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On the Effects of Lamination Artificial Faults in a 15 kVA Three-Phase Transformer Core

EHSAN ALTAYEF[1], **(Graduate Student Member, IEEE), FATIH ANAYI**[1], **MICHAEL S. PACKIANATHER**[1], **AND OMAR KHERIF**[2], **(Member, IEEE)**
[1]Wolfson Centre for Magnetics, School of Engineering, Cardiff University, Cardiff CF24 3AA, U.K.
[2]Advanced High Voltage Engineering Research Centre, School of Engineering, Cardiff University, Cardiff CF24 3AA, U.K.

Corresponding author: Ehsan Altayef (AltayefEM@cardiff.ac.uk)

ABSTRACT Cutting and punching of the steel used in power transformer core may cause edge burrs. This, along with the degradation of the lamination insulation, can lead to interlaminar short circuits. Analysing these faults helps understanding their effect on the transformer reliability and performance. In this light, the actual paper aims to experimentally simulate and analyse both faults using a 15 kVA three phase power transformer. Effects produced from both selected faults are experimentally investigated in this paper where different scenarios are considered such as the area of the affected regions and the number of short-circuited laminations. Various flux densities are considered ranging from 0.5 to 1.8 T. Of interest, the current at no load is recorded and the test is repeated for any given scenario. The obtained results are presented and discussed to study the effect of each fault on the transformer performance. Overall, the transformer current increases with the number of short-circuits between laminations for both faults. This increase is related to the flux density, which is dependent and sensitive to the short circuit location. Such findings represent a good indication of the severity of short circuits relative to their position in the transformer core, and can be exploited to discuss the power losses in the transformer core.

INDEX TERMS Leakage current, lamination edge burrs, lamination insulation fault, power losses, power transformer, steel.

I. INTRODUCTION

Power transformers are central components in transmission and distribution systems of electrical energy. These devices ensure the coordination of networks of different voltage levels [1], [2]. Regarding their importance in the energy systems, reliable and safe operation of the transformers is of great significance to guarantee a long lifetime [3]. Therefore, these transformers have a considerable influence on the costing of power transmission and the distribution flexibility. A power transformer should last for several decades, and monitoring both its condition is crucial [4]–[6]. Health conditions can be assessed through the state of its insulation systems such as the insulating oil [7] and that between windings or inter-laminations [8].

Indeed, it is usually required to employ quality control tests for testing of filled transformers. Reliable monitoring and diagnostic techniques for detecting transformer incipient faults are required to help in avoiding catastrophic failures, and to inform an efficient predictive maintenance program, which improves the reliability of the equipment [9], [10]. Transformer faults can be quickly affected in many locations by one of the reasons, which makes the outage time long, this affects the stability and security of the power grid. Faults in a transformer have a large influence so that the operation statuses of it directly affect the safety of the power system [11].

Power transformers can be affected by numerous issues that may either cause immediate or long term damage. Among many other issues, authors in [12] analysed data on 343 power transformer failures occurring in the voltage range of 33–400 kV. As reported in their work, insulation problems were the most common cause of failure, covering 36.74% of failures in power transformers. Among many other failures, winding, bushings, onload tap changer and core failures are the most pertinent. In low voltage transformers, the rate of insulation failures is reduced whilst core failure can be identified as a primary failure regarding the laminations and inter-laminations issues [13]. Therefore, these failures should be analysed to provide a better understanding of these problems in power transformers as well as

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to identify and develop techniques for the diagnostic and maintenance.

In order to construct transformer cores, a large number of thin electrical steel laminations is used to reduce the eddy current losses, thus increasing the efficiency of the transformers. Normally, each lamination is coated by a thin layer of 1 to 3 μm thickness, preventing direct electrical contacts between the laminations. In fact, different processes should be followed to build transformer cores. During these processes, the core laminations may be subjected to some issues that may have a direct impact on their properties [14]–[16]. For instance, the process of punching and cutting the electrical steel can cause mechanical stress in certain regions of the laminations. These stresses can deform the sheet shape and deteriorate its magnetic properties [16].

