Chapter4. Wavelet Transform Applications

4.1 Introduction

Wavelet transform (WT) has been widely used in power system areas like power system protection, power quality [Pham 1999, Gu 2000, Huang 2001(1)], power system transients [Angrisani 1998, Huang 1999, Poisson 1999, Karimi 2000, Littler 1999], partial discharges [Kawada 2000], load forecasting [Huang 2001(2)], and power system management. Earlier method like Fourier series analysis was used to measure transient phenomena, providing good information about the frequency content of the transient. However, the evaluation of the Fourier series requires a periodicity of the disturbance signal with respect to the fundamental frequency ($\omega_0/2\pi$), hence, the treatment of transient disturbances, whose periodicity with respect to the fundamental frequency cannot be defined by the Fourier series based analysis. Therefore, a time-frequency based analysis provided by wavelet transform is used, which gives simultaneously time and frequency information of the transient.

There are two main approaches to present wavelet theory: the integral transform approach (continuous time) and the multi-resolution analysis (MRA) or filter bank approach (discrete time). The continuous wavelet transform (CWT) is a common signal processing tool for the analysis of non-stationary signals and is defined as the sum over all time of the signal multiplied by scaled, shifted versions of the wavelet function ψ:

$$c(s,\tau) = \int_{-\infty}^{\infty} f(t)\psi^*(s,\tau,t)dt \tag{1}$$

Where f(t) is the original signal, $\psi(s,\tau,t)$ is the mother wavelet defined by:

$$\psi_{s,\tau} = \frac{1}{\sqrt{|S|}}\psi\left(\frac{t-\tau}{S}\right) \tag{2}$$

S is the scale parameter of the wavelet, τ is a translation parameter of the wavelet and C(s,τ) is the wavelet transform. It is apparent from equations (1) and (2) that the original one-dimensional time-domain signal f(t) is mapped to a new two-dimensional functional space across scale S and translation τ by the wavelet transform. The set of all wavelet coefficients C(s,τ) associated with a particular signal are the wavelet representation of the original signal f(t) with respect to mother wavelet ψ(t). The most significant characteristic of the wavelet transform is that the width of the window is changed as the transform is computed for every single spectral component. It uses short time intervals for high frequency components and long time intervals for low frequency components. Another main feature of wavelets is the oscillating and fast decaying behavior that comes along with the location in time and frequency. The common choices for analyzing wavelets for transient modeling are complex Morlet wavelet and Mexican Hat wavelet given by (3) and (4) respectively as:

$$\psi_M(t) = \sqrt{\pi f_b}\, e^{\frac{-t^2}{f_b}}\, e^{j\omega_c t} \tag{3}$$

Where,

f_b is a bandwidth parameter and ω_c is the centre frequency of the wavelet.

$$\psi_{MH}(t) = \left(\frac{2}{\sqrt{3}}\pi^{\frac{-1}{4}}\right)(1 - t^2)e^{\frac{-t^2}{2}} \tag{4}$$

Since calculating the wavelet coefficients at every scale and position requires a large amount of calculations therefore in order to decrease the computational burden, wavelet coefficients are calculated only in bands of uniform frequency width thus performing the wavelet packet transform (WPT). In WPT the original waveform F is decomposed into approximation “A” and the detail “D” and then successive decomposition are performed into approximation and the details thus obtaining the wavelet packet decomposition tree as shown in Fig. 4.1.

