Volume 2021, 1-6 | Article ID : IJETS-2106252112358

International Journal of Engineering & Technology Sciences

Journal homepage: http://htpub.org/International-Journal-Of-Engineering-&-Technology-Sciences/

ISSN 2289-4152

An Efficient Technique to Measure and Examine the Hysteresis Loss of a Transformer under Source Harmonics

Arunava Chatterjee[a,1], Sankar Das[b] , Debashis Chatterjee[c]

[a]*Department of Electrical Engineering, Raghunathpur Govt. Polytechnic,Purulia, India*
[b]*Department of Electrical Engineering, Govt. College of Engineering and Textile Technology, Berhampore, India*
[c]*Department of Electrical Engineering, Jadavpur University, Kolkata, India*

Article

Article history:
Received: 15th June 2021
Received in revised form: 25th June 2021
Accepted: 30th June 2021

Keywords:
transformer, op-amp integrator, harmonics, hysteresis, piecewise-mixed model

Abstract

This paper presents a study on the consequence of source side harmonics on a single-phase transformer. Source harmonics are mostly present in power electronic sources which are commonly used in renewable applications like a fixed frequency inverter for wind power generation. The continued result of source side harmonics is observed on the hysteresis curve of the core of a transformer. Single-phase transformers are used in the proposed study to detect the effect of harmonics on magnetization and demagnetization cycle using an electronic operational amplifier-based integrator circuit. The study also proposes a modified hysteresis model for the transformer which also considers the effect of harmonics. A technique is presented for effectively storing and plotting the hysteresis curve from the terminal measured data of the single-phase transformer. A source harmonic mitigation technique is also proposed in this paper. The proposed study can be an effective tool for easy measurement and detection of harmonic properties on a transformer. The *MATLAB/Simulink* based simulations with suitable experiments validate the proposed study.

1. Introduction

The source voltage and its harmonics effects in different electrical systems is a extensively studied subject. The study of harmonics and their consequence on power and distribution transformers is also well investigated theme. Usually, the effect of harmonics is movement of harmonic currents which causes upsurge in losses leading to increase in internal temperature of the transformer and potential faults [1]. Different studies are completed regarding upshot of harmonics in transformers. In [2], effects of voltage harmonics on transformers are considered for high-power low voltage core. Harmonic contamination for distribution transformers is extensively researched using modest short and open circuit tests [3]. This is a simple method for studying the effects though they require the transformer to

[1]Corresponding author at: Electrical Engineering Department, Raghunathpur Govt. Polytechnic, Purulia, W.B., India
Email address: arunava7.ju@gmail.com
Fax: +84 988076677

be put out of action for such tests. Also, measurement and alteration required for core losses in a transformer is studied [4]. Here, mostly distorted supply voltage is measured. Estimation of core loss when the flux has fundamental and a single odd harmonic component in it is also studied in [5]. Different core sample materials are tested in the research and the core loss is estimated. Core loss forecast from low frequency measurements is done in [6] and shown to be operative for transformer laminations. Finite element-based hysteresis loop is calculated based on energetic hysteresis model. No-load loss estimate under sub-harmonics for power transformers is existing in [7] using two-dimensional finite element model and its analysis. Under supply with non-sinusoidal voltages, the core or the iron losses can be foreseen using improved formulae of core loss as planned in [8]. The same with some modifications can be used for pulsed waveforms. Improved core loss for brushless DC (BLDC) machines are also predicted [9]. It is quite evident that core loss needs some modifications when used for prediction of losses in case of supply with harmonics. In general, the transformer is not loaded at the rated value or it is operated in less than rated value [10]. Transformer excitation current analysis under distorted supply is studied [11]. Method for measurement and rectification of core losses under no-load situations for distorted supply is obtainable for power transformers also [12]. Impact on harmonics for distribution transformers is studied with emphasis on no-load losses [13, 14]. Novel core loss separation method is presented [15]. Methods for accurate measurements of no-load losses for transformers is studied [16]. In general, iron loss prediction for induction motors which are inverter fed is studied [17].

In this paper, examination of effect of harmonics is made for single-phase transformers which are connected to power electronic sources used often in renewable energy applications. The connected inverter with its switching produces non-sinusoidal voltage at output which may encompass harmonics. This study provides a modest yet decisive analysis on transformer operation when the source side contains odd order harmonics. In this study, the supply is made distorted by incorporating harmonics of odd order and the effect for the same is revealed on the hysteresis curve. By analyzing the hysteresis characteristics, an idea about the core loss of the transformer is also made. The analytical measurement and study is extended to laboratory experimental setup for suitable transformer operation.

2. Proposed Measurement Technique and Harmonic Model

The proposed method is designed for determining the transformer hysteresis curve. Consequently, nearly measurements are taken at diverse loading and voltage conditions. It is to be noted that normally it is problematic to find the magnetic field intensity in the core of the transformer. It is also challenging to find the the flux density. Therefore, alternate method for measurement of diverse quantities and analysis is to be made for appropriate study. The proposed system construction along with the block diagram of the proposed scheme is shown in Fig.1.

The transformer diagram for measurement is shown in Fig.2. From Fig.2, the transformer magnetic field strength H of the core material is found using the following,

$$H = (NI_m)/l \tag{1}$$

where, N is number of turns of winding and l is the core length. I_m is the core magnetizing current. With N and l constant for a particular transformer with core fixed. A resistance R_x is linked in series with the primary winding for the precise measurement of I_m.

