The influence of harmonic distortion on losses and efficiency of three-phase distribution transformer

Agus Ulinuha, Eka Muthia Sari
Faculty of Engineering, Universitas Muhammadiyah Surakarta (UMS), Surakarta, Indonesia, 57102
E-mail: agus.ulinuha@ums.ac.id

Abstract. The operation of non-linear load leads to distortion on system and equipment. The nonlinear relation between voltage and current implies higher frequency components of current and voltage called harmonic. This may constitute distortion on the fundamental waveform. If this distorted waveform applies to a transformer, it may lead to additional losses and therefore reduces transformer efficiency. The losses occur due to the degree of harmonic distortion, commonly called total harmonic distortion (THD). This paper discusses the operating condition of three-phase transformer serving nonlinear load in the form of power converter. The related impacts of THD on voltage and current, additional power losses and its efficiency are analysed. The calculation is implemented on a 200 kVA three-phase transformer serving a rectifier supplying a balanced inductive load. For analysis purpose the system is simulated using Simulink in MATLAB environment. From the generated results it is identified the THD of voltage and current distortions of 19% and 18%, respectively. These distortion is analysed to confirm the standard of IEEE 519-2014 verifying the distortions exceeding the maximum limit for both voltage and current. The effect of harmonic on transformer loss is also observed. The loss is calculated taking into account all parameters ensuring the calculation is valid. The result indicates the increase of loss due to considering harmonic distortion from 0.62 kW to 1.854 kW causing reduction of efficiency from 99.65% to 98.97%. This loss addition implies a derating of the transformer to avoid transformer overload that may shorten the device’s lifetime.

1. Introduction
Transformer is a static electrical equipment that takes a very important role in electrical power system. Power system employs a number of transformers for different purposes for transmission and distribution of power. Distribution transformer serves for voltage transformation from transmission and distribution purpose [1]. Transformer may suffer from some disturbances such as voltage fluctuation, waveform distortion, voltage sag/swell, and interruption [2]. Harmonic is one of disturbance in the form of waveform distortion that may lead to serious effect if a sharp resonance happens [3]. Voltage superposition in this situation may cause extremely high voltage leading partial discharge in the transformer winding. A serious destruction will happen to the transformer if this condition happen [4]. In the low level of disturbance, harmonic may result in extra power loss and efficiency reduction [5].

The recent trend of using harmonic generating devices may cause distortion of current and voltage on the system and equipment including transformer. These devices may include static switching components that are widely used in air conditioner, computers and some other power electronic parts such as thyristor, mosfet and diode[6]. It is identified from a comparative
study on the harmonic characteristics of residential, commercial, and industrial feeders. The results indicate that the level of distortion from residential feeder is much higher than that of the industrial and commercial feeders. Furthermore, the third harmonic order is the most pronounced component and the low-order harmonic currents from different homes tend to add to each other [7]. The use of the harmonic generating apparatus will cause a nonlinear relation between voltage and current and make the waveform is no longer sinusoidal [8]. The frequency components taking place in the existing fundamental waveform and make the waveform distorted and its extensive effect on the whole system must be comprehensively considered[9].

Continuous supply for power demand with acceptable quality is essential aspect that should be considered by utility company from the technical and economical perspective. Transformer is one of the important devices in power system and protecting this device from any disturbance is crucial. Due to the growing application of non-linear loads in the power system, the effect of these loads on the transformer should be taken into account. It is necessary to assure the sustainable operation of the transformer and to guarantee the optimal lifetime of the device.

2. Methodology

The harmonic distortion of voltage and current is measured with the level of distortion that is generally indicated with Total Harmonic Distortion (THD). This quantity is generally expressed in percent (%) and is calculated depending on the presence of higher frequency components with respect to the fundamental component. From the graphical standpoint, the existence of these components will determine the non-sinusoidal of the waveform. The more higher frequency components exist with bigger magnitude, the wave will be more far from sinusoidal. This situation implies higher THD and may lead to some undesirable effects on transformer. The level of THD may not exceed the maximum acceptable level.

