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Research Article

Evaluation of Losses and Life of Distribution Transformer under Non-linear Load using Wavelet Transform

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Abstract: In this paper, impact of harmonics on losses and life of distribution transformer is discussed. Wavelet Transform is used to analyze voltage and current signatures of distribution transformer operating under non-linear load. Power loss is calculated using wavelet based current and voltage profiles. Reduction in life time of the transformer has also been calculated which results due to harmonics in power system. Results show that power loss of a transformer increases under non-linear load as compared to its usage under linear loading, increase in power loss causes decay in transformer's operational life.

Keywords: Harmonics, wavelet transform, 3-phase distribution transformer, transformer loss, life of transformer

1. INTRODUCTION

In today's competitive market, power quality, to drive various linear and non-linear loads, is a major concern. Devices and relays in control systems are so sensitive that distorted signal at input leads to the inaccurate results. Harmonics are the major factor which causes distortion in wave form of the signal. Distribution transformer is highly influenced by harmonics. Distribution transformers losses in European Union were assessed to 33 TW.h/yr. Increase in the loss due to harmonics was found to be 15% [1]. Harmonics bring a no of challenges for a distribution transformer including increase in heating loss, insulation degradation, rise in temperature, decrease in efficiency, higher hot-spot temperature, and reduced life time [2-3].

Harmonics, derived by a word Acoustic, are basically the integral multiple frequency components of fundamental frequency. Harmonics are injected where linear behavior between voltage and current loses like power electronic switches

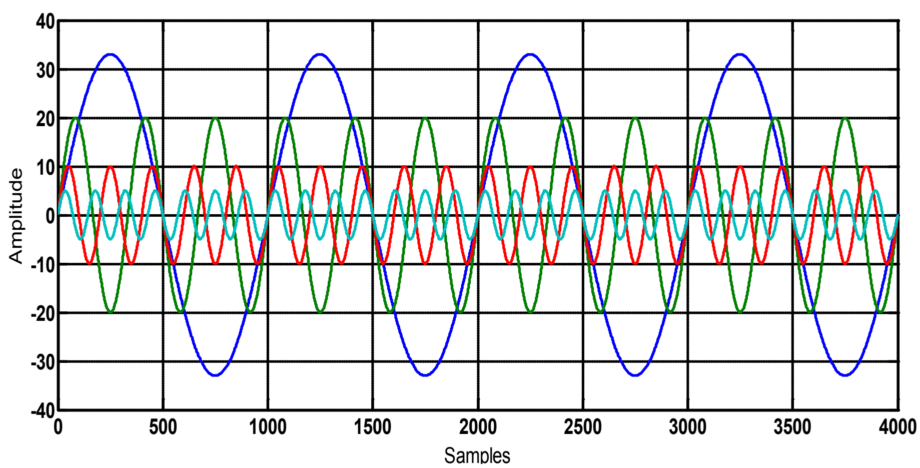

Fig. 1. Fundamental component and its multiple components.

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[4]. For some signal with 50 Hz as its fundamental frequency, 3rd, 5th, 7th, harmonic will be at 150 Hz, 250 Hz, and 350 Hz respectively. Fig. 1 shows the fundamental component and its various multiple frequency components which are commonly known as the distortion of a signal.

Quantitative measure of all the multiple frequencies present in a signal is known as Total Harmonic Distortion (THD) which is given as [4]:

$$THDv = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \quad (1)$$

THD Total harmonic distortion

V_h Voltage under harmonic

V_1 Fundamental component of voltage

A complete analysis of harmonics behavior in time domain as well as in frequency domain is very important. Time domain gives information of signal at every instant of time. In a similar fashion, analysis of signal in frequency domain gives the information of all frequencies present in it. Various techniques are used to examine the harmonics behavior in both time and frequency domain. Laplace transform, Fourier Transform, Short Time Fourier Transform and Wavelet Transform are used to analyze harmonics.