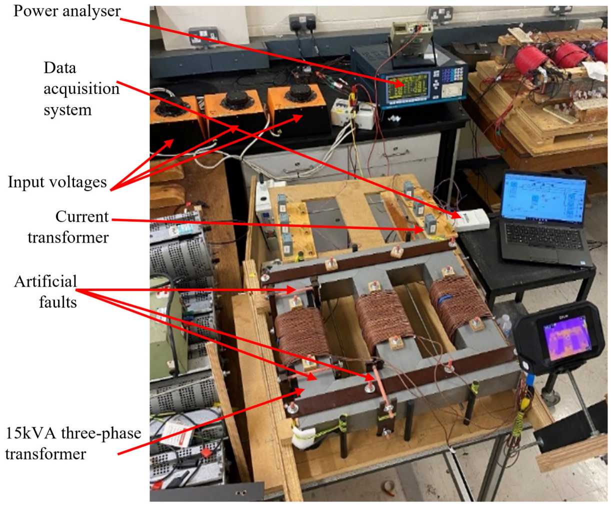
During the processes of cutting, mechanical assembly, rewind or re-wedge, mechanical deformations shear causes burrs on the cut edges. Moreover, vibration, arcing, heating may lead to the degradation of the insulation between the sheets. Both types of faults may result in an electrical shorting between the stacked laminations. In the literature, several works have been carried out to study these faults experimentally (e.g., [17]–[19]). Other authors tried to study the impact of edge burrs and interlaminar short-circuits by computer simulations (e.g, [20]–[22]). FEM models and analysis reveal the skin effect as an important variable when investigating power loss through eddy currents for magnetic cores at both high and low frequency where edge burring affects the core [15]. Iron loss models have been also proposed to help develop a more accurate design of high-speed motors including the punching effects (e.g., [23]).

In this paper, experimental studies have been carried out to provide an indication of the severity of short circuits in the transformer laminations due to edge burrs and insulation degradation faults. A fault-test system has been developed in the Wolfson Centre for Magnetics for such type of testing. A 15 kVA three phase power transformer has been used for the matter where different scenarios of faults have been considered such as the area of the affected regions and the number of short-circuited laminations. Of interest, the current at no load has been recorded for various flux densities ranging from 0.5 to 1.8 T.

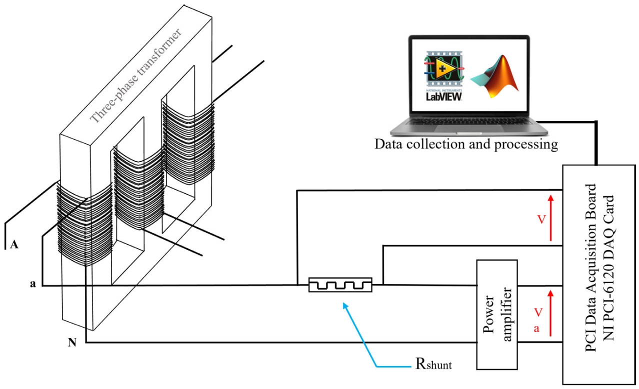
Section II presents the experimental setup used in this paper, and provides a detailed explanation of the data collection system and process used to investigate the impact of laminations faults in power transformers. Section III gives a description of the sample preparation, showing the process followed to create edge burrs and insulation degradation artificial faults. For each type of faults, the obtained results are presented and discussed in Section IV. A brief comparison between both types of faults is given and conclusions are grouped in the last section.

II. EXPERIMENTAL SETUP AND SAMPLE PREPARATION

This section provides a detailed explanation of the data collection system and process used to investigate the impact of laminations faults in power transformers. A fault-test system has been developed in the Wolfson Centre for Magnetics for such type of testing. This system helps measure different electromagnetic parameters and properties (i.e., voltage, current, flux density, etc.). Figures 1a and 1b show a photo of the experimental setup and a schematic diagram of the measurement system, respectively.



(a) Experimental setup



(b) Per phase schematic diagram

FIGURE 1. Experimental setup and a schematic diagram for the laminations faults analysis.

In fact, the test rig consists of several components, including a three-phase power transformer of 15 kVA, current transformers (with shunt-resistance), and data acquisition system, which is connected to a laptop for data analysis and signal processing in LabView–MATLAB software. Clamps are designed to be used for the fixation during the application of faults. Flux densities are calculated from the measured voltages and currents using the power analyser connected to the power transformer. It should be noted that a thermal camera is used in the experimental test, but its results are not within the scope of this paper.

The transformer core is built up from a stack of grain oriented electrical steel laminations (i.e., a total of 520 laminations). As shown in Figure 1, this transformer is characterised by two windows core of 320 mm×120 mm and

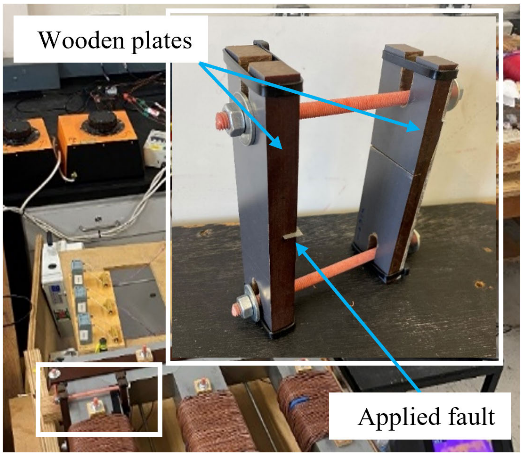


FIGURE 2. Clamping device used for the laminations fault fixation.

an outer core of 540 mm×520 mm. In addition, the primary and secondary windings are evenly wound along the limbs with 50 turns of insulated copper wire (i.e., 1.5 mm^2 cross-section).