This paper discourses harmonic distortion of a three-phase transformer serving a nonlinear load. The nonlinear load used in this case is a power rectifier that also injects some harmonic components into system. This harmonic injection will therefore entail some distortion measured in THD level for voltage and current. The additional losses and the reduction of efficiency will then be calculated. The losses of transformer were calculated including all factors to ensure the comprehensive calculation. The system is simulated using Simulink in MATLAB environment and the generated results are observed. The comparison of transformer conditions is analyzed in terms of losses and efficiency for the transformer considering and disregarding harmonic respectively.

3. Result and Discussion

3.1. System modelling

The model of system is given in Figure 1 showing a single-phase representation of three-phase transformer serving a nonlinear load. The type of nonlinear load is rectifier supplying a balanced load consisting of 1.293 Ω resistor in series with 22 mH inductor. Rectifier is chosen in this case since it may inject higher distortion than controlled rectifier using thyristor or mosfet [10]. The phase to phase voltage of secondary side transformer 380 Volt, and respective resistance and inductance of the nonlinear load is 7.7 m Ω and 0.0089 mH. This system is equipped with a number of measurement devices for simulation purpose. The complete system for simulation is given in Figure 2 showing a three-phase transformer with some measurement devices for simulation purposes.

For modeling the above system, several components available in SimPowerSystem block are used. This includes three-phase source that supplies three-phase system, three-phase measurement for V-I supply measurement, and three nonlinear loads (1, 2, 3). The supporting display equipment includes power GUI used to perform Fast Fourier Transform (FFT) tools, display function as the tool for presenting the simulation results in the form of numbers, and the
Figure 1: Rectifier supplying balanced inductive load

Figure 2: Measurement circuit of the simulated system

scope that displays the simulation in the graphical form, such as waveform. Power measurement tools including voltage measurement of voltage, current, active and reactive power are also employed.

4. Simulation Result and Discussions
From the system under study, simulations are carried out and some results are generated including some numbers and figures. The analysis is carried out for the system distorted by harmonic generating device. This includes the spectrum of non-linear load, the level of voltage
4.1. Distortion Analysis
For the nonlinear load used in this study, the voltage spectrum of the load is given in Figure 3. The figure indicates the existence of higher frequency components of voltage indicated by some bars equivalent with the voltage magnitude in higher frequency. These higher frequency components are called harmonic and these may lead the system to be distorted. From the graphical perspective, the distortion is denoted as the waveform, which is no longer sinusoidal. This distortion may flow to the network and the system will be extensively distorted. The complete picture is not displayed because the fundamental frequency voltage component is much higher than the harmonic components and complete insertion of the figure may take larger space. The figure is cropped to highlight the harmonic component without omitting the reality of fundamental frequency voltage component.

For the purpose of investigating the influence of nonlinear load on transformer, identification of higher frequency component that may appear is carried out. The measurement is taken by observing on the selected signal of 15 cycles as indicated in Figure 4. The Fast Fourier Transform (FFT) is applied in a window for the length of one cycle. The window is marked in red, as shown in the Figure 4.

From the measurement, it may be observed that application of nonlinear load has caused
Figure 5: Spectrum of voltage for transformer serving nonlinear distortion on transformer that leads the device to also have higher frequency voltage components. The voltage spectrum of the transformer is shown in Figure 5 indicating the presence of higher frequency component causing the distortion level in THD of 19%. According to the standard of This IEEE 519-2014, the maximum VTHD for the device nominal voltage less then 1 KV the maximum limit of THD is 8%. It may be concluded that serving nonlinear load will lead the transformer to suffer from harmonic distortion exceeding the maximum allowable limit.