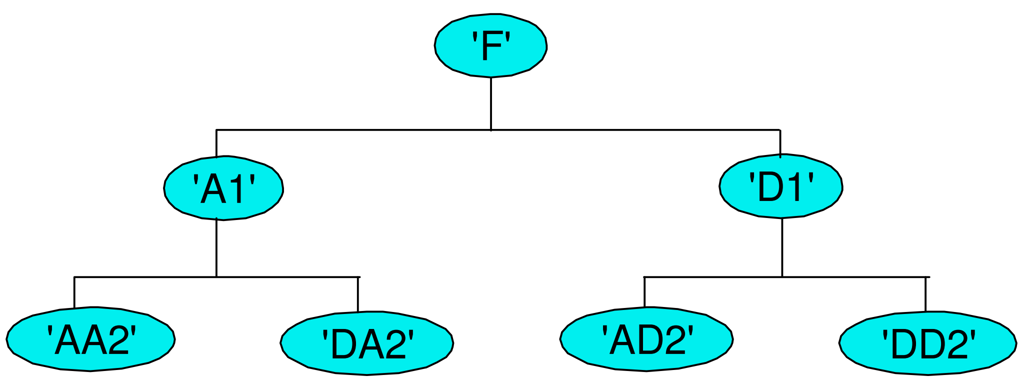

Fig. 4.1 Wavelet packet decomposition tree

In power system applications where it is required to separate the fundamental from the non fundamental components discrete wavelet transform (DWT) is used. DWT decreases the computational effort while preserving the identification of harmonic components required for analysis.

In DWT, the original waveform F is decomposed into approximate and detail at the first stage then successive decompositions are performed on the approximation only with no further decomposition for details, hence obtaining the multi resolution analysis (MRA). The DWT decomposition tree is shown in Fig. 4.2.

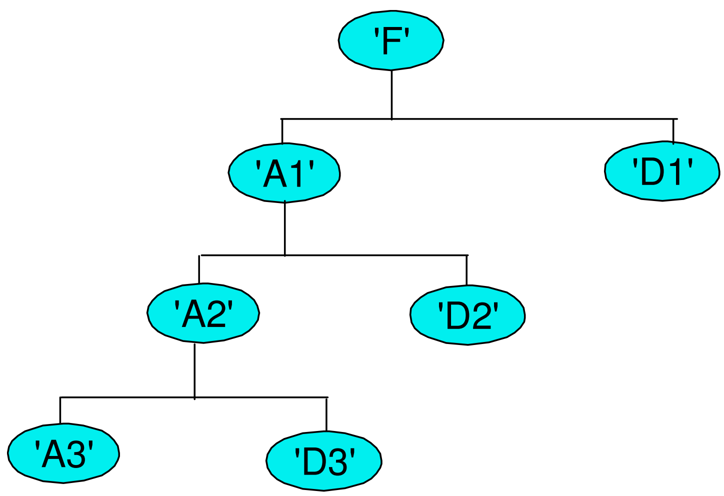

Fig.4.2 DWT decomposition tree

4.2 Frequency Estimation Using Wavelets

Frequency content of switching voltage and current waveforms can be estimated by using either discrete wavelet transform (DWT) or by wavelet packet transform (WPT). The multi resolution concept is proposed by [Mallat 1999] to efficiently perform DWT decomposition. Its basic idea is to use a low pass filter and a high pass filter to decompose a discrete signal into low frequency and high frequency components respectively. The structure of DWT in MRA for three levels is shown Fig. 4.3.

Here F_S is the sampling frequency, A1-A3 is the approximate and D1-D3 is the details at different levels. In each resolution level, the input signal in the upper resolution level is split into the approximation by a low pass filter and detail by the high pass filter in the lower resolution level. Both of output approximation and detail signal then decimated by 2. The highest frequency which can be accurately represented is less than half the sampling frequency F_S.