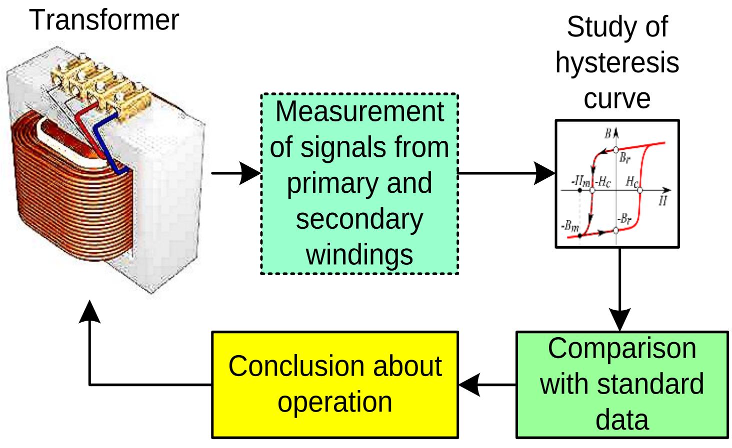


Figure 1. Block diagram of proposed technique.

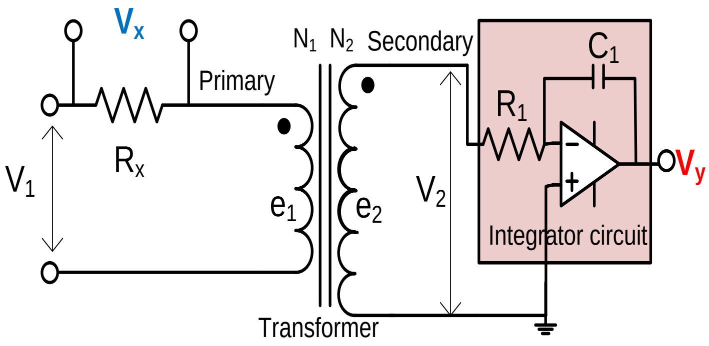


Figure 2. Measurement technique.

The voltage across the resistor is proportionate to the value of magnetizing current which is yet again proportionate to the magnetic field strength of core.

$$V_x = R_x I_m \tag{2}$$

For the hysteresis or B-H curve, the magnetic flux density (B) is found using,

$$B = \phi/A \tag{3}$$

where, ϕ is the magnetic flux (webers) and A is the cross-sectional area of the transformer magnetic core. From (3), it can be detected that the magnetic flux density is right proportional to the magnetic flux. The rate of change of flux is proportionate to the emf induced. This is again proportionate to the output voltage. Thus, the secondary induced emf e_2, is,

$$e_2 = N_2 \frac{d\phi}{dt} \tag{4}$$

Also,

$$\frac{1}{N_2} e_2 dt = d\phi \tag{5}$$

Integrating both sides of (5),

$$\phi = \frac{1}{N_2} \int e_2 \, dt \tag{6}$$

Thus, flux is proportionate to the secondary voltage integral. It is thus obvious from (6), that the secondary terminal voltage can be integrated to form the required signal for flux density derivation. An electronic operational amplifier (ap-amp)-based integrator circuit is used for this purpose.

The op-amp RC integrator will perform as a passive circuit of low-pass filter and voltage across the capacitor is measured as integrated voltage output. From the integrator, thus,

$$V_y = \frac{1}{R_1 C_1} \int V_2 \, dt \tag{7}$$

2.1.1. Parameter selection

For finding the resistors R_x and R_1 and capacitor C_1, the subsequent process is used where the circuit components are selected on the basis physical quantities of the transformer. For the resistor R_x, the number of primary turns be N_1, length of primary wire l and its radius r,

$$l = 2\pi r N_1 \tag{8}$$

Substituting value of (8) in (1),

$$H = I_m / 2\pi r \tag{9}$$

or, $H = Z_1 I_m$ (10)

where, Z_1 is a constant which depends on radius of the transformer primary wire. The value of H is derived by means of I_m from (2) & (10),

$$H = V_x \frac{Z_1}{R_x} \tag{11}$$

If, $Z_1 = R_x$, then $H = V_x$.

Once the primary side resistance value is fixed, the secondary side resistance and capacitor values are designated using the proposed technique. For selecting resistor R_1 and capacitor C_1 in secondary, from (3) and (6), one may derive,

$$B = \frac{1}{AN_2} \int e_2 \, dt \tag{12}$$

Using Laplace transform on (12) at both sides and neglecting initial conditions,

$$B(s) = \frac{E_2(s)}{s} \left(\frac{1}{AN_2} \right) \tag{13}$$

The integrator network transfer function is,

$$\frac{V_y(s)}{E_2(s)} = - \frac{1}{R_1 C_1 s} \tag{14}$$

Thus,

$$B(s) = - \left(\frac{R_1 C_1}{AN_2} \right) V_y(s) \tag{15}$$

Magnetic flux density in core B is pure integral of V_y with a multiplying factor of $(1/AN_2)$. If, $R_1C_1 = AN_2$. Then, (15) becomes,

$$B(s) = -V_y(s) \tag{16}$$

2.1.2. Harmonic model

The core loss model of a magnetic material changes for presence of different harmonic frequencies as hysteresis curve depends on it. The core loss consists of hysteresis and eddy current losses. The hysteresis loss P_h in watts using Steinmetz equation is,

$$P_h = kB_m^x f \tag{17}$$

where f is frequency of flux reversal and k is the coefficient of hysteresis loss. Expecting the harmonic frequencies, (17) is altered from [9] for single-phase system,

$$P_h = k(B_{m1}^x f_1 + B_{m3}^x f_3 + B_{m5}^x f_5 + B_{m7}^x f_7 + \cdots + B_{mn}^x f_n) \tag{18}$$

where subscripts, 3, 5, 7,..., n are the odd harmonic frequencies. For a three-phase system, the triplen harmonic orders will be absent in per phase.