For observing the current distortion, the same procedure as carried out for voltage is implemented. The sampling of wave forms as shown in Figure 4 are taken. For the system of transformer serving nonlinear load, the spectrum of Figure 6 is generated indicating some harmonic components. These imply distortion of current with the level of 18%. To determine if this value is accepted, it is necessary to include the concept of Short Circuit Ratio ($SC_{ratio}$). This may be calculated using Eq. (1).

$$SC_{ratio} = \frac{I_{sc}}{I_{max}}$$  \hspace{1cm} (1)

Where $I_{sc}$ is short circuit current and $I_{max}$ is full load current. For the given system, the calculation has resulted the Short Circuit Ratio $SC_{ratio}$ of 25.07. Based on the IEEE 519-2014 standard, for the $SC_{ratio}$ of 25.07 the THD standard for current recommends the maximum distortion of current ($I_{THD}$) of 8%. Therefore, for the studied system, the transformer has experienced the current distortion exceeding the maximum limit.

4.2. Transformer Losses and Efficiency

The extensive application of harmonic generating devices has caused impact on distribution transformers. One of the impacts is additional power losses in transformer, which may lead to excessive device heating causing reduction of transformer’s life-expectancy [11][12]. It is reported that the losses due to the presence of harmonic distortion is about 15% additional loss [13]. Furthermore, it is also suggested to reduce the no-load losses of distribution transformer since ratio of no-load losses to load losses is almost three.

For the purpose of calculating transformer loss considering harmonic, a number of parameters are considered, such as: current and voltage at high frequency components, active and reactive power, power factor, and total harmonic distortion. Additional power losses are calculated
Figure 6: Spectrum of current for transformer serving nonlinear
according to the proposed mathematical model to highlight the influence of harmonic distortion on transformer losses [14].

For the transformer with the capacity of 200 kVA and for the connected load, the losses may then be calculated by the simulation. These may be distinguished into the condition without harmonic distortion and with harmonic distortion. The loss of transformer includes core loss \( P_{\text{core}} \) and copper loss \( P_{\text{cu}} \). For the condition where the harmonic distortion is disregarded, the \( P_{\text{core}} \) and \( P_{\text{cu}} \) are 480 W and 143.63 W, respectively, resulting in the total loss of 623.63 W.

For the loss under harmonic condition, some additional losses are taking place and for accurate result, these should be taken into account. For calculating the copper loss, the base kW needs to be initially determined. It is recommended to calculate the copper loss of transformer on the per-unit basis [12]. For the given system in this study, power factor \( \cos\phi \) may be calculated resulting in the \( \cos\phi \) of 0.897. Therefore, the per-phase base KW may be calculated using Eq. (2).

\[
P_{\text{base}1\phi} = \frac{(200 \times 0.897)}{\sqrt{3}} = 103.57\text{kW}
\]  

For calculating \( P_{\text{cu}} \) due to harmonic distortion, individual calculation should be carried out to determine the loss at every harmonic order. These losses are due mainly to the ohmic losses as the currents flowing through the transformer windings. Since the rms magnitude of current increases due to harmonic components, then the \( I^2R \) loss will also increase accordingly [12]. The spectrum of current given in Figure 6 is required for this calculation and may be numerically presented in Table 1. From the given data \( P_{\text{cu}} \) may be calculated using Eq. (3) [12], where \( N \) is the maximum number of harmonic order.

\[
P_{\text{cu}} = I_{\text{rms}}^2R = \left( \sum_{h=1}^{N} I_h^2 \right) \times R
\]  

For the system with the spectrum given in Table 1, the additional copper loss of the system due to the presence of higher frequency components may be calculated resulting in \( P_{\text{cu}} \) of 0.011321 p.u. or 1.172 kW. This additional loss is expressed instead of total copper loss to highlight the prominent effect of harmonic on copper loss. This is expected since the THD of current is sufficiently high implying the high additional loss.
Table 1: The magnitude of harmonic spectrum

| Harmonic order | $I_h (A)$ |
|----------------|-----------|
| 1              | 1.000     |
| 3              | 0.161     |
| 5              | 0.086     |
| 7              | 0.059     |
| 9              | 0.046     |
| 11             | 0.037     |
| 13             | 0.031     |
| 15             | 0.027     |
| 17             | 0.024     |

Eddy-current loss is conductive $I^2R$ loss produced by circulating currents induced in response to ac flux linkage, flowing against the internal resistance of the core [15]. At fundamental frequency, eddy-current loss ($P_{EC}$) is assumed to be proportional to the square of load current and the square of frequency [12]. This loss implies excessive core losses that may cause temperature rise in the transformer. The existence of current at higher frequency entails additional eddy current losses that may be expressed using Eq. (4).