Root Mean Square (rms) values of voltage and current profiles with a time period "T" are given with the help of following mathematical expressions in analog form [21]:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2 dt} \quad (2)$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2 dt} \quad (3)$$

Same can be written for digitized nature of both the signals [21]

$$V_{rms} = \sqrt{\frac{1}{2^N}\sum_{i=0}^{2^{N-1}} v_i^2} \quad (4)$$

$$I_{rms} = \sqrt{\frac{1}{2^N}\sum_{i=0}^{2^{N-1}} i_i^2} \quad (5)$$

Voltage harmonics are very harmful for distribution transformer just like current harmonics. Voltage harmonics causes winding insulation degradation however current harmonics are major cause of increase in power loss of transformer [5]. In distorted signal of a distribution transformer, voltage harmonics not only exist at some particular instants of the voltage signature rather they exist throughout the signal. In this paper, behavior of harmonics on voltage signal is studied at every instant of time. Further more, impact of harmonics on winding insulation deterioration and transformer losses is to be studied at every instant of time throughout the signal to check whether harmonics are more harmful near peaks of the signal or near zero crossings of current and voltage profiles. Fig. 2 shows the actual voltage signature of a distribution transformer where harmonics exists near peak value and Fig. 3 makes the idea clear that harmonics exists near zero crossings.

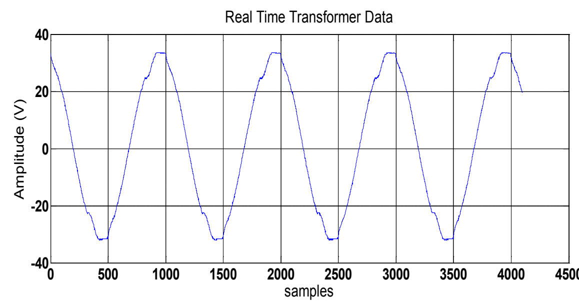

Fig. 2. Transformer's voltage profile.

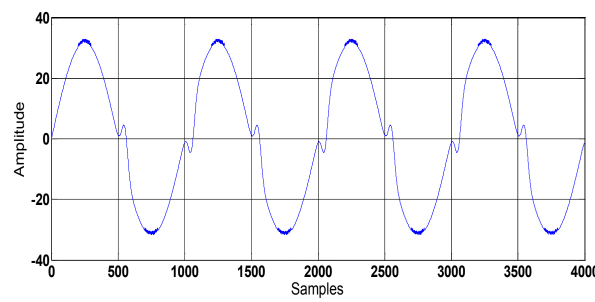

Fig. 3. Voltage harmonics near zero.

2. WAVELET TRANSFORM

Different transformation tools are used to deal with both time and frequency domains with various constraints. Fourier Transform gives information about all the frequencies present in a signal. It also aids to determine the order of frequencies and their magnitudes present. However it does not give any info of varying frequency in a signal. Fourier Transform of a signal with multiple frequencies and that of having continuously changing frequency is same. It does not distinguish between stationary and non-stationary signals and gives the same result for both however there is a difference in the behavior of such signals. Fourier Transform determines only the number of frequencies present in non-stationary signal but does not give any information where (at which instant of time) frequencies exist [6].

Fig. 4 and Fig. 5 show a stationary signal with different frequencies in it and its Fourier transform which shows different frequencies at different points on frequency scale. Fig. 6 & 7 show a signal with varying frequency and its Fourier transform respectively. Fig. 5 and Fig. 7 make the idea clear that Fourier transform of both Stationary and Non-Stationary signal is same. Moreover, it can be used only in one domain in one time. Fourier Transform ignores positive and negative peaks, it only gives information of frequencies present in a signal. On the other hand, Short Time Fourier Transform (STFT) is capable to work in both domains but it works like Heisenberg Uncertainty Principle which states that speed and position of any atomic particle cannot be measured accurately at a same time [6]. In case of electronic signals, it is not possible to simultaneously know the frequency of a signal and the time instant where it exists and vice versa. Detailed analysis of signal is impossible in both time and frequency domains simultaneously using STFT. If signal is studied in frequency domain, its time resolution becomes inaccurate and vice versa. Resolution problem occurs because of fixed window height in STFT. However, it is capable of distinguishing between stationary and non-stationary signals unlike Fourier transform. Fig. 8 shows STFT of Non-Stationary signal and it is obvious that STFT is capable of working in both time and frequency domain simultaneously. Fig. 8 shows STFT of a signal which gives detailed information of frequency domain but poor resolution for time domain. In Fig. 9, with the variation in window size, time domain resolution becomes better but frequency is not accurate because it show frequency spectrum on frequency axis. In Fig. 10, frequency resolution is much accurate and time domain resolution is very poor.