As the supply contains odd harmonics, the hysteresis loss shall also change which will be reflected in the B-H curve. The B-H curve can be then related for a healthy running transformer for sinusoidal supply without harmonics for understanding the transformer functioning behaviour.

3. Proposed Technique to Mitigate Source Harmonics

For the transformer to mitigate the source harmonic effect, some special connection can be used at the supply side. A capacitor and inductor shunt filter is connected on the source side in parallel to the magnetizing branch. When the source contains harmonics, the components of harmonics current are also present in the magnetizing branch. The LC filter thus formed will be tuned at 4th harmonic frequency of 200Hz taking fundamental at 50Hz. Thus it can mitigate both 3rd and 5th order of harmonics at the source at frequencies of 150Hz and 250Hz respectively. Accordingly, values of inductor and capacitor can be selected as 650mH and 1μF respectively. Only problem is during variable loading, the value will vary but sufficient tolerance can be used to counter this. The LC filter is connected to a power electronic switch which can be operated depending on the amount of source harmonics. The connection for the same is shown in Fig.3.

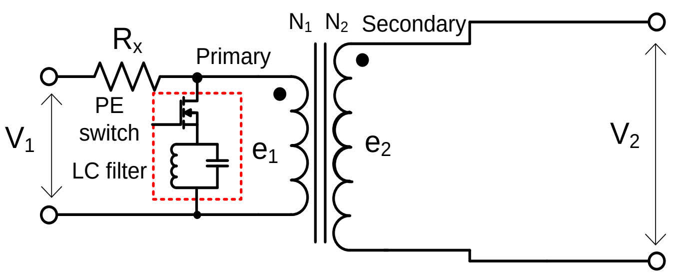
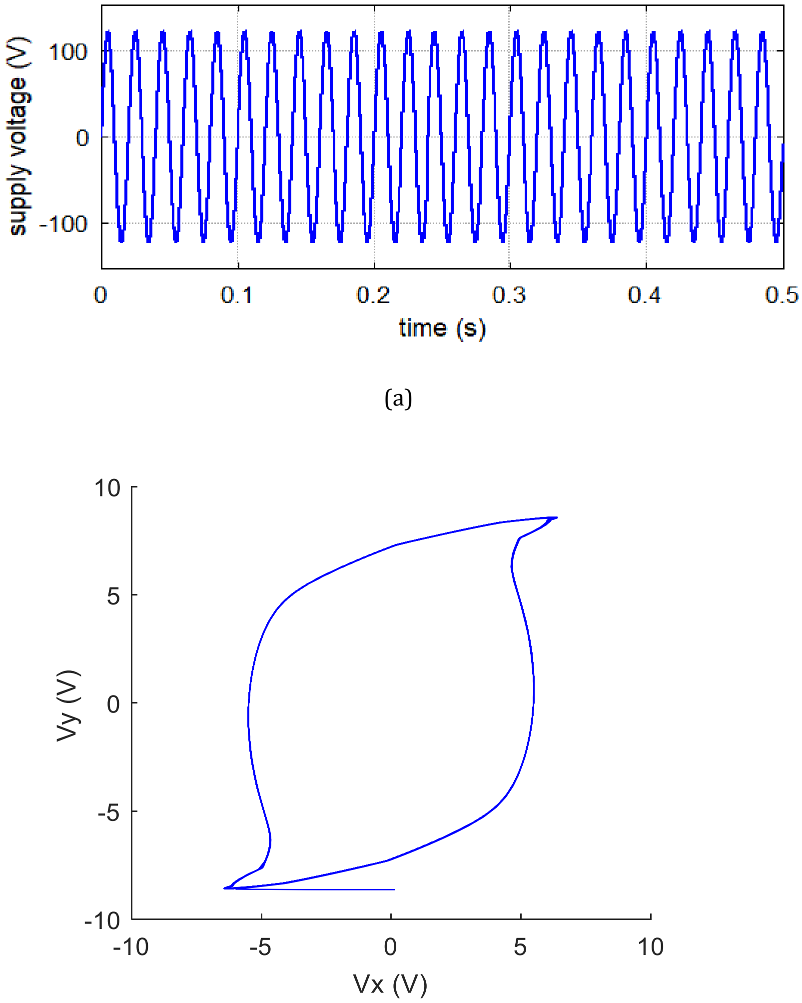


Figure 3. Proposed technique to mitigate the effect of source harmonics.

4. Results and Discussion

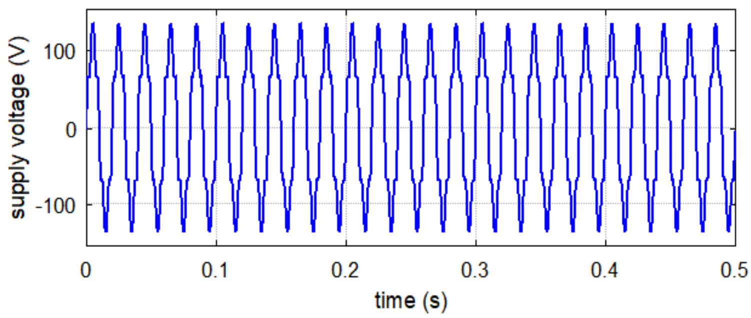
The simulations are done using *MATLAB/Simulink* environment for single-phase transformers for the proposed technique. The rating of the transformer used in the present work is 750VA with 60/120V, 50Hz for simulation and laboratory experimentation. The simulations are carried with considering both source harmonics and without source harmonics. The simulation waveform of supply voltage and the hysteresis curve are shown in Fig.4(a) and Fig.4(b) when the supply is devoid of any harmonics.