$$P_{EC} = P_{EC-R} \sum_{h=1}^{N} \left( \frac{I_h}{I_R} \right)^2 h^2$$  \hspace{1cm} (4)

Where $P_{EC-R}$ is eddy-current loss under rated conditions for transformer winding. However, for practical design the eddy-current losses is calculated as a portion of copper losses [12]. It ranges from 2% to 5%. In this study the portion of 5% is used and for the problem in hand the additional of eddy-current losses due to the presence of higher frequency components is 58.6 W.

Hysteresis loss is a type of core loss which occurs in the core of transformer. This is due to non-linear relationship between magnetic field intensity and magnetic flux density. This happens due to the reversal of magnetization of transformer core whenever the core is subjected to an alternating magnetic field. The domain present in the material will change their orientation after every half cycle [16]. The power consumed by the magnetic domains for changing the orientation after every half cycle is called hysteresis loss. For the given constant $K_h$, hysteresis may be calculated using Eq. (5) [17].

$$P_{hyst} = K_h \times \sum_{h} I_h \times h$$  \hspace{1cm} (5)

For the problem under study, the value of $K_h$ of 0.26 is taken. For the spectrum of Table 1. The hysteresis loss may be calculated for every harmonic order as shown in Table 2. resulting in the loss of 0.12589 W.

Therefore, for the transformer serving nonlinear load, additional losses due to the presence of higher frequency components may be calculated using Eq. (6).

$$P_{losses}^h = P_{cu} + P_{EC} + P_{hyst}$$  \hspace{1cm} (6)

According to the previous calculation results, the additional losses due to harmonic distortion stated in Eq. (7).
Table 2: The calculation of hysteresis loss

| Harmonic order | $I_n$(A) | $P_n$(W) |
|----------------|---------|----------|
| 1              | 1.000   | 0.26000  |
| 3              | 0.161   | 0.12558  |
| 5              | 0.086   | 0.11128  |
| 7              | 0.059   | 0.10793  |
| 9              | 0.046   | 0.10647  |
| 11             | 0.037   | 0.10582  |
| 13             | 0.031   | 0.10546  |
| 15             | 0.027   | 0.10530  |
| 17             | 0.024   | 0.10519  |
| Total          |         | 0.12589  |

\[ P_h^{losses} = 1,172 + 58.6 + 0.12589 = 1,230.72589W \] (7)

Where $P_h^{losses}$ is additional losses at harmonic frequencies. Inclusion of power losses at fundamental frequency of 623.63 W results in the total losses of the transformer as in Eq. (8).

\[ P_{tot}^{losses} = P_{1}^{losses} + P_h^{losses} = 623.63 + 1,230.72589 = 1,854.35589W \] (8)

Where $P_{tot}^{losses}$ is total loss of the transformer and $P_{1}^{losses}$ transformer losses at fundamental frequency. It may be observed from the calculation, that the presence of higher frequency current components as given in Table 1 has caused the harmonic components contributing significant losses with respect to the total transformer losses. The portion of transformer losses generated by harmonic components as shown in Eq. (9).

\[ P_h^{losses}(\%) = \frac{P_h^{losses}}{P_{tot}} \times 100\% = \frac{1,230.72589}{1,854.35589} \times 100\% = 66.37\% \] (9)

One of the important characteristics of transformer is efficiency at the specific operating condition. For the transformer serving nonlinear load, its efficiency is influenced by the existence of harmonic components. To highlight the effect of considering harmonic distortion, the efficiency is initially calculated by excluding the higher frequency component. The efficiency of the transformer is calculated using Eq. (10). Where $\eta$ is transformer efficiency and $P_{in}$ is transformer input power. For the transformer loaded at the rated capacity of 200 kVA and for the $Cos\phi$ of 0.897.

\[ \eta(\%) = [1 - \frac{P_{tot}^{losses}}{P_{in}}] \times 100\% \] (10)

\[ P_{in} = 200 \times 0.897 = 179.44kW \]

The efficiency of transformer considering only fundamental frequency result is 99.65%, while the efficiency of transformer that also considers harmonic frequency components is 98.97% as summarized in Table 3.