It is well known that the transformer total loss is composed of ohmic loss, iron loss and additional loss. According to [24], the core-loss component is usually much larger in magnitude than the other two components in transformers with a magnetic core. Indeed, this investigation mainly considers the iron loss since both types of faults are directly applied to the transformer core (laminations). The magnitude of the iron loss is basically independent of the magnitude of the load, which means that the no-load loss is equal to the iron loss at the load, but it is the case at the nominal voltage. No-load loss or iron loss can be expressed by the no-load current measurements. For this reason, a transformer no-load test has been carried out applying the nominal voltage (220 V) of the primary set of transformer coils when the secondary coils are open.

A 1Ω-resistors and DAQ instrument have been used to record the current waveforms of the transformer based on the voltage readings. The output data (i.e., voltages and currents) are then transferred to the National Instrument Data Acquisition card (NI-DAQ USB-6211, 16 AI multifunction I/O) where the LabView software is used to save the current data as ".xlsx" and/or ".csv" format, which is easily used for further processing using a computer tools (i.e., MATLAB code).

In the initial stage of the experiments, a clamping device, shown in Figure 2, was designed to fit the experimental core of the transformer described in this investigation. This device helps to ensure a good contact of the artificial burr materials with the side of the sample stacks of laminations.

As shown in this figure, the clamping device consists of two wooden plates secured by two plastic bolts, enabling a good pressure to the copper foil on both sides of a stack of laminations. Both wood and plastic are transparent to electromagnetic waves. Thus, their effects on the experimental results can be neglected. In fact, several works have neglected the effect of the clamping device (e.g., [17]).

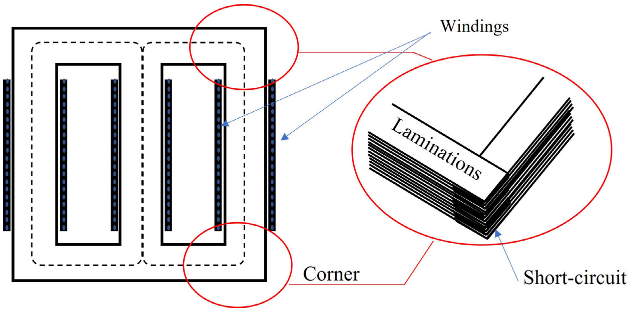


FIGURE 3. Representation of edge burrs faults in three-phase power transformer - laminations short-circuit.

III. ARTIFICIAL LAMINATION FAULTS

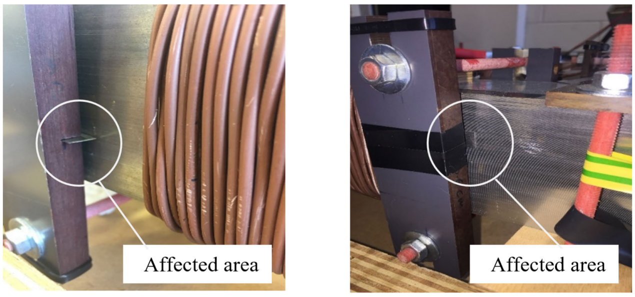
Mechanical deformations shear causes burrs on the cut edges usually followed by the process of punching and cutting the electrical steel as represented in Figure 3. These deformations may affect the performance of the transformer and cause power losses. In this investigation two types of faults have been considered in the transformer core. These faults are the edge burrs and insulation deterioration between laminations, which both are most commonly appeared faults in transformers. The forthcoming parts explain each fault individually.

In order to study the impact of the edge burr fault, healthy operation mode is firstly investigated. In this mode, voltage and current in the three phases have been recorded for different flux densities to guarantee satisfactory results. Flux densities of 0.5, 0.8, 1.0, 1.5, 1.7 and 1.8 T have been considered. The measured results are re-examined several times to ensure reliable and feasible quality. For instance, a whole day is allotted to take the data of each fault separately in order to leave the transformer core enough time to cool down.

