AN EXPERIMENTAL STUDY FOR COMPARING THE EFFECT OF THE MAGNETIC FIELD ON HUMAN HEALTH AROUND TRANSFORMERS IN SINUSOIDAL AND NON-SINUSOIDAL CURRENT CONDITIONS

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ABSTRACT

It is known that high voltage transmission lines are used for energy transmission to decrease power losses and increase system efficiency. The energy, which is transmitted at high voltages for long distances, is distributed at medium voltages through a step-down transformer near residential areas. Then the energy is introduced to the end users by reducing the voltage to lower levels. Today, these transformer stations are planted as close as possible to living areas to enhance system efficiency. These transformer stations placed in urban areas cause magnetic fields to occur due to the reason of carrying high load currents. Especially due to the decreasing voltage level at these mentioned transformer substations, the load current increases significantly. Because of that, magnetic field strength is enhanced near these urban areas. Additionally, according to the developing technology, characteristic currents of electrical loads are changed at recent years. High penetration of power electronic loads in industrial applications cause a significant increase in high frequency components in the current drawn from electric grid. Similarly, these currents also generate magnetic fields which consists high frequency components. As known there may be some influences to people who is exposed to a magnetic field over a threshold value for quite a while. For this reason, some standards were published to limit the magnetic field strength and exposure time values. In this study, magnetic field variations around a transformer are analyzed for several loading conditions with and without harmonics. For this purpose a test system with electronic load bank, transformer and regulator is built on laboratory and tests are done in several loading conditions. The gathered results are analyzed for sinusoidal and non-sinusoidal current conditions considering the standards.

Keywords: Human Health, Transformer, Harmonics, Magnetic Field

1. INTRODUCTION

According to developing technology and population growth consumption of electrical energy is increasing. Especially high population zones like urban areas considerable power is demanded. Therefore high voltage transmission lines are used to decrease power losses while delivering the energy to urban areas. Because of this, big sized step-down transformers have to be placed near living spaces. As the voltage is low on the secondary side of the transformer, current is extremely high. And also the current characteristic of the electric loads are changing due to the developing technology. There is a significant increase on electric loads that consists power electronic devices. As known the current of mentioned electric loads contains high frequency components that is called harmonic. The non-sinusoidal current of these loads has several negative impacts on energy quality. There are lots of studies in the literature that examines these impacts (Gobba, Bargellini, Scaringi, Bravo, & Borella, 2008).

As mentioned above high powered distribution transformers placed near living spaces and considerably high currents are drawn through secondary sides of these transformers. High magnetic field strength is occurred due to these currents (Röösli, Jenni, Kheifets, & Mezei, 2011). Because of this, possibility to be exposed to high magnetic field is increased (Ali, & Memari, 2010). There are known negative effects of magnetic field to human nervous, immune system (Gobba et al., 2008). Because of that for the protection of humans exposed to magnetic field in the low-frequency range (1 Hz to 100 kHz) of electromagnetic spectrum standards are published (ICNIRP, 2010).

In literature lots studies done to show the effects of magnetic field on human health (Grellier, Ravazzani, & Cardis, 2014) also there are several studies that concentrated on especially transformers (Nicolaou, Papadakis, Razis, Kyriacou, & Sahalos, 2011). And very rare studies investigate the effect of harmonics on measuring magnetic field (Cortes, Brüggemeyer, Dib, Mombello, & Ratta, 2013) (Brandolini, D'Antona, Faifer, Lazzaroni, & Ottoboni, 2004).

Different from the papers in literature, harmonic currents which are generally drawn from the grid in present time are taken into account in this study. By this way the measurements are done in high frequency range and the results are analyzed by using the ICNIRP standards. In following section the effects of the harmonics to magnetic field is proved by using mathematical equations. A representation of experimental test system is done in Section 3 and also results are presented. Discussion of the results and suggestion for the future studies is given on the last section.