The previous calculations indicate some additional effects due to the presence of harmonic distortion. Some measure may be required to assure the transformer working properly, e.g.
Table 3: The Summary of calculations

| Calculation        | Without Harmonic | With Harmonics |
|--------------------|------------------|----------------|
| Total Losses (W)   | 623.63           | 1,854.38       |
| Efficiency (%)     | 99.65            | 98.97          |

temperature rise. The high THD and additional losses may lead to suggestion for transformer derating to assure transformer working properly and may reach optimal life expectancy [5][18].

Beside analysing the level of harmonic distortion and the related effects, it is also suggested to mitigate the harmonic distortion using a number of strategies. Some popular strategy is installing the harmonic filter to suppress the distortion [19]. This strategy is normally chosen to block some harmonic components injected by nonlinear load not to flow to the whole system. There some available choice of filter that may be used, including passive filter or active filter with their own performance and characteristic [20]. On the other hand, the position on where the filters are installed determine the effective of harmonic distortion suppression [21].

5. Conclusion
Transformer is an important device in distribution system. This may suffer from some disturbances that may lead to abnormal operation and lifetime reduction. One of the disturbances is due to the existence of harmonic distortion. The excessive harmonic distortion may lead to some detrimental effects such as temperature rise, and additional power losses causing efficiency reduction. The ever-increasing application of nonlinear loads may not be avoided and, therefore, their effects should be carefully analyzed. For the transformer serving nonlinear load, the analyses on Total Harmonic Distortion (THD), power losses and efficiency are required. It is verified that for the transformer serving nonlinear load in the form of three-phase rectifier, it suffers from excessive THD on voltage and current, higher power loss and lower efficiency. This condition suggests power derating of the device to assure optimal operation and to maintain device life expectancy. Employing harmonic filter to suppress the distortion will be another choice to improve the situation. However, careful selection of type, size, and location of filters is crucial for optimal system enhancement.

References
[1] Das, B. P., & Radakovic, Z. (2018). Is Transformer kVA Derating Always Required Under Harmonics? A Manufacturer’s Perspective. IEEE Transactions on Power Delivery, 33(6), 2693–2699. https://doi.org/10.1109/TPWRD.2018.2815901.
[2] Jettanasen, C., Ngaopitakkul, A., Asfani, D. A., & Negara, I. M. Y. (2017). Fault classification in transformer using low frequency component. 2017 IEEE 10th International Workshop on Computational Intelligence and Applications (IWClA), 199–202. https://doi.org/10.1109/IWClA.2017.8203584.
[3] Chen, Z., Luo, A., Kuang, H., Zhou, L., Chen, Y., & Huang, Y. (2017). Harmonic resonance characteristics of large-scale distributed power plant in wideband frequency domain. Electric Power Systems Research, 143, 53–65. https://doi.org/10.1016/j. EPSR.2016.09.001.
[4] Crotti, G., Gallo, D., Giordano, D., Landi, C., Luise, M., & Modarres, M. (2017). Frequency Response of MV Voltage Transformer Under Actual Waveforms. IEEE Transactions on Instrumentation and Measurement, 66(6), 1146–1154. https://doi.org/10.1109/TIM.2017.2652638.
[5] Cazacu, E., Petrescu, L., & Ionita, V. (2017). Derating of power distribution transformers serving nonlinear industrial loads. 2017 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) 2017 Intl Aegean Conference on Electrical Machines and Power Electronics (ACEMP), 90–95. https://doi.org/10.1109/OPTIM.2017.7974953.
[6] Ulinuha, Agus. (2016b). The impact of harmonic filter locations on distortion suppression. 2016 International Seminar on Intelligent Technology and Its Applications (ISITIA), 503–508. https://doi.org/10.1109/ISITIA.2016.7828711.
[7] Wang, Y., Yong, J., Sun, Y., Xu, W., & Wong, D. (2017). Characteristics of Harmonic Distortions in Residential Distribution Systems. IEEE Transactions on Power Delivery, 32(3), 1495–1504. https://doi.org/10.1109/TPWRD.2016.2606431.