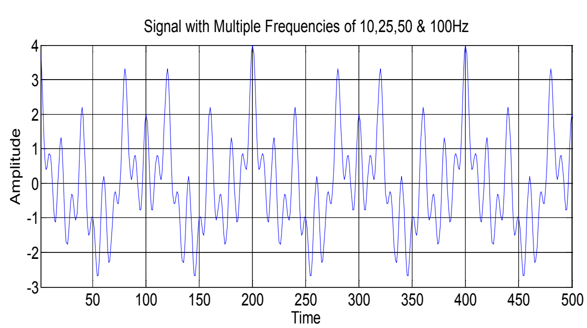

Fig. 4. Stationary signal with multiple frequencies.

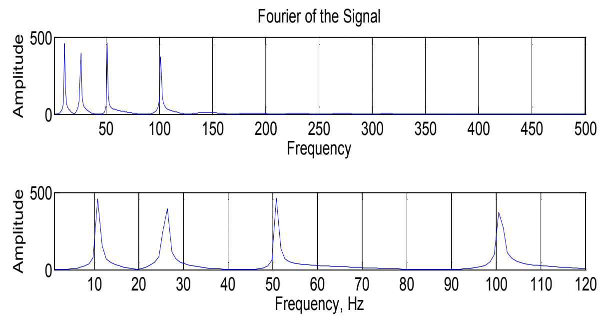

Fig. 5. Fourier of stationary signal.

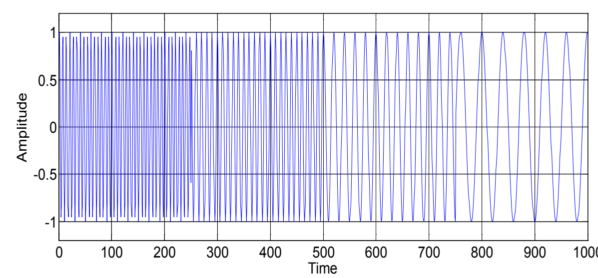

Fig. 6. Non-stationary signal.

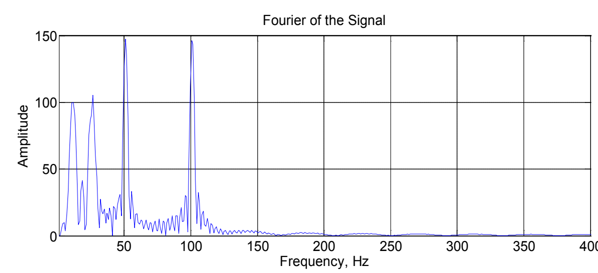

Fig. 7. Fourier of non-stationary signal.

Wavelet transform is most suitable technique to analyze harmonics both in time as well as frequency domains simultaneously. It does not show resolution problem in either time or frequency domain unlike STFT [6]. In Wavelet Transform, correlation of signal is found with the help of Mother Wavelet. Wavelet Transform has a series of mother wavelet functions like Haar, Meyer, DMeyer, Shannon, Mexican Hat, Daubechies, Symlets, Coiflets, and Gaussian etc. Unlike STFT, Wavelet transform is taken at every slice of the signal in time domain. It gives information about the behavior of a signal for both positive and negative peaks. Mathematically, wavelet transform is represented as follows [6]:

$$W.T(\tau, s) = \frac{1}{\sqrt{|s|}} \int x(t) \, . \, \Psi^{*}\left(\frac{t-\tau}{s}\right) dt \qquad (6)$$