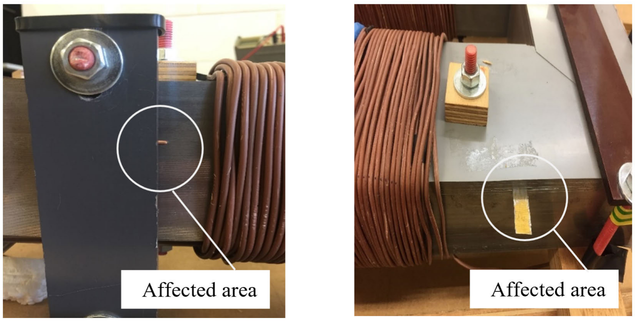
A. EDGE BURR FAULT

In order to simulate the edge burr fault, a short-circuit has been created between laminations of the transformer core. According to the number of sheets in short-circuit (affected area), four scenarios have been selected for this type of faults. Figure 4 shows the four considered faults (From scenario 1 to 4) and indicates the affected area of the transformer core.

In the first scenario of the edge burr fault shown in Figure 4(a), a metal chip has been inserted to create a short-circuit between two adjacent laminations out of 520 in the transformer core. The coverage area of the short circuit is 45 mm length and 0.5 mm thickness (i.e., 22.5 mm^2), which is guaranteed two laminations be short circuited on a certain location and then increase the number of places. In addition, a 9.7 mm chip is used to increase the number of short-circuits between laminations up to 33 laminations. As demonstrated in Figure 4(b), the coverage area in this scenario is 45 mm length and 10 mm thickness (i.e., 450 mm^2). In Figure 4(c), 1.3 mm copper wire has been used to create a short-circuit between 4 laminations, covering an area of 58 mm^2 : 45 mm length and 1.3 mm thickness. The fourth scenario of faults is shown in Figure 4(d). In this scenario, a short-circuit between 2 laminations has been created, which covers an area of 135 mm^2 (9 mm×15 mm).



(a) Scenario 1 (b) Scenario 2



(c) Scenario 3 (d) Scenario 4

FIGURE 4. **Artificial edge burr lamination faults (a) scenario 1, (b) scenario 2, (c) scenario 3 and (d) scenario 4.**

B. LAMINATION INSULATION FAULT

It is clear that the cores of electrical machines are formed by thin electrical steel laminations to reduce the eddy current loss for high efficiency operation. Each lamination is coated on both sides with an inorganic coating. This thin layer is usually of 1 to 3 μm in thickness, used to prevent any direct electrical contact between laminations. Degradation of the inter-laminar insulation in the transformer core can occur from a number of sources, such as ageing of lamination coating, mechanical damage from external objects, and/or overheating of laminations in the region of a winding failure. In order to study the impact of such types of lamination faults, the experiment involved applying these faults, and then gathering data to examine the transformer state in faults from insulation breakdowns (see Figure 5).

Insulation faults have been prepared by removing the insulation on the corresponding laminations, and putting a copper chip between them to maintain connectivity (Fig. 5). Damaged insulation faults are created on the two opposing sides of a selected number of transformer core laminations. Short-circuit of 2, 6, 8, 12 core laminations are considered for flux density of 0.5, 1.0, 1.5, 1.7 and 1.8 T. Damage has been generated by removing around 40 mm^2 of the insulation material by applying rotary equipment. It is worth noting that the faults are produced at different locations in the transformer core. A total of 5 sites on the core of the transformer have been selected as described below:

- Central area of the middle limb
- Joint connecting the right-hand most limb to the yoke
- Joint connecting the central limb to the central yoke
- Upper or lower yoke
- Middle area of the limb on the left or right.

FIGURE 5. **Experimental setup used for the laminations fault analysis.**

IV. RESULTS AND DISCUSSIONS

This section gives certain selected results of the experimental work presented in this paper. These results consist of the current waveform in the transformer, measured for various values of flux density. Firstly, Figure 6 shows the current waveforms for normal conditions before applying any faults to provide a better understanding of the impact of these faults. Since the current signal obtained for 0.5 T is lower than that obtained for 1.8 T, the results are separated into two sub-figures for a better visualisation of the results.

For healthy conditions of the transformer core, one can see that the flux density has an important effect on the magnitude and the waveform of the current in a no-loaded power transformer. For low flux density in Figure 6a, the current is of very low magnitude in the order of 0.1 A. In the same range of flux density, the current waveform is approximately similar to a noise signal accompanied by a periodical signal of lower amplitude.

Using Fourier analysis, Figure 7 illustrates an example of the frequency spectrum of the current signal for 1.7 and 1.8 T flux densities, obtained under healthy conditions.

From this figure, it was found that the healthy state is characterised by a low magnitude of the current fundamental, which is around 0.6 A. This operation state is also characterised by the appearance of harmonics of the order 3, 5 and 7. Other odd harmonics of higher order can not be seen for lower flux densities, but a very low magnitude of the harmonic of order 9 is noticed for 1.8 T flux density.

