idc is the current responsible for compensating of the dc losses due to the change in the dc capacitor voltage. Then taking the sine wave template from the supply voltage, the reference supply current will b

$$i_s^* = (i_{loadfund} + i_{dc}) \sin \omega t \rightarrow \quad (4)$$

and from equation (1) & (4)

$$i_f^* = i_s^* - i_{load} \rightarrow \quad (5)$$

Therefore

$$i_f^* = \left(|i_{loadfund}| + i_{dc}\right) \sin \omega t - \left(i_{loadfund} + i_{harmon}\right.$$

$$i_f^* = i_{dc} \sin \omega t - i_{harmonics} \rightarrow \quad (6$$

III. Spectral Model

The fundamental idea behind spectral analysis is to analyze the recorded current signal at different scales or resolutions, which is called multi resolution analysis. For the analysis of current signal in multi spectral domain frequency domain transformation and analysis is carried out. For the decomposition of current signal pulse into individual resolution for analysis is carried out using advanced signal transformation technique called Wavelet transformation [11]. Wavelets are a class of functions used to localize a given signal in both space and scaling domains. Compared to Windowed Fourier analysis, a wavelet is stretched or compressed to change the size of the diagnosis window. In this way, wavelets give an approximate better analysis of the signal, while smaller and smaller wavelets explore the details of the signal. Wavelets automatically adapt to both the high frequency and the low-frequency components of a signal by different sizes of windows. Any small change in the wavelet representation produces a correspondingly small change in the measured signal, which means a local mistake does not influence the entire transform. With these property wavelet transform is best suited for the analysis of non-stationary current signals, which are very brief signals and with interesting components at different scales.

For the analysis of the measured current signal a wavelet function is used. The wavelet function is generated from one single function ψ, called prime wavelet, by dilations and translations defined by,

$$\psi_{a,b}(x) = |a|^{-1/2}\, \psi\left(\frac{x-b}{a}\right)$$

Where ψ satisfy the property of ∫ ψ (x) dx = 0.

The transformation represent any arbitrary function 'f' as a decomposition of the wavelet basis or write 'f' as an integral over 'a' and 'b' of $\psi_{a,b}$. For a given continuous current pulse, if it is defined $a = a_0^m, b = nb_0a_0^m$ with m, n € integers, and $a_0>1$, $b_0>0$ fixed. Then the multi-band spectral decomposition is given $f = \sum c_{m,n}(f)\psi_{m,n}$. by,

for the processing of wavelet transformation a bank f filters having low pass and high pass characteristic is used. The frequency response for such filter coefficient is as illustrated in figure 6.

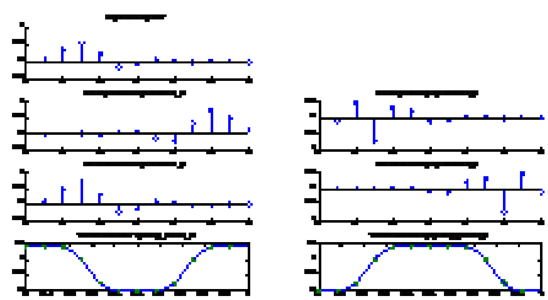

Fig.1 Frequency response plot for filter coefficients used for spectral decomposition

The procedure starts with passing this signal (sequence) through a half band digital low pass filter with impulse response h[n]. Filtering a signal corresponds to the mathematical operation of convolution of the signal with the impulse response of the filter. The convolution operation in discrete time is defined by:

$$x[n] * h[n] = \sum_{k=-\infty}^{\infty} x[k] \cdot h[n-k]$$

A half band low pass filter removes all frequencies that are above half of the highest frequency in the signal. One way to built sub-band codification is to split the spectrum into frequency bands which consumes more processing time. Therefore it is convenient to split the given signal into two bands of spectral components such as low pass filtered and high pass filtered components. The high pass filtered components gives the smallest information where as low pass filtered components gives information regarding further minutely varying details until desired number of bands.