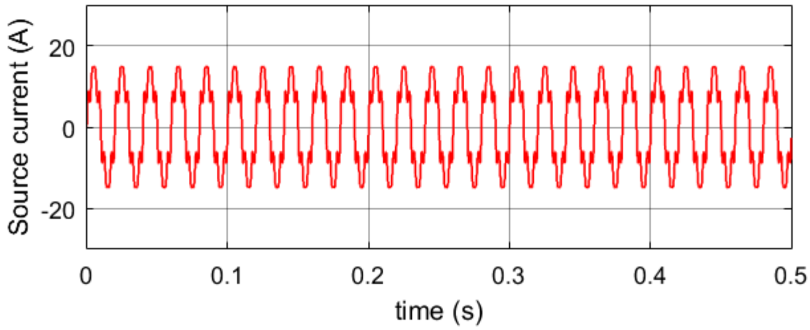
(a)

(b)

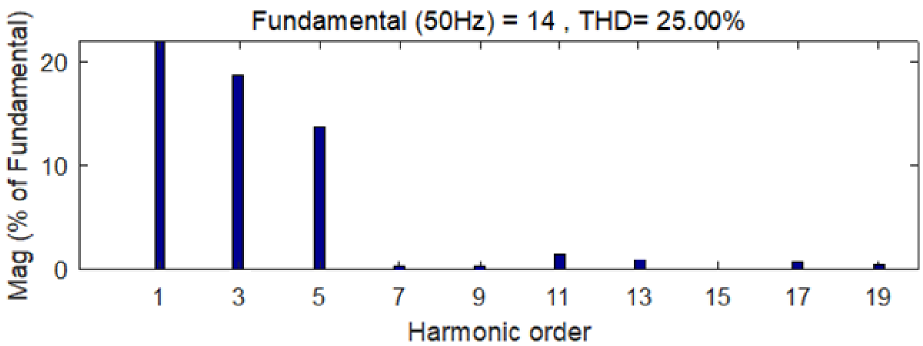
Figure 4. (a) Voltage waveform and (b) corresponding hysteresis curve for sinusoidal supply.



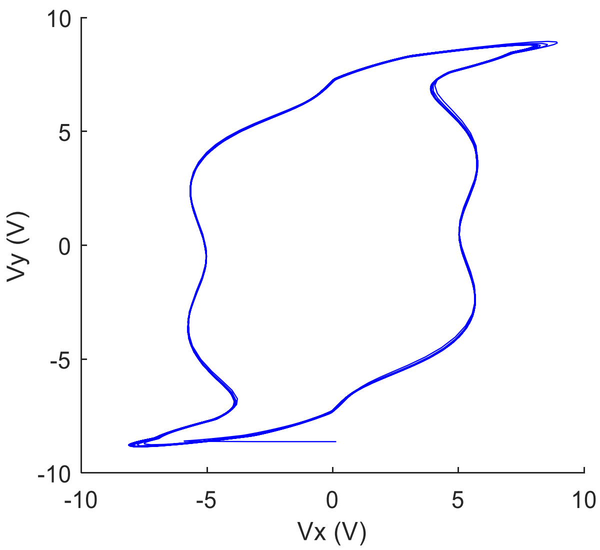
(a)



(b)



(c)

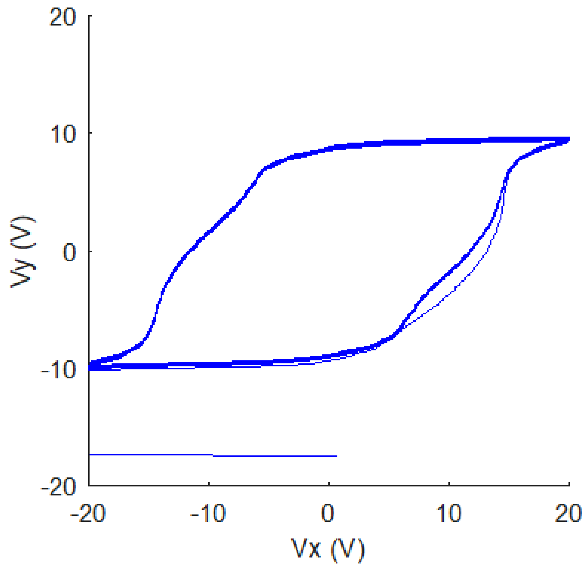


(d)

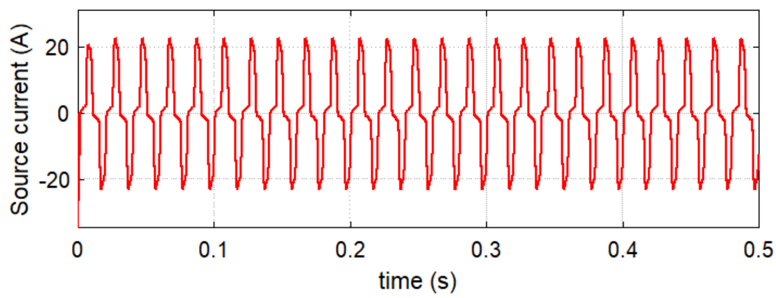
Figure 5. (a) Voltage waveform (b) source current, (c) source current harmonic spectrum and (d) corresponding hysteresis curve for sinusoidal supply with 3rd and 5th order harmonics.