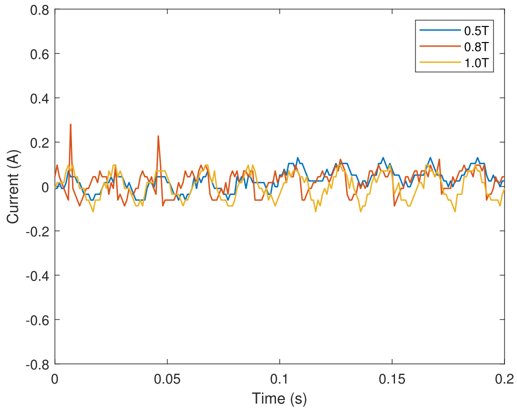
A. EDGE BURRS RESULTS

The results of the first selected type of faults (i.e., edge burrs faults) has been presented in this part. The same type of fault has been applied in two and three different places within the transformer core. Figure 8 shows the current waveforms for the considered cases. Two flux densities (i.e., 0.8 and 1.8 T) have been selected in this figure to highlight the effect of the flux density on the current waveform of the transformer under edge burr faults.

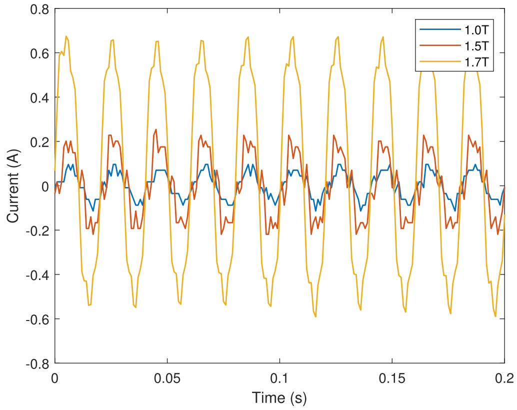
From the results of this figure, one can see that the current waveforms obtained during edge burr faults are characterised by different shapes compared to those obtained in the healthy

TABLE 1. Fourier Analysis parameters for a edge burr faults applied to the transformer core at 1.7 T.

		THD (%)	average value , fundamental (fd) and first harmonics in (A)					
			average	fd	3rd order	5th order	7th order	9th order
Healthy conditions		16.64	0.0682	0.6149	0.0719	0.0664	0.0196	0.0024
Edge burrs fault	2 places	16.12	0.0677	0.684	0.0786	0.0759	0.0198	0.0020
	3 places	16.10	0.0596	0.765	0.0895	0.0887	0.0244	0.0015

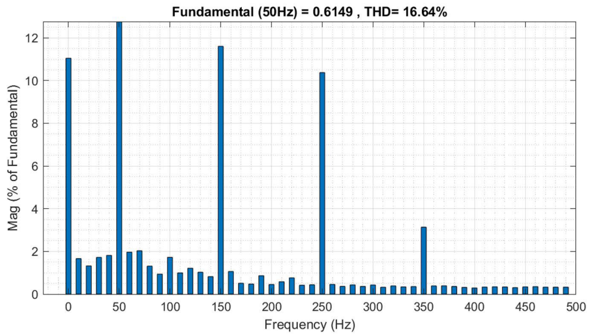


(a) Low flux density

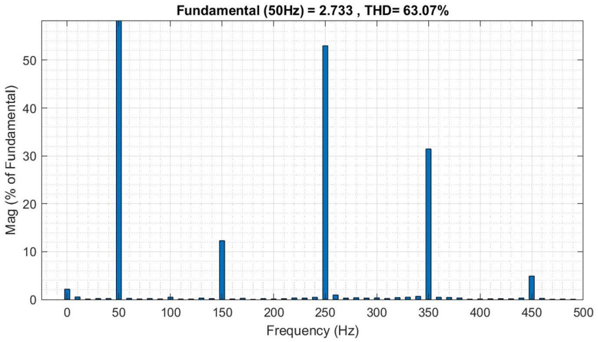


(b) High flux density

FIGURE 6. Current waveforms under healthy conditions.



(a) 1.7 T flux density



(b) 1.8 T flux density

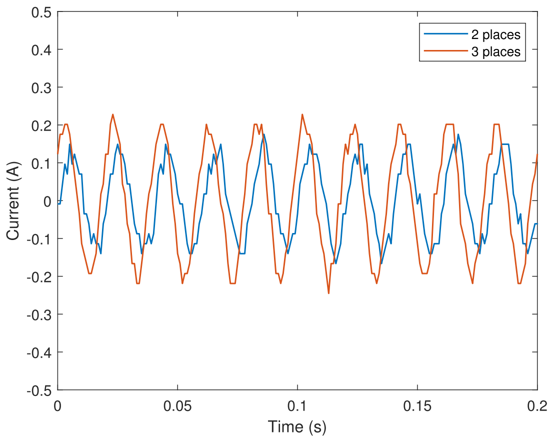
FIGURE 7. Frequency spectrum of the current signal in normal mode with 1.7 and 1.8 T flux density.