s Scale

τ Translation

WT Wavelet transform

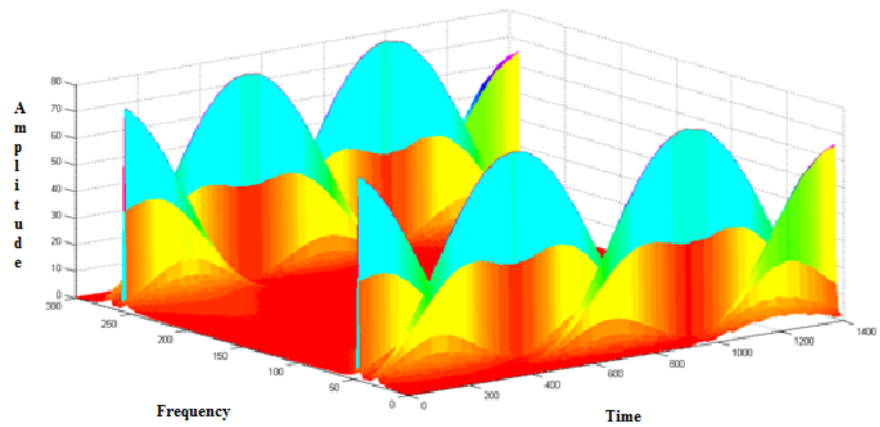

Fig. 8. STFT of a signal.

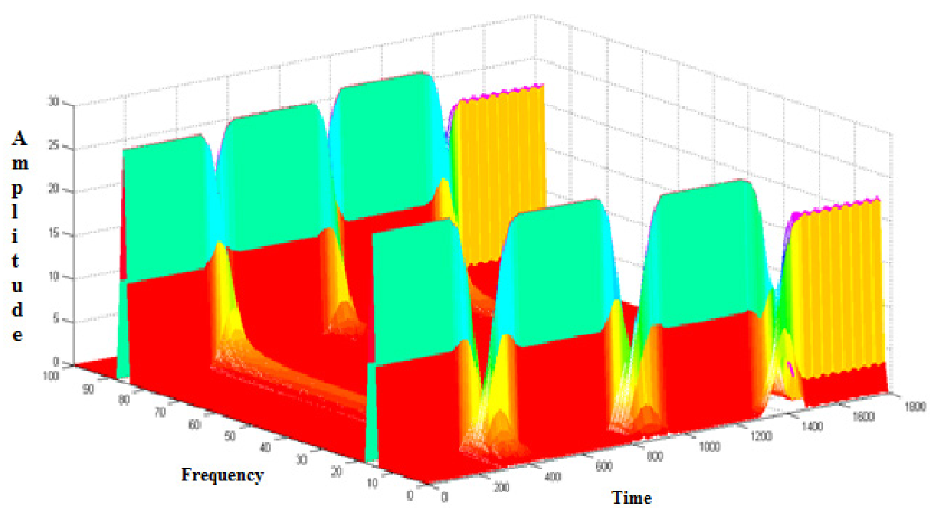

Fig. 9. STFT of same signal with new window size 1.

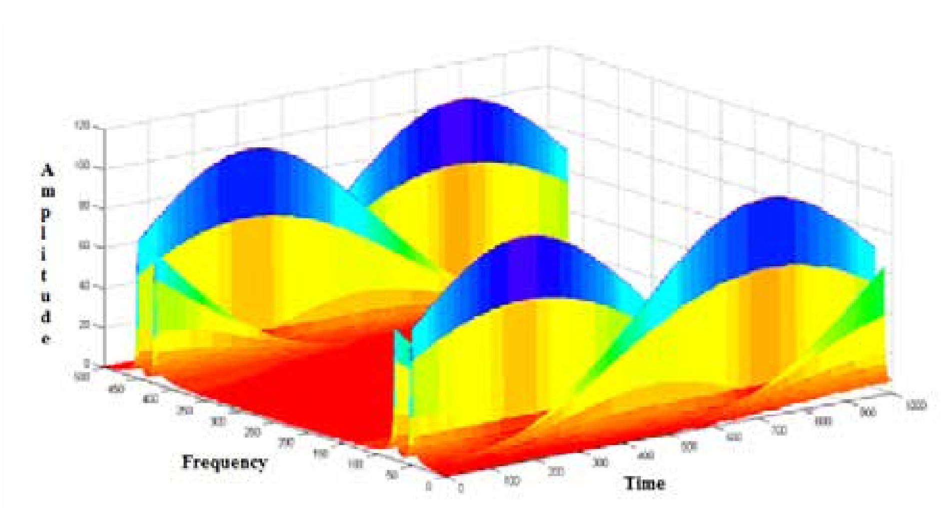

Fig. 10. STFT of same signal with new window size 2.