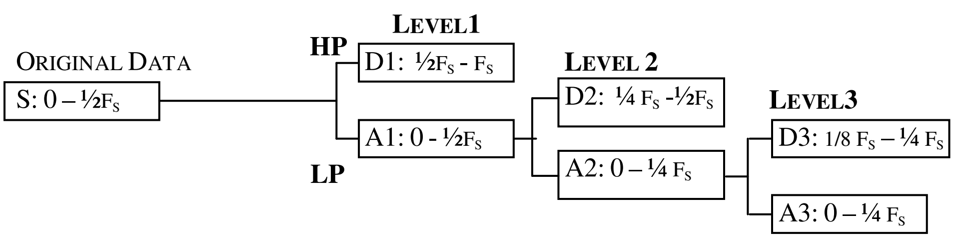

Fig. 4.3.Signal decomposition in three levels

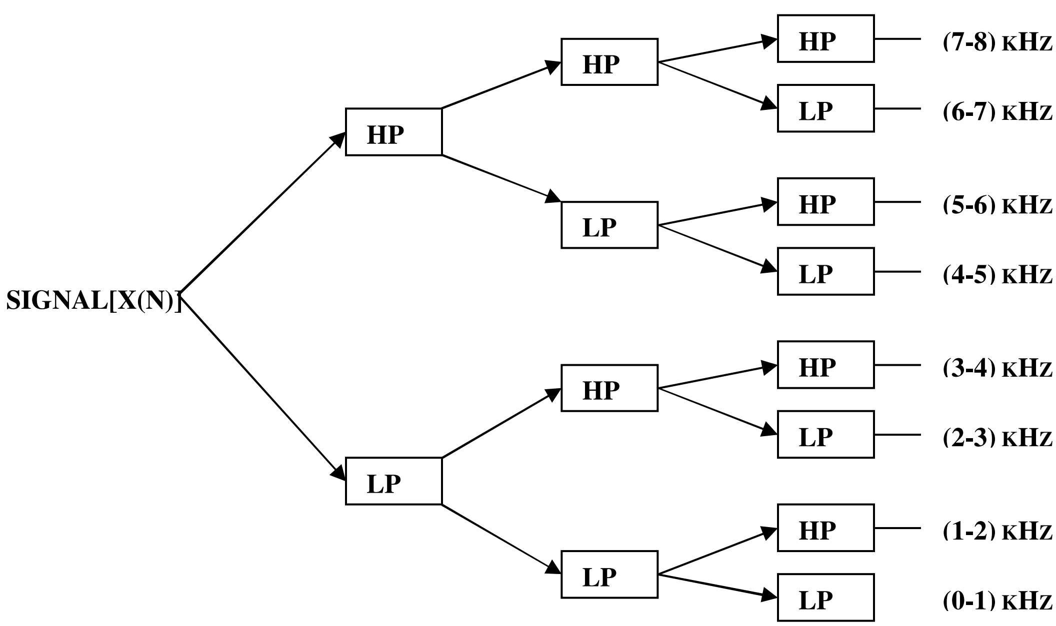

Fig. 4.4.Three level WPT decomposition tree

For a sampling frequency of 16 kHz and using three level decomposition tree, the frequency range of the output is divided into eight bands with uniform 1 kHz interval when we use WPT. This is shown in Fig. 4.4

Two other major applications of wavelets in power system are a) calculation of active and reactive power and b) feature extraction of non-sinusoidal current for active power filtering applications. Based on these ideas, switching loss analysis in a solid state device has been presented in this chapter. Switching power loss analysis using wavelets [Kumar 2007(2)] is applied in soft switching inverter for power loss calculation. Application of wavelets in active filter [Gupta 2006] is left as a future scope to improve the performance of inverters used in active filters.

4.3 Switching Power Loss Analysis [Kumar 2007(2)]

Transient nature of voltage and current during switching instants of solid state devices like MOSFETs and IGBTs makes it difficult to calculate the switching power loss with conventional mathematical models. Various methods of switching power loss have been proposed in literature. [Shen 2006] investigate the internal physics of MOSFET switching processes using a physically based semiconductor device modeling approach, and subsequently examines the existing switching loss estimation method based on the new physical insight. They also claim that in calculation of losses the output capacitance loss term is redundant and erroneous. [Bai 2004] calculates the losses taking into account the effect of parasitic like L_s and derives the expression for drain to source voltage V_{ds} which includes the inductance L_s. The power loss is calculated by taking the integral of the product of drain to source voltage and drain current over the period of interest. [Hiraki 2002] discuss the switching power loss analysis with a feasible power loss analysis simulator. It makes use of feasible switching loss data-based table accumulated from the measured transient switching operation and periodic steady state conduction voltage and current operating waveforms of semiconductor switching devices used in power electronic converters. [Lai 1994] utilize well established mathematical formulae based on voltage and current ratings, device parameters and switching frequency. [Cavalcanti 2003] proposes energy based second order polynomial equation which takes into account the parameter variations, such as temperature for power loss calculation.