operation mode. This means that edge burrs faults considerably affect the transformer currents, thus, the performance of the transformer. Indeed, the current magnitude increases and harmonics become pertinent. For instance, the magnitude increased approximately from 0.1 to 0.2 A for a flux density of 0.8 T, corresponding to a rate of 100%. This rate of increase becomes more important with the increment of the flux density and the number of the affected places within the transformer core as shown in Figure 9. This figure illustrates the magnitude of the current signals as a function of the flux density obtained for normal and faulty operation modes. For 1.8 T flux density, the current has a large magnitude compared to the other studied cases. For this reason and for better visualisation and comparison, the figure gives only the results for flux densities up to 1.7 T.

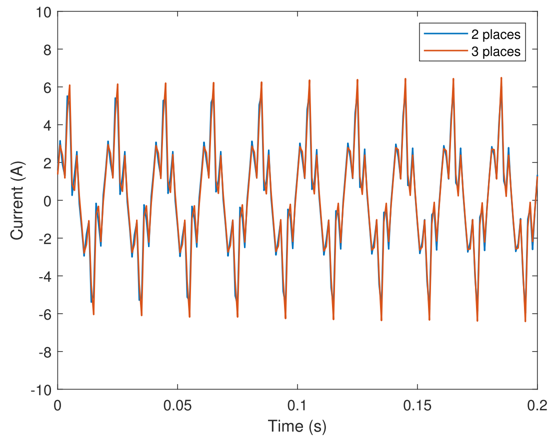
In this figure, the obtained results show a non-linear variation of the current magnitude with respect to the flux density. Slight augmentation has been observed in the current magnitude for low flux density. Dramatical increase is recorded for higher values of the flux density. In general, edge burrs fault in three places is characterised by the highest magnitude ranging between 0.15 and 0.82 A whilst the healthy condition is of lower values between 0.4 and 0.65 A.

Table 1 gives a brief comparison between the results measured with and without edge burr faults in the transformer core. The table shows some parameters obtained using Fourier Analysis such as THD, Average, Fundamental and the magnitude of first four harmonics.

As shown in this table, the edge burr faults affect the transformer currents. A remarkable increase of magnitude in the current fundamental as well as the first order harmonics. Overall, the increase is in the order of 150 mA for the fundamental and up to 22 mA in the harmonics. However,



(a) 0.8 T flux density



(b) 1.8 T flux density

FIGURE 8. Current waveform in transformer primary windings for edge burr faults applied in two and three different places.

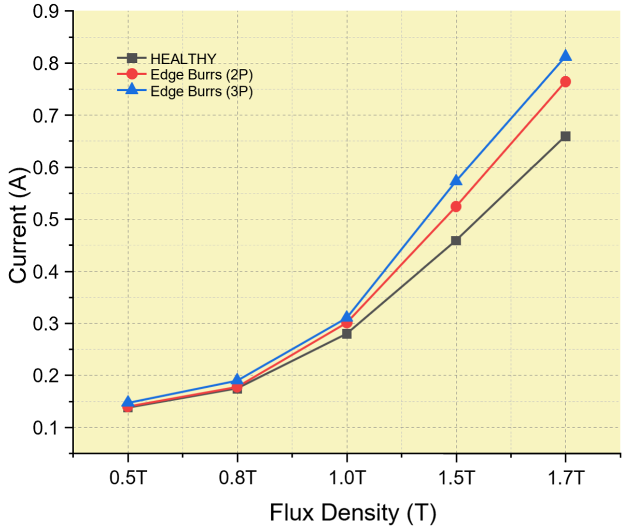
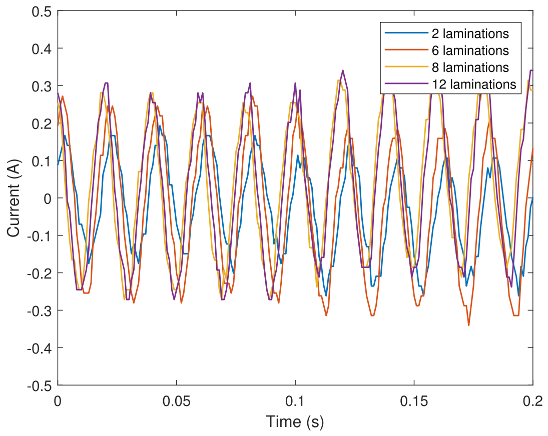
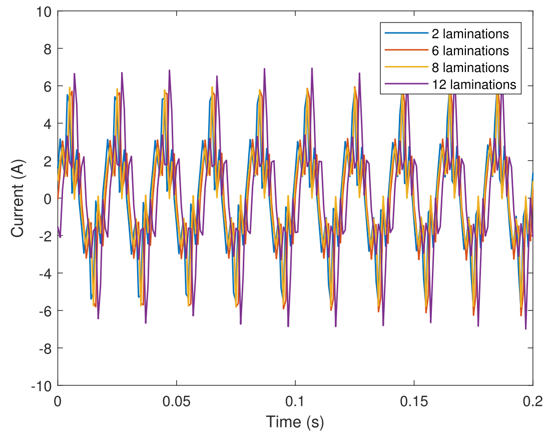