2. SYSTEM AND METHODOLOGY

Currents of conventional electric loads are generally sinusoidal. But due to the developing power electronic technology, there is a significant increase on electric loads which consist of power electronic components. These power electronic loads can draw non-sinusoidal currents from electric grid because they chop the load current to control energy flow. To analyze these, Fourier series expansion of the current waveform is used that shown in Eq. (1):

$$f(x) = A_0 + \sum_{n=1}^{\infty} C_n \cos(nt + \theta_n) \quad (1)$$

In Eq. (1) A_0 is the DC component of the current. n is the harmonic order which is an integer of fundamental frequency. For example, if the fundamental frequency is 60 Hz, 5^{th} harmonic will be $5 \times 60 = 300\ Hz$. C_n is the amplitude of the n^{th} harmonic. As the same θ_n is the phase angle of the n^{th} harmonic current. Another parameter that is used to analyze non-sinusoidal currents is crest factor (CF) which is the ratio of the peak current to rms value. As seen on Eq. (2):

$$CF = \frac{I_{max}}{I_{rms}} \tag{2}$$

One of the most common load types in industrial applications is 6 pulse converters. These converters convert AC voltage to DC, at the same time controlling the amount of the converted energy. The current (i_a) of the mentioned converter is given in Eq. (3) (Kocatepe, Uzunoglu, Yumurtacı, Karakaş, & Arıkan, 2003):

$$i_a(\omega t) = \frac{2\sqrt{3}}{\pi} I_d\left(\cos\omega t - \frac{1}{5}\cos5\omega t + \frac{1}{7}\cos7\omega t - \frac{1}{11}\cos11\omega t + \frac{1}{13}\cos13\omega t - \cdots\right. \tag{3}$$

I_d is the DC current of the converter. A current waveform of a 6 pulse rectifier load is given in Fig. 1. Fourier expansion of this signal is given in Eq. (4):

$$i_a(\omega t) = 122\cos\omega t - 22\cos5\omega t + 15\cos7\omega t - 10\cos11\omega t + 8\cos13\omega t - \cdots \tag{4}$$

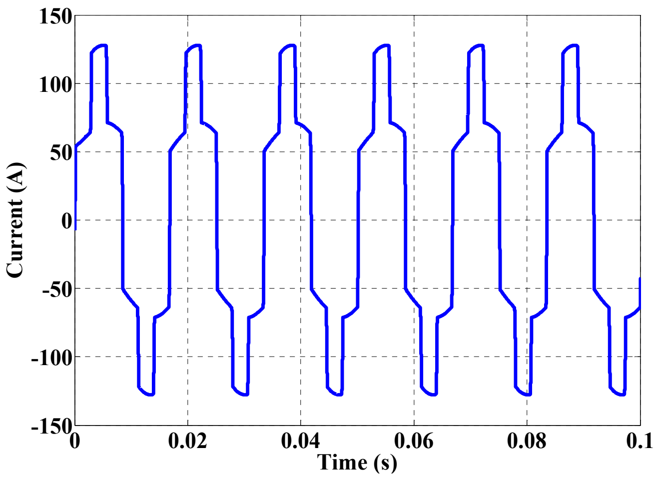

Fig. 1 Six Pulse Rectifier Current Waveform

As seen in Eq. (4) this kind of loads generates high frequency components in current waveform. The root mean square (rms) current is given in Eq. (5) (Kocatepe et al., 2003):

$$I_{rms} = \sqrt{\sum_{n=1}^{\infty} I_n^2} \tag{5}$$

The rms value of the current waveform given in Eq. (4) is 125.53A as the current in fundamental frequency is 122 A. As seen high frequency components of the current increases the rms value. This current passes through the distribution transformers and according to the Ampere law as shown in Eq. (6), magnetic field strength (*H*) varies related to this current (Chapman, 2007).

$$H = \frac{N \times i}{l_c} \tag{6}$$

N is the number of winding, l_c is the length of average magnetic field way. Similarly magnetic flux density (*B*) varies related to *H* as shown in Eq. (7) (Chapman, 2007):

$$B = \mu \times H \tag{7}$$

μ is the magnetic permeability of the material. As seen on Eq. (6) and Eq. (7) high frequency currents generate high frequency magnetic flux densities.