Equation (6) shows a function x(t) whose wavelet is to be taken. Ψ(t)is a mother wavelet which has translated versions of a signal delayed or advanced by "τ" and scaled by "s". Fig. 11 shows variable window size pattern in Wavelet Transform. Variable window size is actually the translated and scaled versions of mother wavelet which is to be multiplied with original signal. Translation is basically the location of mother wavelet and scale is 1/f. in order to compute the wavelet of a signal, translated and scaled versions of mother wavelet are multiplied at every segment of signal in time domain and also with every spectral component in frequency domain [6].

Fig. 11 gives the idea of variable window size in Wavelet Transform. Each box in Fig. 11 has same area with different lengths and widths and each box represents one coefficient of Wavelet Transform. Region "A" has small length along "Scale axis" and relatively wider along "Translation". This region deals with low frequencies. Region "B" deals with the signal at lower scale as compared to "A". Region "C" gives the detailed information of higher frequency components because higher frequencies lie at lower scale in Wavelet transform. In fact, this variable scale is responsible for complete behavior of higher frequencies in a signal or harmonics of that signal. Analysis of every frequency in frequency spectrum can be performed in wavelet environment due to different values of scale. Wavelet transform is also capable to analyze a signal in time domain because mother wavelet has time shifted versions at various instants in time domain. It can be observed in Fig.11.

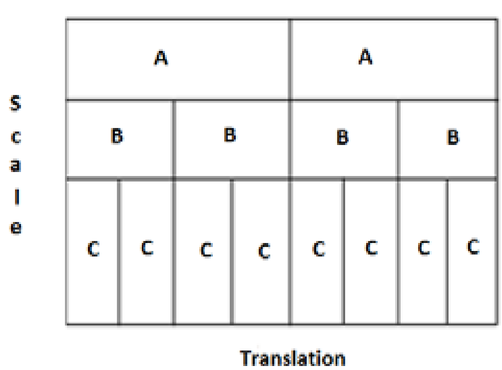

Fig . 11. Variable window size.

Mathematically, Wavelet of digitized values of current and voltage in equations (4) and (5) can be expressed in the following manner [21]:

$$V_{rms} = \sqrt{\frac{1}{2^N}\sum_{i=0}^{2^{N-j-1}}\sum_{k=0}^{2^{j}-1}(d_{j,k}^{*j})^2} \quad (7)$$

$$I_{rms} = \sqrt{\frac{1}{2^N}\sum_{i=0}^{2^{N-j-1}}\sum_{k=0}^{2^{j}-1}(d_{j,k}^{j})^2} \quad (8)$$

Where $d_{j,k}$ and $d^*_{j,k}$ are coefficients of Wavelet transform at i^{th} node, j^{th} level and k^{th} sample.

3. POWER LOSS IN DISTRIBUTION TRANSFORMER

Distribution Transformer's losses can be divided into two types as No-load Loss and Load Loss.

3.1 No-load Loss

No-load Loss is also studied as core loss of distribution transformer which is result of core excitation i.e. such type of loss is due to the hysteresis and eddy currents which are highly dependent upon frequency and flux density. Due to their high dependency on frequency, they are influenced by harmonics. No-load loss can be determined by performing Open Circuit Test on distribution transformer.

3.2 Load Loss

Load loss is the resultant of different losses like Cu- loss, winding eddy current loss and other stray loss. Other stray loss is due to the structural parts of distribution transformer like clamps, tanks, etc. Winding eddy current loss and other stray loss are lumped together and known as Total Stray Loss [7].

$$P_T = P_{C.L} + P_L \quad (9)$$

$$P_L = P_{ohmic} + P_{T.S.L} \quad (10)$$

$$P_{T.S.L} = P_{E.C} + P_{O.S.L} \quad (11)$$

P_T Total power loss

P_{CL} Core loss

P_L Load loss

P_{TSL} Total stray loss

P_{OSL} Other stray loss

P_{EC} Eddy current loss for winding

All the above mentioned losses are dependent upon harmonics according to the following mathematical expressions [8]:

$$P_{ohmic} = \sum_{h=1}^{h_{max}} I_h^2 * R \tag{12}$$

$$P_{E.C} = P_{E.C.R} * \sum_{h=1}^{h_{max}} [\frac{I_h}{I}]^2 h^2 \tag{13}$$

$$P_{O.S.L} = P_{O.S.L.R} * \sum_{h=1}^{h_{max}} [\frac{I_h}{I}]^2 h^{0.8} \tag{14}$$