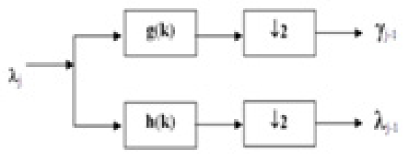

Fig. 2 Implementation of one stage iterated filter bank.

The process of splitting the spectrum is graphically represented in figure 2. The advantage of this scheme is that it is necessary to design only two filters & the disadvantage is that the signal spectrum coverage is fixed. The wavelet transform is the same as that of a sub-band coding scheme using a constant-Q filter bank. The detail coefficients cD are consisting high-frequency content and the approximation coefficients cA contain the low frequency content of the signal. The actual lengths of the detail and approximation coefficient vectors are slightly more than half the length of the original signal. This has to do with the filtering process, which is implemented by convolving the signal with a filter. By observing the features obtained by discrete wavelet transform it is easy to detect, locate and classify the disturbance. A program was developed and implemented in MATLAB environment using the following steps.

Step 1: Obtain the wavelet coefficients of the pure sinusoidal signal.

Step 2: Calculate the square of the wavelet coefficients obtained in the above step.

Step 3: Calculate the signal energy, in each wavelet coefficient level which is given by Parseval's theorem.

Step 4: Repeat the above procedure for distorted signal.

Step 5: Compare the total distorted signal energy to that of pure signal energy value.

The evaluated wavelet coefficients after the execution of the suggested algorithm as outlined above results are the processed by a neuro controller for the controlling of power flow for quality improvement in power system.

IV. Simulation Parameters

For the evaluation of the developed controlling system a 13-Bus IEEE bus structures is used with the variation in line parameters. To evaluate the process of power flow controlling carried out the process is as outlined below.

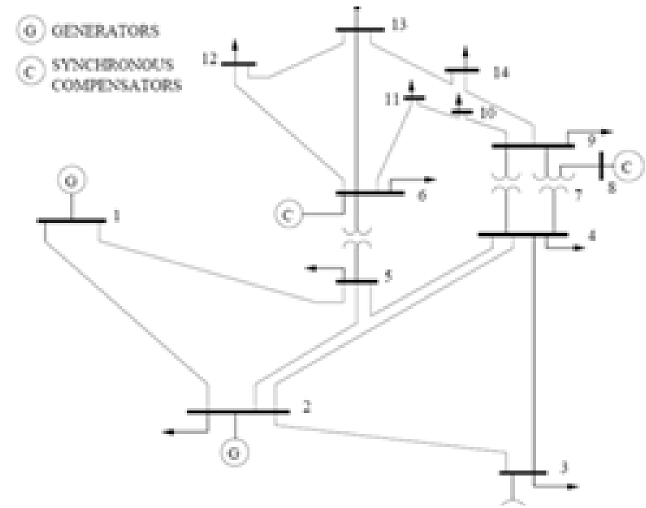

Fig. 3 IEEE-13 Bus system line diagram

Above figure illustrates the line diagram for a 13 Bus distributed network considered for simulation perspective

Table I Parameters in case of Balanced Load

V_s	170v
Ls	1mH
Lf	4mH
Lr	2mH
Load	Rr=50Ω

Table II Parameters in case of Unbalanced Load

V_s	170v
Ls	1mH
Lf	4mH
Lr	2mH
Loads	Load1:Rr=50Ω Load2:R2=15 Ω Load3:R3=15Ω, L3=0.1H