When the supply contains harmonics of 3rd and 5th order, the supply voltage, source current waveform, its current harmonic spectrum and the hysteresis curves are shown in Fig.5(a), Fig.5(b), Fig.5(c) and Fig.5(d) respectively. In contrast to the supply without harmonics, when the supply contains harmonics, the hysteresis curve shows some curvatures unlike the smoother flux reversal of Fig.4(b).

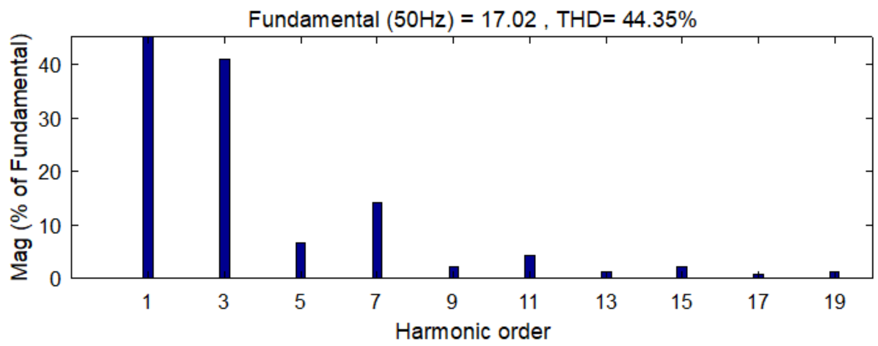
In general, if the load is non-linear, the supply side will contain odd harmonics. To test the effect of non-linear load on a single-phase transformer, the transformer is loaded with a switched mode power supply (SMPS) load. The SMPS is a non-linear load containing power electronic based solid-state devices like diodes and can incur harmonics at source end. An SMPS load is connected across the transformer secondary with RL load with R = 100Ω and L = 100mH.



(a)



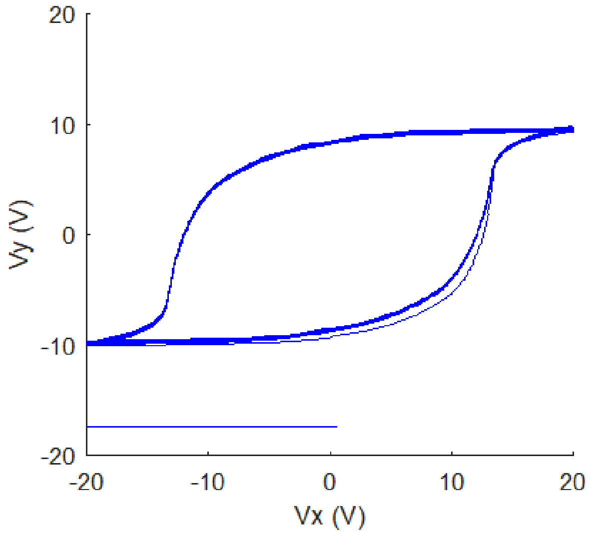
(b)



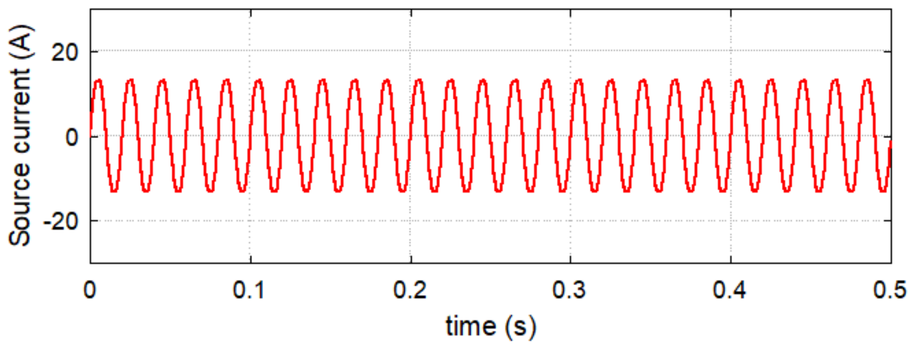
(c)

Figure 6. (a) Hysteresis curve (b) corresponding source current and (c) source current spectrum for single-phase transformer with SMPS load.

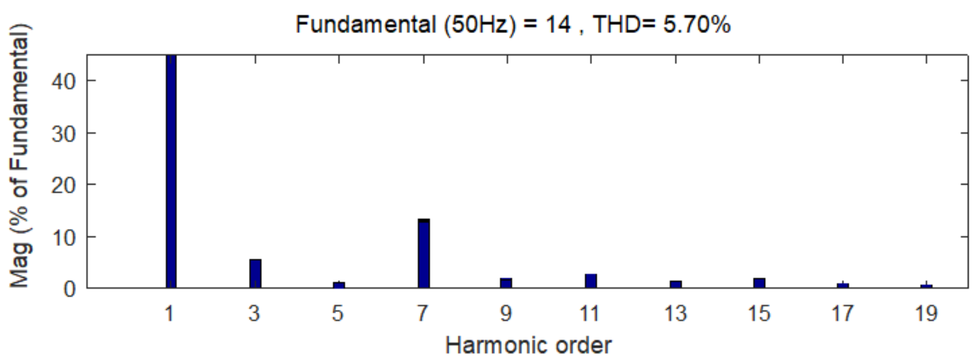
It can be seen from Fig.6(a) that the hysteresis curve has some curvatures. It is because of the dominant 3rd and 7th harmonics as seen from the source current waveform and its total harmonic distortion (THD) spectrum of Fig.6(b) and Fig.6(c) respectively. With the proposed harmonic mitigation technique, the hysteresis waveform is much smoother with reduced current THD as shown in Fig.7.