Similarly to rms value of the current, harmonics increase the magnetic flux density due to the high frequency components. These effects of the non-sinusoidal currents on magnetic field can be seen on the measurement results in the sections below. But the effect of the magnetic field strength to human health changes unlikely to rms value. As given in Eq. (8) exposure time to high frequency components of magnetic field strength is strictly limited (ICNIRP, 2010).

$$\sum_{j=1\,Hz}^{10\,MHz} \frac{H_j}{H_{R,j}} \leq 1 \tag{8}$$

H_j is the magnetic field strength at frequency j and $H_{R,j}$ is the magnetic field strength reference level at frequency j as given in Table 1 (ICNIRP, 2010).

Table 1. Reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values).

Frequency range	**E-field strength E (kV m^{-1})**	**Magnetic field strength H (A m^{-1})**	**Magnetic flux density B (T)**
1 Hz-8 Hz	20	1.63 X $10^5/f^2$	$0.2/f^2$
8 Hz-25 Hz	20	2 X 10^4/f	2.5 X 10^{-2}/f
25 Hz-300 Hz	5 X 10^2/f	8 X 10^2	1 X 10^{-3}
300 Hz-3 kHz	5 X 10^2/f	2.4 X 10^5/f	0.3/f
3 kHz-10 MHz	1.7 X 10^{-1}	80	1 X 10^{-4}

In this paper, in order to specify the effect of the harmonics to exposure time limits of magnetic field; a sinusoidal and non-sinusoidal current drawn from grid through a transformer and magnetic flux density around the transformer is measured and the measured values analyzed according to International Commission on Non-Ionizing Radiation Protection (ICNIRP) standard. In the section below, the experimental test system is clarified.

3. EXPERIMENTAL TEST SYSTEM AND RESULTS

Distribution transformers has high secondary current, at the same time has lots of turns. So that the magnetic field strength around distribution transformers is extremely high. In order to protect human health exposure to time- varying electric and magnetic fields are limited by standards. Because of this, magnetic field exposure limits around the transformers has to be examined. For this purpose, a test system consists of a regulator, a test transformer and a programmable electronic load bank is built. General scheme of the test system is given in Fig. 2.