Table III Parameters in case of Variable Load

V_s	170v
Ls	1mH
Lf	4mH
Lr	1mH
Variable Load	V_{dc}=120v,R=1Ω,L=20mH

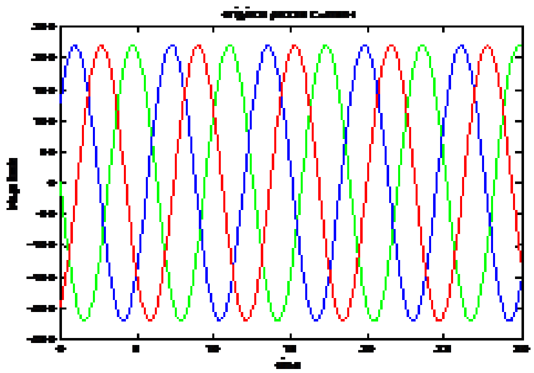

Fig. 4 Original disturbance free 3-phase current

Spectral Analysis of the Measured Current Pulse

The measured 3 phase line currents are processed for spectral analysis using dynamic wavelet coefficients. Two approach of wavelet coefficient are used for the processing namely complex morlet wavelet and frequency B-spline transform. The suitability of these filters for spectral analysis is observed to be effective due to its adaptive nature of analysis and synthesis filtration. The frequency characteristic for used filter coefficient is as shown below.

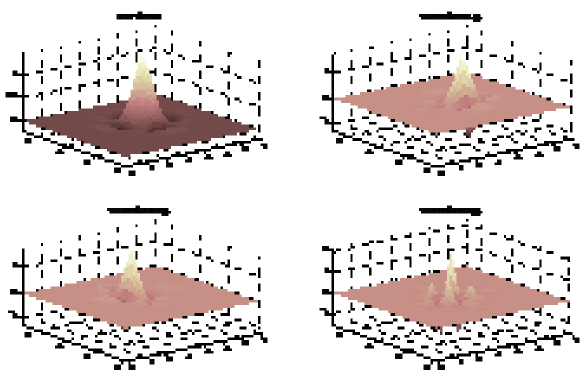

Fig. 5 Frequency characteristic of morlet wavelet coefficient used for spectral analysis

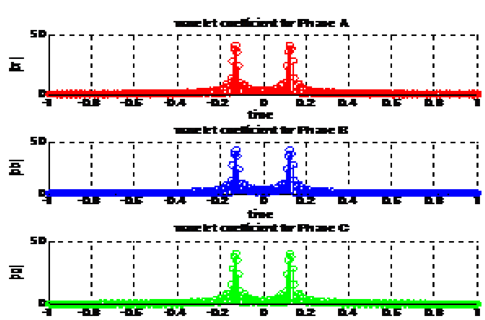

Fig. 6 The coefficient density per phase on the application of wavelet transform

The per phase current is processed for spectral analysis using the stated filter coefficient. the magnitude of the three line currents are observed to be at a range of 50dB magnitude. The disturbance free coefficients are hence observed to give a reference margin of 50dB spectral content which is set as a reference in coefficient mapping for selecting coefficients. A similar transformation is also carried out using frequency B-spline transformation as they are very effective in processing any continuous signal with frequency variation with respect to time. The coefficient characteristic for such filter could be observed below.

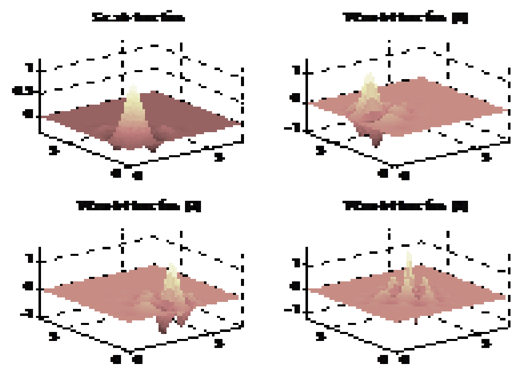

Fig. 7 Response characteristic for frequency B-Spline coefficient used for transformation