FIGURE 9. Magnitude of the current waveform in transformer primary windings with and without edge burrs faults.

the THD shows a slight decrease when the faults are applied. This decrease might be justified by the increase of the overall magnitude of the transformer current.



(a) 0.8 T flux density



(b) 1.8 T flux density

FIGURE 10. Current waveform in transformer primary windings for insulation degradation faults.

It should be noted that such a problem may be considerable and the consequences can be significant, especially if the studied faults happen in an oil-immersed power transformer of high capacity. For instance, the edge burrs faults result in an increase of the transformer current, which, in its round, can increase the temperature inside the transformer. This rise of temperature might affect the properties of the insulating oil and/or insulating paper, thus, reducing the performance of the transformer. For this reason, it would be better to examine the effect of such faults in high capacity transformers.

B. RESULTS OF LAMINATION INSULATION FAULTS

As described in Section II, artificial short circuits, as a second type of fault, have been applied between transformer core laminations by removing the insulation covering the laminations. Figure 10 shows the measured current waveforms in the primary windings of the transformer. The results correspond to faults between 2, 6, 8 and 12 laminations for 0.8 and 1.8 T flux densities as indicated in Figures 10a and 10b, respectively. It should be noted that the impact of the position of the short circuit applied between laminations has been investigated previously in [20]. For this reason, the same

TABLE 2. Fourier Analysis parameters for lamination insulation faults applied to the transformer core at 1.7 T.

		THD (%)	average value , fundamental (fd) and first harmonics in (A)					
			average	fd	3rd order	5th order	7th order	9th order
Lamination insulation faults	2 laminations	50.14	0.0612	1.113	0.0790	0.4618	0.2771	0.5676
	6 laminations	57.85	0.0612	1.303	0.2149	0.6254	0.3531	0.0325
	8 laminations	56.94	0.0587	1.175	0.0834	0.5499	0.3630	0.0916
	12 laminations	54.77	0.0612	1.459	0.2626	0.6653	0.3487	0.0729

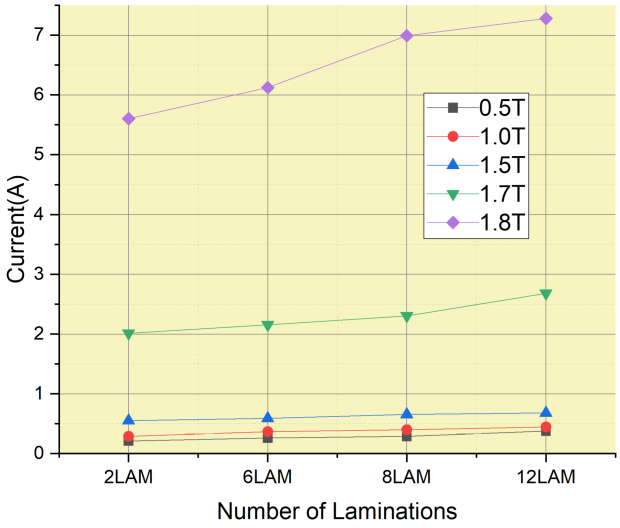


FIGURE 11. Magnitude of the current waveform in transformer primary windings with insulation degradation faults applied between 2, 6, 8 and 12 laminations.

position of the applied faults has been considered in this investigation.

From this figure, it is clear that the size (number of affected laminations) of faults has an important effect on the current within the transformer windings. The results show that the short circuit current is approximately a linear function of the number of the affected laminations as can be seen in Figure 11. This figure shows the current magnitude as a function of the number of the affected laminations at flax density between 0.5 and 1.8 T.

From this figure, it is shown that the current caused by the insulation damage fault is related to the number of the laminations in short circuit as well as to the flux density. It was found for two, six, eight and twelve shorted laminations that the current magnitude is extremely high at flux density of 1.8 T. In addition, the current magnitude follows a non-linear function with respect to the flux density.

Table 2 gives the THD, Average, Fundamental and the magnitude of the first four harmonics of the current signal for lamination insulation faults in the transformer core.