These methods are based upon device parameter like input and output capacitances, parasitic inductance of the MOSFETS and their physical modeling. In these calculations information regarding the snubber to be added in the practical circuits, their losses and also the oscillation during transients due to parasitic is not mentioned. Also, information regarding frequency content is missing in all the above mentioned loss analysis, which is useful for snubber design and analysis of EMI during switching. Wavelet is being used for transient analysis and wide range of frequency contents in it. [Heydt 1997] analyzed wavelet transform application for transient signal with its advantages and disadvantages. [Driesen 2003] have quantified transient power by complex wavelet transform. [Hamid 2002] provide a theoretical basis of using wavelet packet transform for power measurement in different frequency bands. The present work proposes the wavelet based method for switching power loss calculation. The proposed method calculates the power loss with accuracy as compared to the simple integration method and also gives information about the frequency content of voltage and current waveforms during transients. Multi resolution analysis using wavelets makes it possible to identify and locate the frequency content of these transients. Multi resolution analysis is used to decompose signals in wavelet domain. The voltage and current signals are transformed in different frequency bands which accommodate transient frequencies. The power is calculated in each frequency band by multiplication of current and voltage wavelet coefficients [Yoon 1998, Yoon 2000, Zhu 2004, Zhu 2006]. The total power is sum of all the sub band power. A simple clamped inductive load circuit is taken for the analysis of switching power loss.

To implement the idea for MOSFET switching loss analysis, a SIMULINK model of clamped inductive load circuit is described below.

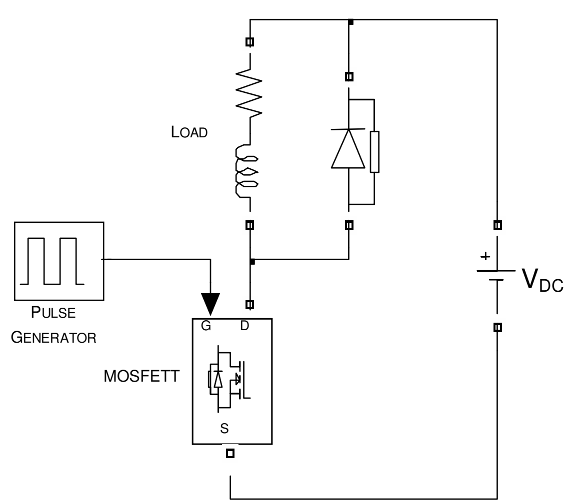

Fig.4.5. SIMULINK model of the clamped Inductive load circuit

Fig.4.5 shows the inductive load circuit for MOSFET under test. When the MOSFET turns on, a high peak current flows through the MOSFET, induced by diode reverse recovery and by output capacitances of MOSFET and diode. Significant ringing is observed in the MOSFET voltage waveform when substantial inductance is present in series with the MOSFET. The ringing caused by these inductances is visible in the MOSFET voltage and current. The method proposed takes into account all these effects and calculates the power loss depending upon the actual waveform in the MOSFET.

Snubber parameters are designed using following equations [Krein 2003].

$$C_{opt} = \frac{I_L t_f}{\sqrt{12} V_{off}} \tag{5}$$

$$R < \frac{DT}{2C} \tag{6}$$

$$L_{opt} = \frac{V_{off} t_f}{\sqrt{12} I_{on}} \tag{7}$$

$$R > \frac{2L}{(1-D)T} \tag{8}$$

Where C_{opt} is the optimal snubber, t_f if fall time, I_L is the load current, L_{opt} is the optimal inductance, D is the duty cycle, T is the time period, R is the snubber resistance.

Simulated device voltage and current waveforms are shown in Fig. 4.6.