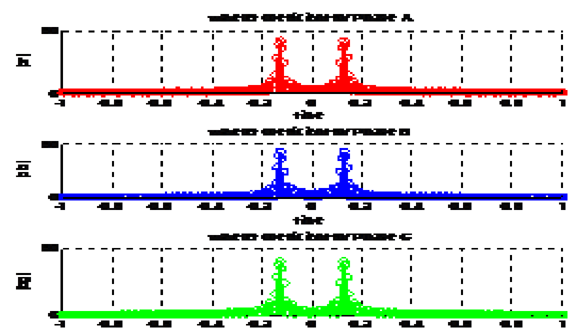

Fig. 8 Spectral coefficients derived from frequency B-spline transformation

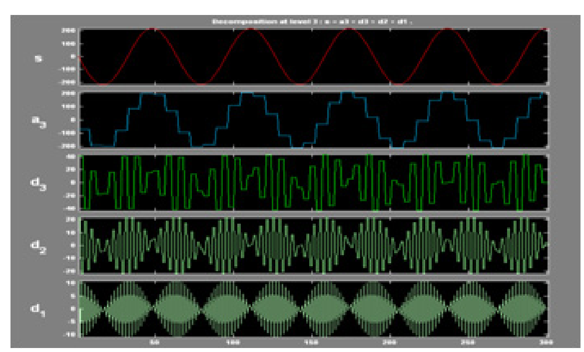

Fig. 9 Spectral coefficient of first four bands for a non effected current pulse

The spectral analysis for a single phase non effected current pulse is as shown in figure above. It is clearly observed that the current pulse have very dominant coefficient density at lower frequency region as compared to higher frequency band. The coefficient domination at the particular frequency band helps in extracting the required coefficient suppressing the other frequency content than the fundamental frequency.

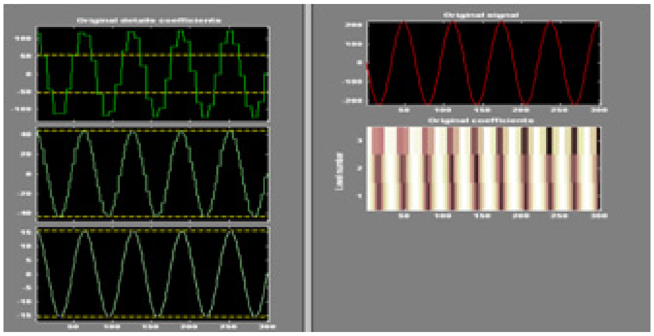

Fig. 10 The processed detail coefficient for compression and disturbance removal approach using spectral analysis

Figure above illustrates the coefficients extracted after compression and decomposition of the current pulse. The coefficients are observed to be effectively reducing the coefficient counts and improve the current pulse quality by removing additional coefficients.

Table IV Complex Morlet wave transformation

phase	$\|D1\|^2$	$\|D2\|^2$	$\|D3\|^2$
R	48.3	47.4	48.5
Y	48.5	48.3	47.97
B	46.7	46.33	46.12

Table V Frequency B-Spline wave transformation

phase	$\|D1\|^2$	$\|D2\|^2$	$\|D3\|^2$
R	49.11	49.44	49.76
Y	48.7	48.74	48.97
B	47.8	47.43	47.52

The density of magnitude for the three phase current and its detail coefficients are as presented in above table. These figures are taken as reference for the extraction of actual current pulse from the measured one. For the evaluation of the suggested approach the measured current pulse is applied with a fault effect and is processed for its effect removal. For the evaluation of the suggested approach, a three-phase line distortion due to line effects of a 100 ms duration is created at the middle of the transmission line connecting bus-1 and bus-2.