(a)



(b)

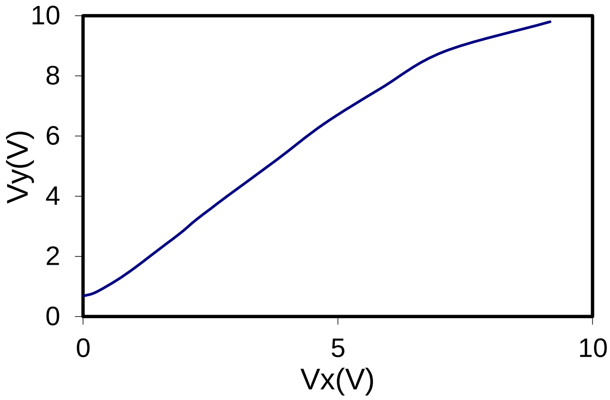


(c)

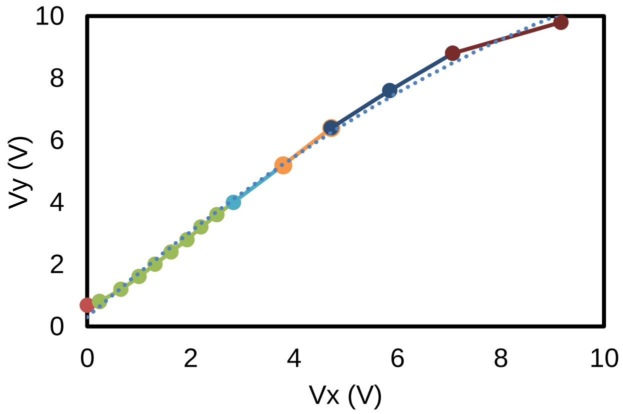
Figure 7. (a) Hysteresis curve (b) corresponding source current and (c) source current THD spectrum for single-phase transformer with SMPS load using the proposed harmonic mitigation technique.

From the hysteresis waveforms obtained, it is observed that the curve has infrequent curvatures than a normal hysteresis curve when the supply is sternly sinusoidal. This can be mathematically analysed using standard obtained data and curve fitting methods. The method used in this paper for curve fitting and storage is the popular piecewise mixed model [18]. The magnetization characteristics of the transformer is obtained using suitable experiments in this method. The obtained curve is then fragmented into piecewise mixed model for storing and later reconstruction. The curve data thus stored can be compared with standard data in parts and the implication about the operating condition can be made. The magnetization curve is shown in Fig.8(a) for sinusoidal supply. It is observed from the figure that the magnetization curve is linear up to some degree and afterwards it becomes non-linear. It is broken in to similar small sections of linear dimensions for storing. A mathematical examination with the standard magnetization curves can be done afterwards.

Fig.8(b) also indicates that the magnetization curve can be broken into small linear segments for storing purpose and later on, comparisons with a standard magnetization characteristic can be made. Similarly, the hysteresis plot can be stored as a whole. This magnetization curve is kept in an *Atmega* microcontroller unit. This magnetization data can be compared with magnetization data obtained for transformer with source harmonics. A simple subroutine is used for comparison which tracks the changes in the obtained data for a high deviation. If the deviated data is greater than a tolerance value, then the transformer should be used in derated mode or with adapting harmonic mitigation procedure.



(a)



(b)

Figure 8. (a) Magnetization characteristics (b) the characteristics broken into piecewise mixed model with the trendline.

A subroutine is used for comparison of transformer operating with supply free from harmonics to that of a transformer operating with source harmonics. The data obtained from magnetizing curve is compared and the deviation is measured. If the deviated data is greater than a tolerance value, then the transformer should be used in derated mode [19]. Instead, if the source side contains predominant 3rd and 5th order of harmonics, then the power electronic switch connected with the LC filter as proposed in section 4 is turned on. This LC filter mitigates the supply harmonics as proposed. The subroutine flowchart for comparison is shown in Fig.9.

In future, some intelligent technique can be applied for the comparison purpose and better identification of harmonics present in source. It is evident that in that case, some learning techniques can be applied which will also increase the computational time. For controlling the loads connected to the transformer or for switching the harmonic mitigation PE switch, some intelligent techniques may also be applied. An internet of things-based control can also be applied [20].