I_h Current under Harmonic

I Fundamental current component

4. LIFE ESTIMATION

Rated losses of a distribution transformer are increased when it is used to work under non-linear load. This rise in loss results an increase in transformer's temperature, hotspot temperature and ultimately decrial in life time of the machine. Equations (15-17) show temperature of top oil of a transformer and hotspot temperature [9, 10]. Equation (18) shows life of a transformer working under non-linear load in per unit [10,11]. Equation (19) represents the actual life of a transformer [9, 12].

$$\Delta T = T * (\frac{P_{L.H}}{P_L})^{0.8} \quad {}^0\text{C} \tag{15}$$

$$\Delta T_{T.O} = T_{T.O} * (\frac{P_{L.H} + P_{C.L}}{P_L + P_{C.L}})^{0.8} \quad {}^0\text{C} \tag{16}$$

$$T_{H.S} = T_A + \Delta T + \Delta T_{T.O} \quad {}^0\text{C} \tag{17}$$

$$L = 9.8 * 10^{-18} * \exp\left(\frac{1.5*10^3}{273+T_{H.S}}\right) p.u \tag{18}$$

$$Remaining\ Life = L * Original\ Life \tag{19}$$

ΔT_{TO} Rise of Top-Oil Temperature over Ambient temperature

T_{TO} Top oil rise in temperature under rated conditions

ΔT Under Non-linear load, rise of Hot spot temperature over Top Oil temperature

T_{HS} Hot Spot temperature

Ta Ambient temperature

L(pu) Life in per unit

5. TENTATIVE ARRANGEMENT

Data was gathered from Awais Textile Industries, situated at Abdullahpur, Faisalabad, Pakistan, which consists of printing and dyeing units. Printing section of the industry comprises of various induction motors of different rating which are used to open the fabric rolls and passing it through printing area. Most of these motors are fed through VFDs furthermore a large number of CFLs are used for lighting purpose. All of the mentioned equipment is being supplied by a 200 kVA distribution transformer. Due to non-linear load attached with the transformer, it run under the effect of harmonics. Data was collected in the form of voltage and current of the said transformer and it was processed for its analysis in MATLAB using Wavelet Transform.

A Digital Oscilloscope was used for observing the voltage profile at the terminals of transformer which has a provision of plugging in external storage device like USB for data storage. A Clamp on meter was used to measure both current and voltage to verify results, in order to, minimize the chance of error. Wave form was observed at screen of the oscilloscope and then it was stored in CSV (Comma Separated Values) format directly on USB. The procedure was repeated for several times, in order to, minimize the probability of any procedural mistake while taking data.

6. RESULTS AND DISCUSSION

Real time voltage and current profiles of 200 kVA distribution transformer working under non-linear load were taken from the above mentioned experimental set up. Real time voltage profile is shown in Fig. 2. A closer look of Fig. 2 makes it clear that real time voltage signature is distorted signal due to harmonics. Harmonics have significant impact near both the peaks of voltage signature. Mexican hat is used as Mother Wavelet because it is very symmetrical function in nature. Wavelet transform of voltage profile is depicted in Fig. 12, it shows that maximum distortion occurs up to scale of 54. Harmonics are the higher frequency components so they exist at lower scale. As the scale gets closer to zero, distortion level increases significantly. Maximum correlation between input signal and mother wavelet is shown from the brightest point at scale 250. Fig. 13 depicts the same result in 3D view. Pink and yellow humps represents the positive and negative peaks whereas at lower sale just like as depicted in Fig. 12. Translation axis shows the behavior of signal at various instants of time while scale axis illustrates various frequency components in it. Fig. 12 also makes it clear that there is resolution problem neither in time domain nor in frequency