[8] Senra, R., Boaventura, W. C., & Mendes, E. M. A. M. (2017). Assessment of the harmonic currents generated by single-phase nonlinear loads. Electric Power Systems Research, 147, 272–279. https://doi.org/10.1016/j.epsr.2017.02.028

[9] Ulinuha, A. (2018). The influence of nonlinear loads on optimal operation control of electrical distribution system. Proceedings of the International Conference on Industrial Engineering and Operations Management, 2018-March.

[10] Sheelvant, V., Kalpana, R., Singh, B., & Saravana, P. P. (2017). Improvement in Harmonic Reduction of a Zigzag Autoconnected Transformer Based 12-Pulse Diode Bridge Rectifier by Current Injection at DC Side. IEEE Transactions on Industry Applications, 53(6), 5634–5644. https://doi.org/10.1109/TIA.2017.2734892.

[11] Das, B. P., & Radakovic, Z. (2018). Is Transformer kVA Derating Always Required Under Harmonics? A Manufacturer’s Perspective. IEEE Transactions on Power Delivery, 33(6), 2693–2699. https://doi.org/10.1109/TPWRD.2018.2815901.

[12] Pejovski, D., Najdenkoski, K., & Digalovski, M. (2017). Impact of different harmonic loads on distribution transformers. Procedia Engineering, 202, 76–87. https://doi.org/10.1016/j.proeng.2017.09.696.

[13] Kefalas, T. D., & Kladas, A. G. (2010). Harmonic Impact on Distribution Transformer No-Load Loss. IEEE Transactions on Industrial Electronics, 57(1), 193–200. https://doi.org/10.1109/TIE.2009.2030207.

[14] Dao, Thinh, & Phung, B. T. (2017). Effects of voltage harmonic on losses and temperature rise in distribution transformers. IET Generation, Transmission & Distribution, 12(2), 347–354. https://doi.org/10.1049/iet-gtd.2017.0498.

[15] Hurley, W. G., Duffy, M. C., Acero, J., Ouyang, Z., & Zhang, J. (2018). 17—Magnetic Circuit Design for Power Electronics. In M. H. Rashid (Ed.), Power Electronics Handbook (Fourth Edition) (pp. 571–589). https://doi.org/10.1016/B978-0-12-81407-0.00019-2.

[16] Dao, T., Phung, B. T., & Blackburn, T. (2015). Effects of voltage harmonics on distribution transformer losses. 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 1–5. https://doi.org/10.1109/APPEEC.2015.7380953.

[17] Taher, M. A., Kamel, S., & Ali, Z. M. (2016). K-Factor and transformer losses calculations under harmonics. 2016 Eighteenth International Middle East Power Systems Conference (MEPCON), 753–758. https://doi.org/10.1109/MEPCON.2016.7836978.

[18] Fuchs, E. F., Lin, D., & Martynaitis, J. (2006). Measurement of three-phase transformer derating and reactive power demand under nonlinear loading conditions. IEEE Transactions on Power Delivery, 21(2), 665–672.

[19] Ulinuha, Agus. (2016a). Harmonic filter design using intelligent method for mitigation of distribution system distortion. ARPN Journal of Engineering and Applied Sciences, 11(06), 3985 – 3992.

[20] Motta, L., & Faúndes, N. (2016). Active / passive harmonic filters: Applications, challenges trends. 2016 17th International Conference on Harmonics and Quality of Power (ICHQP), 657–662. https://doi.org/10.1109/ICHQP.2016.7783319.

[21] Ulinuha, A. (2017). The impact of harmonic filter locations on distortion suppression. Proceeding - 2016 International Seminar on Intelligent Technology and Its Application, ISITIA 2016: Recent Trends in Intelligent Computational Technologies for Sustainable Energy. https://doi.org/10.1109/ISITIA.2016.7828711.