When applying lamination insulation faults, the results show a considerable increase in the THD as well as the magnitude of fundamental and harmonics compared to the healthy conditions. For instance, the THD rises from 16.64% with 0.6 A fundamental to 50.14% THD with a fundamental of 1.11 A for insulation faults between two laminations. This is equivalent to a 66.81% increase in the THD value and 45.95% in the fundamental magnitude. In general, these rates increase with the number of the affected laminations as given in Table 2. In addition, the obtained results are considerably affected by the flux density as shown in Figure 11.

Overall, the results demonstrate that the healthy operation mode can be distinguished from faulty one in most proposed cases. In addition, the results associated to this type of faults are also different to those obtained when applying edge burrs faults. This means that a fault detection and classification technique can be considered in these types of faults using the current waveforms as information support.

V. CONCLUSION

This investigation studied the impact of edge burrs and damaged insulation systems between laminations on the performance of power transformers. Experimental methodology was presented to simulate both laminations faults. A three-phase transformer was used where different scenarios of the faults were applied and several flux densities were considered. Overall, the obtained results demonstrated that burrs and insulation degradation both can cause flux distortion regarding the recorded current signals, which considerably affect the reliability of the transformer.

Edge burrs and/or insulation degradation affecting the transformer core can increase the transformer currents. These later become important with the increase of the flux density and the number of short-circuited laminations. Therefore, high current loss might be developed for the transformer core under faulty conditions. This can cause flux distortion in cruciform stacked cores and high localised heating within and outside of the affected region.

Current loss caused by the insulation damage fault is related to the number of the laminations in short circuit as well as to the flux density. It was found for two, six, eight and twelve shorted laminations that the current magnitude is extremely high at flux density of 1.8 T, increased with the number of the affected laminations. This important increase of current may lead to the increase in power losses, hence, the transformer efficiency or engendering thermal power transformer failure.

Such findings represent a good indication of the severity of short circuits in the transformer core, and manufacturers should take precautions to eliminate burrs as far as practicable, especially for transformers of high capacity where the consequences might be more significant. Moreover, it is noticed that the transformer currents are affected in different ways according to the applied faults. This implies that detection and classification of faults can be achieved using these currents.

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EHSAN ALTAYEF (Graduate Student Member, IEEE) received the higher diploma degree in electricity from the Higher Institute Al-Zahra, Libya, in 2008, and the M.Sc. degree in renewable energy and resource management from the University of South Wales, U.K., in 2016. He is currently pursuing the Ph.D. degree in electrical engineering with the School of Engineering, Cardiff University, U.K. He worked as a Laboratory Demonstrator and a Lecturer Assistant with Al-Zahra Higher Institution, from 2009 to 2012. His research interests include renewable energy and resource management and power system protection.

FATIH ANAYI was born in Baghdad, Iraq. He received the B.Sc. degree in electrical and electronic engineering from the University of Baghdad, Baghdad, in 1975, the M.Sc. degree in electrical engineering from the University of Wales, Wales, U.K., in 1988, and the Ph.D. degree in electrical engineering from Cardiff University, Cardiff, U.K., in 1992. After receiving the B.Sc. degree, he worked in industry in Iraq for ten years. He has been a Researcher and an academician with Cardiff University, since 1992. He has published 51 papers related to electrical machine design, electromagnetic, and power electronics. He participated in writing two books: *Analogue Electronic Circuits and Systems* (Cambridge University Press, 1991) and *Permanent-Magnet DC Linear Motors* (Oxford University Press, 1996).

MICHAEL S. PACKIANATHER received the B.Sc. degree (Hons.) in electrical and electronic engineering and the M.Sc. and Ph.D. degrees in artificial intelligence from the University of Wales Cardiff, in 1991, 1993, and 1997, respectively. From February 1997 to 2001, he worked as a Research Associate at the Cardiff School of Engineering before becoming a Lecturer. He was promoted to the position of a Senior Lecturer in 2011. He is serving as the PGR Tutor for mechanical, medical, and manufacturing engineering.

OMAR KHERIF (Member, IEEE) received the M.Eng. and Ph.D. degrees in electrical engineering from the École Nationale Polytechnique (ENP), in 2015 and 2019, respectively. He was a Mathematical-Analysis Assistant Teacher with ENP, from 2016 to 2018. He was also a Volunteer Researcher with the Laboratoire de Recherche en Electrotechnique, ENP, where he co-supervised several master's theses. He is currently a KTP Associate with Cardiff University. His research interests include high-voltage techniques, electromagnetic transients, and earthing and power system protection. He is an active member of different scientific organizations in electrical engineering such as CNHT, IEEE SIGHT, and EMTP Users Group.

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