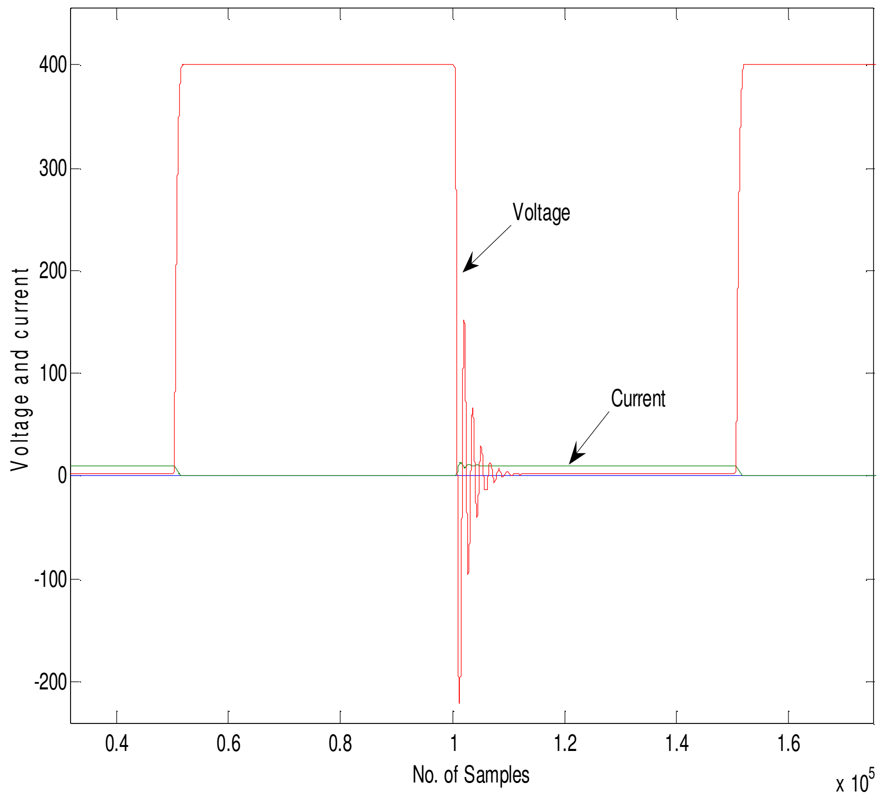

Fig.4.6. Simulated device voltage and current waveform (voltage is in volts and current is in amperes)

Power calculation using DWT

A wavelet transform maps the time domain signals of voltage and current in a real valued time-frequency domain, where the signals are described by the wavelet coefficients as given below:

$$i(t) = \sum_{k} c_{N,k}\phi_{N,k}(t) + \sum_{m=1}^{N}\sum_{k} d_{m,k}\psi_{m,k}(t) \tag{9}$$

$$v(t) = \sum_{k} c'_{N,k} \phi_{N,k}(t) + \sum_{m=1}^{N} \sum_{k} d'_{m,k} \psi_{m,k}(t) \tag{10}$$

Where,

$$c_{m,k} = \sum_{k} i(t) \bar{\phi}_{m,k}(t) \quad \text{and} \quad d_{m,k} = \sum_{k} i(t) \bar{\psi}_{m,k}(t) \tag{11}$$

$$c'_{m,k} = \sum_{k} v(t) \bar{\phi}_{m,k}(t) \quad \text{and} \quad d'_{m,k} = \sum_{k} v(t) \bar{\psi}_{m,k}(t) \tag{12}$$

The power is calculated as an averaged sum of the power transfer over transient period given by:

$$P = \frac{1}{T} \int v(t).i(t)dt = P_{j,0} + \sum_{j \geq j_0}^{N-1} P_j$$

$$= \frac{1}{2^N} \left(\sum c_{j_0,k} c'_{j_0,k} + \sum \sum d_{j,k} d'_{j,k} \right) \tag{13}$$

Power loss is calculated for different mother wavelets as given in Table 4.1.

Table 4.1
Power loss calculation of MOSFET switching

Types of Wavelets	Average Power Loss (Watt)		
	Level 1	Level 2	Level 3
Sampling Frequency $f_s = 10^{10}$			
db1	15.1577	15.1572	15.1560
db2	15.1571	15.1560	15.1535
db3	15.1565	15.1535	15.1487
db10	15.1523	15.1415	15.1199
db20	15.1479	15.1281	15.0876
Sampling Frequency $f_s = 10^{9}$			
db1	15.1147	15.1087	15.0966
db2	15.1087	15.0966	15.0719
db3	15.1026	15.0726	15.0244
db10	14.060	12.0278	8.3003
db20	15.409	15.9950	17.1640

4.4 Case Study

To verify the accuracy of the method proposed, analysis of power measurement using instantaneous values of voltage and current, power measured by SIMULINK block and power measured by wavelets has been carried out on simulated waveform of known nature given by equations (14) and (15). Power calculated by the above mentioned methods are given in Table 4.2. Fig.4.7 shows the SIMULINK block used for power calculation.