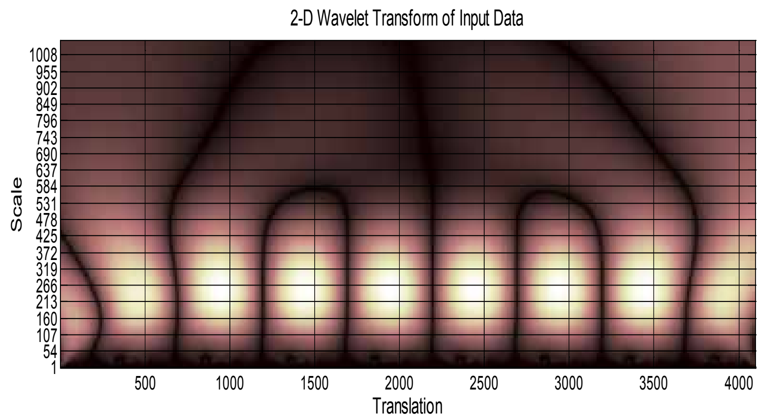

Fig. 12. Wavelet of input signal.

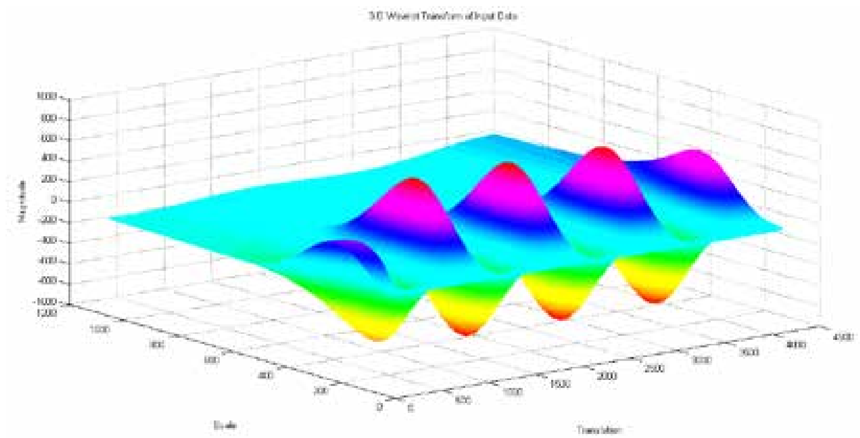

Fig. 13. 3D Wavelet transform of input data.

domain using wavelet. Harmonics which exist in the voltage signature of distribution transformer are shown in Fig. 14. It shows higher frequency component throughout the whole signal which corresponds to scale 50. In the similar fashion, Fig. 15 depicts the impact of another harmonic which exists at scale 36. Same is the case for Fig. 16 but on comparing these figures, it is obvious that frequency increases as scale becomes smaller which causes distortion level to increase. Distortion level in Fig. 16 is very high as compared to that of Fig. 14.

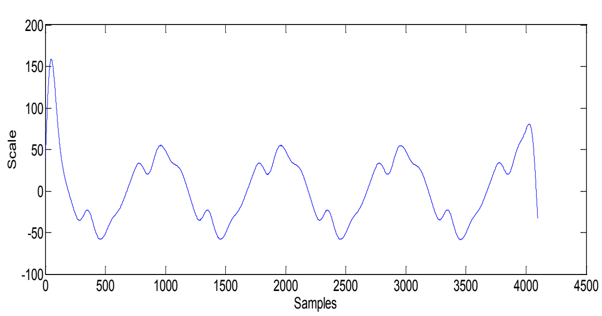

Fig. 14. Harmonics on scale 50.

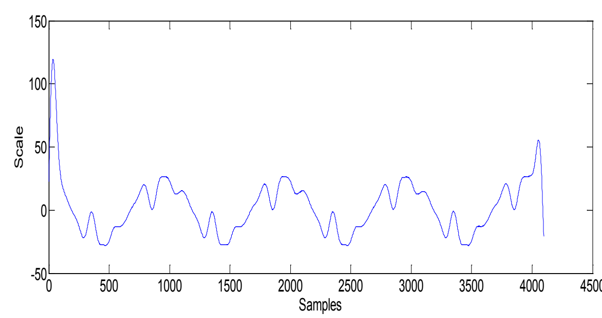

Fig. 15. Harmonics on scale 36.