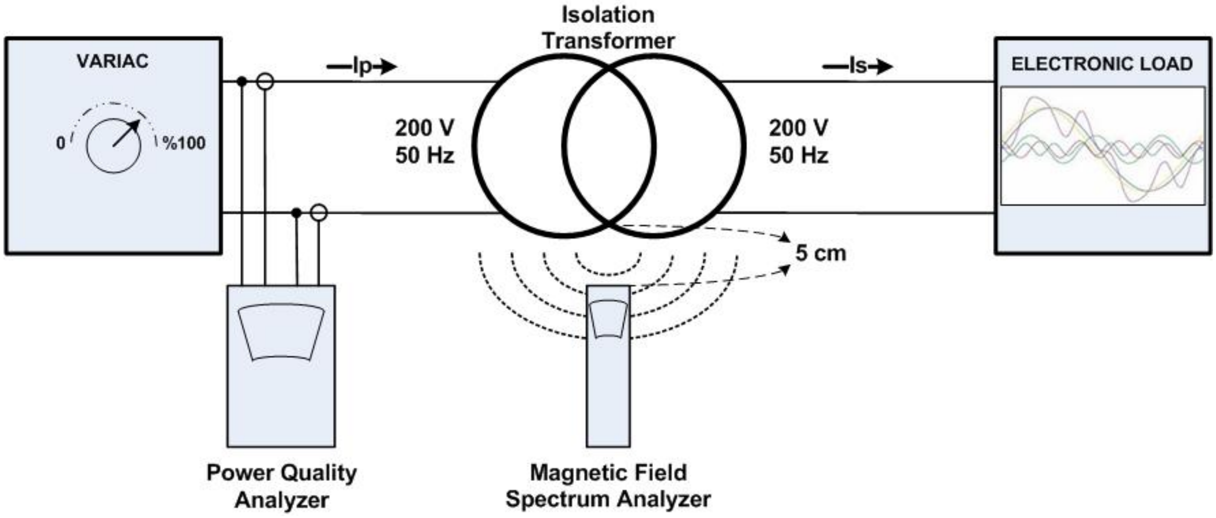

Fig. 2 General Scheme of the Test System

In this system, voltage level is regulated to 200 V by a variac manually. As the load values don't change dynamically, voltage is easily regulated. To measure the magnetic field around the transformer a magnetic field spectrum analyzer is used. As the magnetic field strength changes around the transformer significantly due to the distance, the magnetic field spectrum analyzer is fastened by a clamp as shown in Fig. 3 in order to avoid incorrect measurement.

Fig. 3 Transformer and Magnetic Field Spectrum Analyzer

In the tests perfomed the rms value of the current and the harmonic levels of the current can be stabilized with the electronic load bank. But idle current of the transformer may change due to the voltage fluctuations. To avoid these changes voltage level is stabilized to 200 V with a variac. Altough the voltage is stabilized, harmonic levels are increased because of the variac. At the same time the current and voltage quality parameters like harmonics, rms, power and energy values are measured and stored from primer side of the transformer. In this situation idle current of the isolation transformer consists harmonics. But these harmonics are measured and considered. After all as the idle current is considerably smaller than the load currents and also the magnetic field strength occurred due to the idle current can be neglected as seen on Table 2.

Table 2 Harmonic and Magnetic Field Strength Values for Idle Current

Harmonic Order	Magnetic Field Strength	H_n%f of the Current
1 (50 Hz)	1,525 μT	100
3 (150 Hz)	205 nT	26.8
5 (250 Hz)	136 nT	9.7
7 (350 Hz)	22 nT	3.1
9 (450 Hz)	45,6 nT	1.0
11 (550 Hz)	20,6 nT	0.4
13 (650 Hz)	9,5 nT	0.3
15 (750 Hz)	8,3 nT	0.3

As the rms value of the current in full load is 4 A which is much more greater than 0.168 A in idle condition. The values of the harmonic components are very smaller so that the effect of these small values doesn't have to be considered.

An electronic load bank is used to control the current that drawn from grid through the transformer. It is connected to transformers secondary side to measure the magnetic field strength around the transformer in a linear (without harmonics) and two different nonlinear loading conditions. In first condition, 4 A sinusoidal current is drawn through the transformer. The measured values with this 4 A current without harmonic are given in Table 3.

Table 3 Harmonic and Magnetic Field Strength Values for Sinusoidal Current

Harmonic Order	Magnetic Field Strength	H_n%f of the Current
1 (50 Hz)	26.76 μT	100
3 (150 Hz)	317 nT	1.1
5 (250 Hz)	760 nT	2.5
7 (350 Hz)	69 nT	0.2
9 (450 Hz)	59 nT	0.2
11 (550 Hz)	59 nT	0.2
13 (650 Hz)	50 nT	0.2
15 (750 Hz)	74 nT	0.3

It is clearly seen that magnetic field strength values at the frequencies except the fundamental one are considerably low. When the transformer fully loaded with a sinusoidal current, the harmonic rates decreased as it is compared to idle condition as mentioned before. 5^{th} and 15^{th} harmonic orders are more than the near frequencies as seen on Table 3. It shows that there is a resonance in those harmonic levels. The increase on the magnetic field strength at 250 and 750 Hz frequencies depends on that.

After measuring the values in sinusoidal current condition, the electronic load bank is configured to drawn non-sinusoidal current with a crest factor 2 which is 1.414 in sinusoidal condition. Rms value remains 4 A as same as the sinusoidal current but the peak value of the current increases from 5.6 to 8 A. Because of that changes the THD value of the current increased from 2.8 (THD value of the current given in Table 3) to 58.9. For that condition harmonic and magnetic field strength values are shown on Table 4.