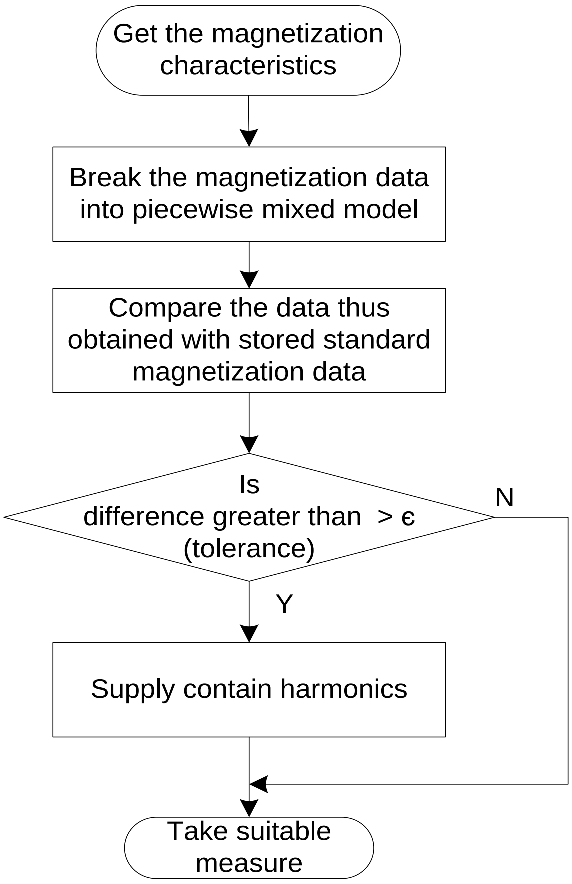


Figure 9. Flowchart for comparison and operation.

Some suitable laboratory scale experiments are also carried out on a laboratory prototype with similar ratings for the transformer used during simulation. The experimental setup photograph is shown in Fig.10. With the transformer having 5th and 7th harmonics in the source, the experimental source current waveform is shown in Fig.11(a). For the purpose of current measurement, LEM hall effect-based current sensor LTS-25NP is used in the experimental setup. The corresponding experimental hysteresis curve is shown in Fig.11(b).

With the proposed harmonic mitigation technique, the experimental source current and corresponding hysteresis waveform is shown in Fig.12(a) and Fig.12(b) respectively. As observed from the figures, the experimental results closely follow the simulated results obtained.

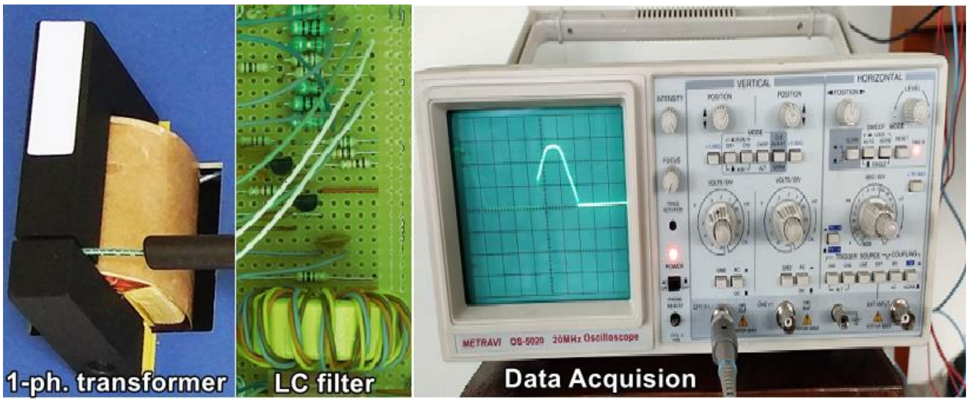
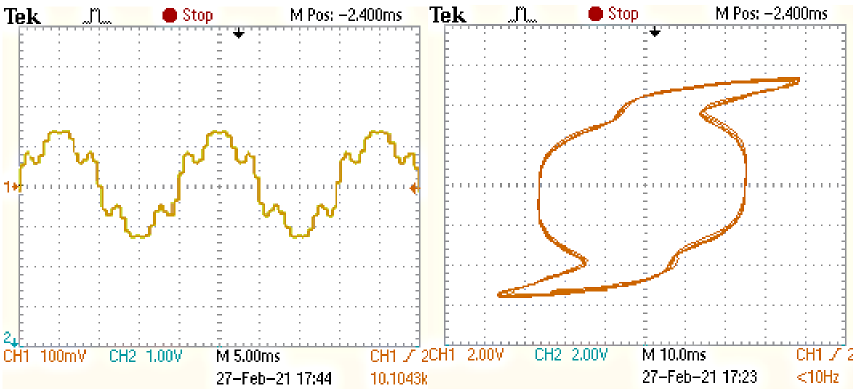
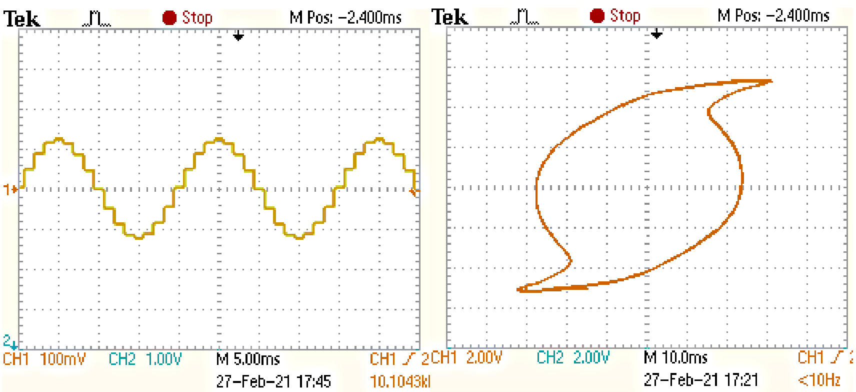


Figure 10. Experimental setup for the proposed technique validation.



(a) (b)

Figure 11. Experimental waveforms for (a) source current and (b) hysteresis curve for supply containing 5th and 7th harmonics.



(a) (b)

Figure 12. Experimental waveforms for (a) source current and (b) hysteresis curve for supply with proposed harmonic mitigation.