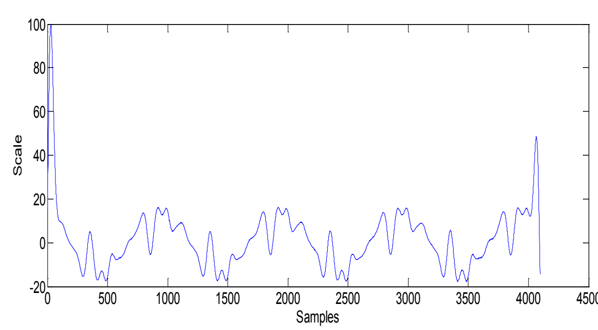

Fig. 16. Harmonics on scale 28.

By using the data of voltage and current profiles along with wavelet transform coefficients as in equations (7) and (8), power can be calculated with the help of equation (20) [13, 21].

$$P = \frac{1}{T} \int_0^T i_t v_t \cong \frac{1}{2^N} \sum_{i=0}^{2^{N-j}-1} \sum_{k=0}^{2^j-1} d_{j,k}^i d_{j,k}^{*i} \quad (20)$$

This is the power at i^{th} node, j level and k sample. By using equation (20), total power loss for three phase distributed transformer working under non-linear load is *3,714 W*. Rated power loss of transformer was *3000 W* and percentage rise in power loss due to non-linear load is 23.8%. Along with increase in power loss, winding temperature and hot spot temperature of transformer also increases. Power loss is directly related with temperature. Rise in hotspot temperature also causes to weaken winding insulation overall and particularly at that point where the temperature of winding is maximum. Hotspot temperature of transformer under non-linear load rises and equation (17) shows that temperature rose upto 116.47 ^{0}C. Life of transformer is also reduced due to harmonics and increased power loss, equation (18) shows useful life of distribution transformer in per unit which is 0.8 *p.u* in this case. Effective life of distribution transformer working under rated conditions is 50 years, provided by manufacturer (Transformer's data is given in appendix-I). Equation (19) shows the remaining life of transformer if it is being operated under the said conditions which is just 43 years and it is reduced to 14% compared to its normal life. With the increase in THD, life gets reduced beyond 14%.

Appendix-I. Distribution transformer's specifications.

Parameters	Ratings
Manufacturer	PEL
Distribution Transformer, kVA	200
H.T Voltage, kV	11
L.T Voltage, kV	0.4
H.T Current, A	10.5
L.T Current, A	266.7
Primary Side Resistance, Ω	14.75
Secondary Side Resistance, Ω	0.0062
Primary Side Leakage Inductance, H	0.003
Secondary Side Leakage Inductance, mH	0.067
Core Loss Resistance (Rc), kΩ	728
Magnetization Inductance, H	32105
Cooling Method	ONAN
No. of Phases	3
Insulation Class	A
Frequency, Hz	50
Ambient Temperature, ^{0}C	35
Winding Temperature, ^{0}C	65
Vector Group	Dy_n11
No-load Loss, W	500
Load Loss, W	3000
Life	50 Yrs

In order to get rid of harmonics, filters are used which filter out the unwanted signals from required fundamental component. But these filters are normally used for low voltage level and for small ratings. These filters can't be used in power system of high voltage level which requires specially designed active devices for filters for HVDC. However SHE (Specific Harmonic Elimination) method is used normally for industrial purpose which injects reverse harmonics to nullify the effect of unwanted signals. ABB, Siemens, G.E etc provides such specially designed filters for industries based upon SHE technique.

7. CONCLUSIONS

In this paper, transformer losses and reduction in its life, working in harmonics environment, are focused. Tool used for analysis purpose is Wavelet Transformation because it does not compromise between time and frequency domain. Calculations show that hotspot temperature of transformer increased to 116.47 °C under non-linear load. Increase in transformer losses is 23.8% compared to its rated loss. Increase in power loss and hotspot temperature of transformer causes its winding insulation to deteriorate and its effective life reduces. Working of transformer under non-linear load resulted 14% reduction in its life time. Harmonics impact can be reduced by changing design considerations of winding insulation and hot spot temperature may be focused to use a transformer to its maximum life in future.

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