Table 4 Harmonic and Magnetic Field Strength Values for Non-Sinusoidal Current (CF:2)

Harmonic Order	Magnetic Field Strength	H_n%f of the Current
1 (50 Hz)	21.96 μT	100
3 (150 Hz)	13.86 μT	56.5
5 (250 Hz)	3.63 μT	14.3
7 (350 Hz)	1.408 μT	6.2
9 (450 Hz)	1.067 μT	4.6
11 (550 Hz)	497 nT	2.2
13 (650 Hz)	563.5 nT	2.5
15 (750 Hz)	221 nT	1.1

Increasing the high frequency components of the load current and remaining the rms at the same value causes decrease on fundamental frequency current as it can be seen on Eq. (5). But there is a significant increase on high frequency components of the current as it is also reflected to magnetic field strength values. High frequency currents generates high frequency magnetic fields. To test the results with a diffirent harmonic distortion crest factor of the current increased to 2.5 so peak value of the current increases up to 10 A. In this condition THD value of the current increases to 94.5. In the same way high frequency magnetic field strength values increases similiarly to current values as seen in Table 5.

Table 5 Harmonic and Magnetic Field Strength Values for Non-Sinusoidal Current (CF:2.5)

Harmonic Order	Magnetic Field Strength	H_n%f of the Current
1 (50 Hz)	14.34 μT	100
3 (150 Hz)	11.93 μT	76.2
5 (250 Hz)	7.903 μT	49.8
7 (350 Hz)	3.84 μT	22.9
9 (450 Hz)	0.985 μT	3.9
11 (550 Hz)	607 nT	6.1
13 (650 Hz)	670 nT	6.3
15 (750 Hz)	222 nT	2.7

In the next section these results are analyzed in order to see the effects of the harmonics to exposure limits for the human health. Results are discussed and future studies are given.

4. CONCLUSION

The results that given in the section above are used to examine the effect of magnetic field on human health by using ICNIRP standarts. To clarify the diffirence between non-sinusoidal and sinusoidal currents, the exposure time for both conditions are analyzed. The measured magnetic field strengths for sinusoidal current that given in Table 3 and for non-sinusoidal current that given in Table 4-5 are used with the constants ($B_{R,j}$) that given in Table 1 to calculate the limit parameter that shown in Eq. (8). The results of the mentioned equation is given in Table 6:

Table 6 Calculated Results for Magnetic Field Exposure

	Sinuosidal	Non-Sinusoidal CF=2	Non-Sinusoidal CF=2.5
Limit Parameter	0.02840746	0.04511666	0.04324993

It can be easily comprehend from the results that non-sinusoidal currents even the same rms value with sinusoidal one have significantly more risk to exceed the limits for human health. In the mentioned standard this parameter has to be below 1. As we used small sized transformer at low currents, this values are considerably low. But the aim of the study is to show the effect of the diffirences between non-sinusoidal and sinusoidal currents. If a big size distribution transformer is used the effect will be similarly to this results. As it can be seen from Eq. (8) and Table 1 the magnetic field strengths with high frequency are strictly limited than low frequency ones. So that high frequency components increased limit parameter more. For this reason, limit parameter for non-sinusoidal current with CF 2 is 1.5 times higher than the one for sinusoidal current. But limit parameter for non-sinusoidal current with CF 2.5 is less than the one with CF 2. The harmonic orders more than 15 (750 Hz) are not considered in this study because of the power quality analyzers limits. This maybe the reason of the limit parameter of the current with CF 2.5 is calculated less than the one with CF 2.

In the future studies, measurements can be done for high power distribution transformers in non-sinusoidal current conditions. As these transformers placed to basement flat in the skyscrapers, measurements can be done from several points by changing the distance of the measurement point. And also the effect of the winding connection of the transformer to magnetic field strength can be examined.

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