5. Conclusions

This paper presents a study on the effect of harmonics present in source side on transformer action and operation. The study recommends measurement of hysteresis curve and a modified hysteresis-loss model with the effect of source harmonics. Also, a new technique is presented for easy measurement and the hysteresis curve plotting. The study also is an effective tool for analysis of core loss by checking the obtained hysteresis curve with standard curve using a modest subroutine. A harmonic mitigation technique for the transformer operation with source side harmonics is presented which can efficiently reduce the source harmonics. Also, the transformer can be operated in derated mode to reduce the winding current below the rated value and avoid faults when source contain harmonics. In future, a closed loop control can be added for better control. *MATLAB/Simulink* based simulations backed by suitable experiments validate the proposed study.

Acknowledgements

The Authors acknowledge the help obtained from Electrical Engineering department, Jadavpur University, for helping in conducting experiments used in the present work.

Author's contribution

All the authors have contributed equally for the research work and have mutually agreed upon its content and publication.

Compliance with ethical standards

All the authors and co-authors assure that this research article is their original work, conducted according to the existing scientific ethical practices.

Ethical approval

All the authors mentioned in the manuscript have agreed for authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.

Conflict of interest

The authors declare that there is no conflict of interest associated with this publication.

Funding details

This research work is not supported by any funding.

Declaration of interest statement

All the authors are listed and have mutually agreed for publication.

References

[1] Dao T., Phung B.: Effects of voltage harmonic on losses and temperature rise in distribution transformers. IET Generation Transmission and Distribution, 12, 347–354 (2018).

[2] Ioniță V., Cazacu E., Petrescu L.: Effect of voltage harmonics on iron losses in magnetic cores with hysteresis. in 18th International Conference on Harmonics and Quality of Power (ICHQP), Ljubljana. (2018).

[3] Dao T., Halim H., Liu Z., Phung B.: Voltage harmonic effect on losses in distribution transformers. in International Conference on Smart Green Technology in Electrical and Information Systems (ICSGTEIS), Bali. (2016).

[4] So E., Arseneau R., Hanique E.: No-load loss measurements of power transformers under distorted supply voltage waveform conditions. IEEE Transactions on Instrumentation and Measurement, 52, 429-432 (2003).

[5] Lavers J., Biringer P., Hollitscher H.: Estimation of core losses when the flux waveform contains the fundamental plus a single odd harmonic component. IEEE Transactions on Magnetics, 13, 1128-1130 (1977).

[6] Zhang Y., Pillay P., Ibrahim M., Cheng M.: Magnetic characteristics and core losses in machine laminations: high-frequency loss prediction from low-frequency measurements. IEEE Transactions on Industry Applications, 48, 623-629 (2012).

[7] Arslan E., Sakar S., Balci M.: On the no-load loss of power transformers under voltages with sub-harmonics. in IEEE International Energy Conference (ENERGYCON), Cavtat, (2014).

[8] Amar M., Kaczmarek R.: A general formula for prediction of iron losses under nonsinusoidal voltage waveform. IEEE Transactions on Magnetics, 31, 2504-2509 (1995).

[9] Nag T., Santra S., Chatterjee A., Chatterjee D., Ganguli A.: Fuzzy logic-based loss minimisation scheme for brushless DC motor drive system. IET Power Electronics, 9, 1581-1589 (2016).

[10] Faiz J., Ghazizadeh M., Oraee H.: Derating of transformers under non-linear load current and non-sinusoidal voltage – an overview. IET Electric Power Applications, 9, 486-495 (2015).

[11] Ece D., Ackay H.: An analysis of transformer excitation current under nonsinusoidal supply voltage. IEEE Transactions on Instrumentation and Measurement, 51, 1085-1089 (2002).

[12] Arseneau R., So E., Hanique E.: Measurements and correction of no-load losses of power transformers. IEEE Transactions on Instrumentation and Measurement, 54, 503-506 (2005).

[13] Kefalas T., Kladas A.: Harmonic impact on distribution transformer no-load loss. IEEE Transactions on Industrial Electronics, 57, 193-200 (2010).

[14] Pejovski D., Najdenkoski K., Digalovski M.: Impact of different harmonic loads on distribution transformers. Procedia Engineering, 202, 76-87 (2017).

[15] Olivares-Galvan J., Escarela-Perez R., León, F., et al.: ‘Separation of core losses in distribution transformers using experimental methods’, IEEE Canadian Journal of Electrronics Computing Eng., 35, 33-39 (2010).

[16] Liu X., Yao C., Liang S., Wang J., Liu T.: Measurement of the no-load characteristics of single-phase transformer using an improved low-frequency method. IEEE Transactions on Industrial Electronics, 65, 4347-4356 (2018).

[17] Boglietti A., Cavagnino A., Lazzari M.: Fast method for the iron loss prediction in inverter-fed induction motors. IEEE Transactions in Industry Applications, 46, 806-811 (2010).

[18] Chatterjee D.: A novel magnetizing-curve identification and computer storage technique for induction machines suitable for online application. IEEE Transactions on Industrial Electronics, 58, 5336-5343 (2011).

[19] Bagheri M., Naderi M., Blackburn T., Phung B.: Transformer efficiency and de-rating evaluation with non-sinusoidal loads. in IEEE International Conf. Power System Technology, Auckland, New Zealand (2012).

[20] Chatterjee A., Das S., Chatterjee D.: Smart analysis and measurement of hysteresis loss of an inverter-fed transformer for renewable energy application. in International Conference on Industrial Instrumentation & Control (ici2c-2021), India (2021).