Voltage, current and power corresponding to equations (14), (15) and (16) are shown in Fig.4.8., Fig.4.9 and Fig.4.10 respectively. It is clearly seen that power measured by wavelets is more accurate than the power calculated by other methods. Based upon these analysis details about switching loss calculation for MOSFET has been presented with the proposed method.

Average power over one cycle has been calculated for simulated waveforms of voltage and current given by the following equations:

$$v(t) = 1.2\cos(\omega t) + 0.33\cos(3\omega t) + 0.2\cos(5\omega t) \tag{14}$$

$$i(t) = 0.6\cos(\omega t + 30^\circ) + 0.1\cos(5\omega t + 45^\circ) + 0.1\cos(7\omega t + 60^\circ) \tag{15}$$

The average power is given by

$$p_{av} = \frac{(1.2)(0.6)}{2}\cos(30^\circ) + \frac{(0.2)(0.1)}{2}\cos(45^\circ) = 0.3188 \tag{16}$$

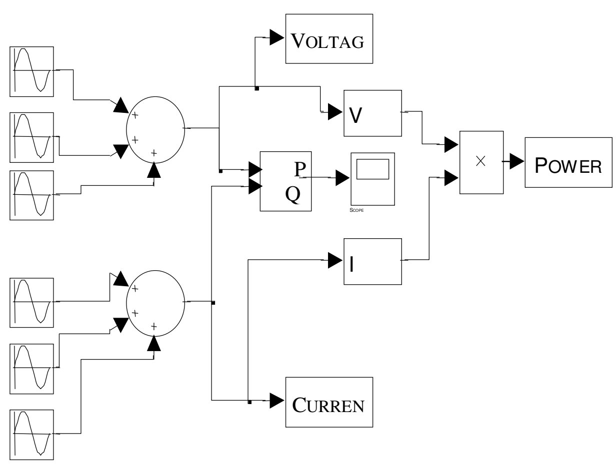

Fig.4.7. SIMULINK block for power measurement of known waveform

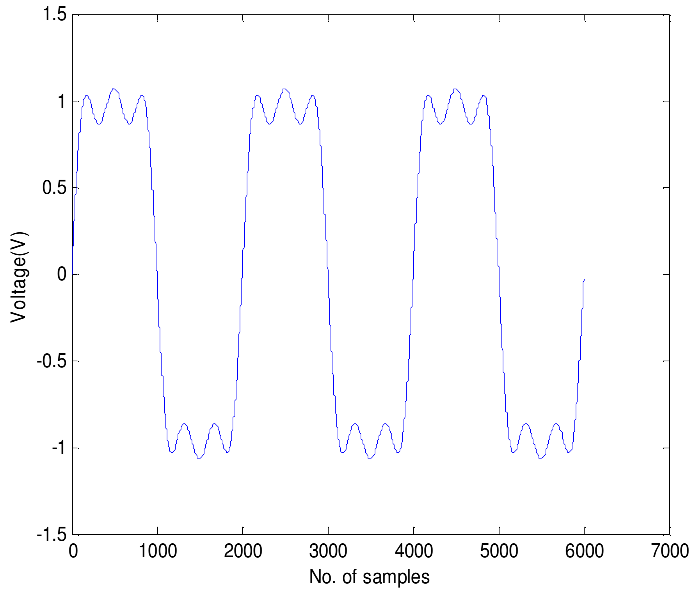

Fig.4.8.Simulated voltage Waveform with fundamental, 3rd, and 5th harmonics

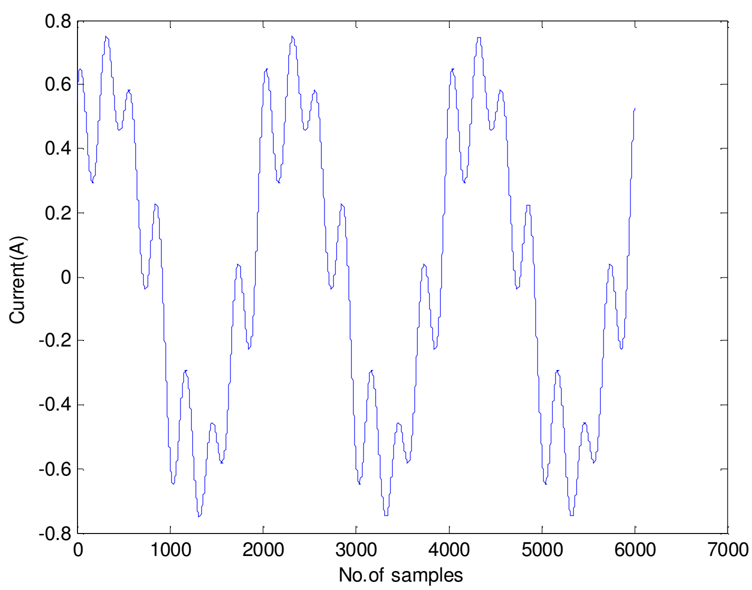

Fig.4.9. Simulated current Waveform with fundamental, 5th and 7th harmonics