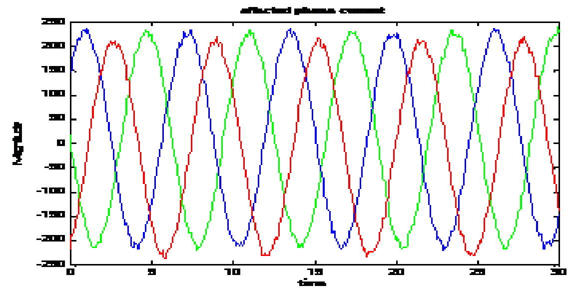

Fig.11 Measured effective current pulse after the fault effect

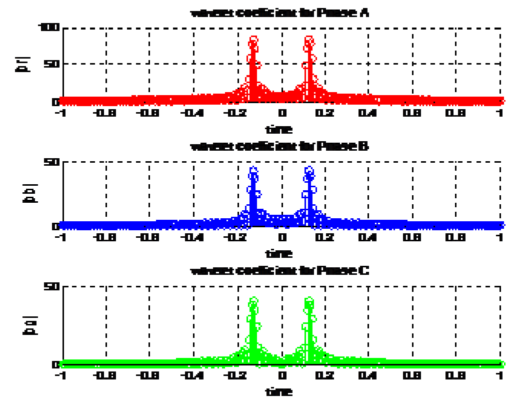

Fig. 12 Coefficient density plot for the three phase spectral coefficients

Figure 12 illustrates the effective coefficient density observed after fault effect. it could be clearly observed that the coefficients under fault condition is dominantly increased to about 80 units in faulty condition as compared to a healthy condition.

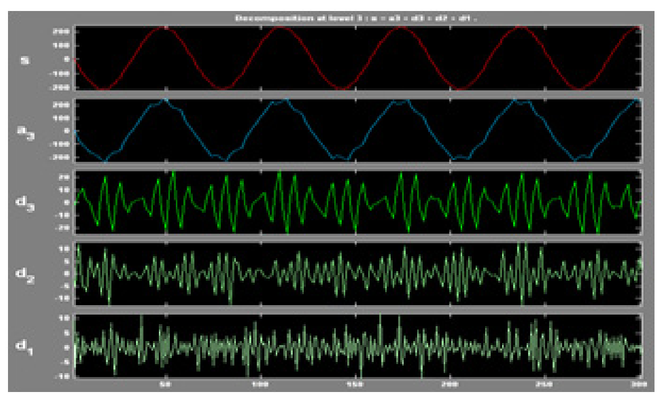

Fig. 13 Spectral coefficient analysis for the measured fault current

Figure illustrates the spectral coefficient analysis under fault condition. the analysis clearly illustrates the density of variation in detail coefficient magnitudes due to variation in the current magnitude

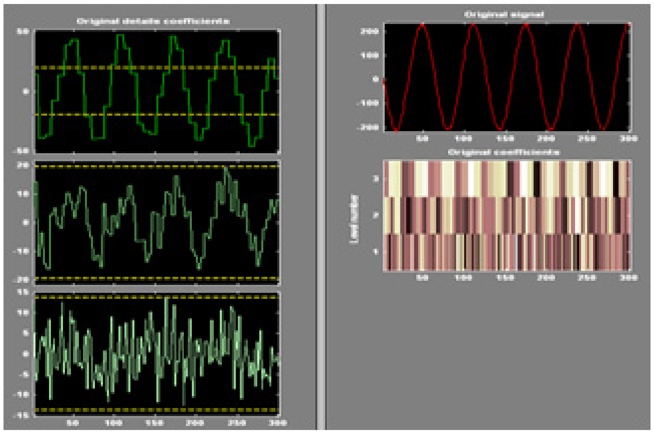

Fig. 14 Decomposed and extracted noise signal from the processed signal

The signal after removal of additional disturbances could be observed in above figure. The process clearly illustrates that the spectral analysis of the current pulse remove the undesired coefficient as well reduces the coefficient counts for processing. This improves the efficiency of neuro controller to make the decision faster and accurately.

V. Conclusion

This research paper presents a Shunt Active Power Filter based on Wavelet controller are designed by considering harmonic and power factor constraints under distorted source voltages. The Proposed APF design is simpler and improves the overall system performance than conventional approaches. The strength and validity of proposed controller are tested under balanced, unbalanced and variable load conditions on IEEE- 13 bus system. By observing the simulation results, it is found that proposed compensating method is flexible and effective to control the source current distortion caused by non linear loads. The above proposed APF method also limits the % THD within IEEE – 519 standard. Source current harmonic distortion under wavelet controllers are compared and observed that reactive power compensation had improved.

The APF performance is demonstrated by simulation using matlab and simulink. Results yield a good agreement with the expected APF performances by using wavelet controller than by using other controllers.

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