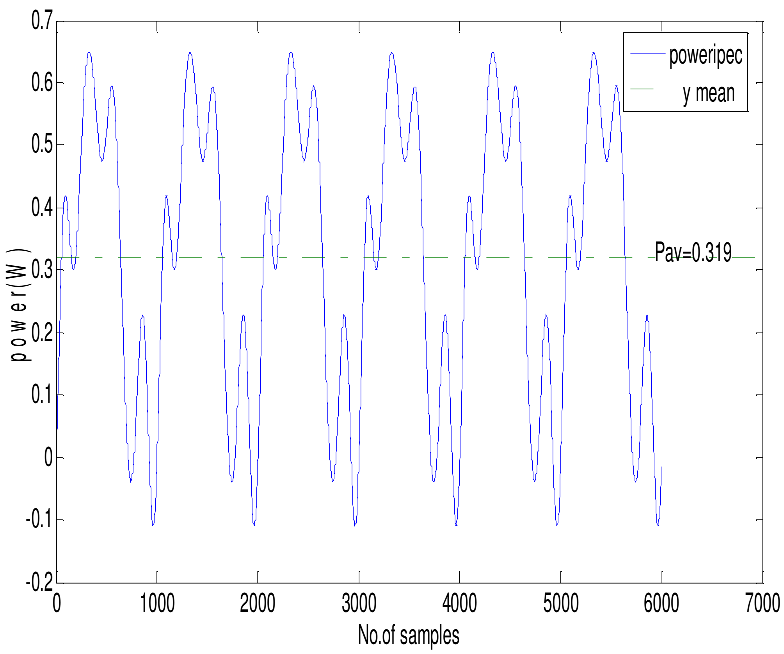

Fig.4.10. Simulated power waveform

For comparison purpose power is calculated by taking the instantaneous values of voltage and current and averaging it for three cycles and also by wavelets using the mother wavelet db2. The result is given in Table 4.2.

Table4.2
Average Power (per cycle) Calculation for Simulated Waveforms

Power (Watt)	Instantaneous	Wavelets(db2)	Simulink	Calculated (using (16))
	0.3190	0.3188	0.312	0.3188

Form results given in Table 4.2 we can say that the power calculated by wavelets is more accurate than that of instantaneous value method with suitable choice of mother wavelet.

4.5 Conclusions

A new application of wavelet based analysis is presented in this chapter. Switching power loss analysis using wavelets helps in calculating switching loss with and added information about the frequency content of the transients. This information may be further utilized for EMI analysis and designing of snubber for the devices. Results are presented using DWT only but with continuous wavelets these results are likely to improve.