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DC Bias in the Power Grid and Possibilities of Compensation

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SUMMARY

Direct currents (DC) in the power grid negatively affect the performance of modern power transformers, causing both increased noise emissions and losses. The highly efficient grain-orientated steel used in modern transformer cores, which results in low core flux density values, makes these devices susceptible to even minor DC biases in the grid. Increased noise and losses exhibited by transformers subject to DC bias is attributable to a phenomenon known as ‘half-cycle saturation’, which refers to a partial saturation of the transformer’s core.

The origins of DC in the power grid are not yet fully understood. However, sources that have been identified include: HVDC transmission lines; power electronics for railroad and subway systems; and converter electronics from renewable power generation equipment, such as wind power or photovoltaics. Factory tests and field experience have shown that two possible paths exist for the flow of direct current in transformers. The DC may either flow between the power lines and ground, known as ‘symmetrical DC’, or alternatively it may flow between the phases, referred to as ‘asymmetric DC’.

In addition to the core material, a major factor influencing the sensitivity of a transformer to DC is the core type. Independent from the source of DC in the grid, transformers with high magnetic conductivity paths for zero sequence flux – such as single phase or three-phase five-limb units – are most sensitive. Three-phase three-limb units are also very sensitive to asymmetric DC; however, they are relatively insensitive to symmetrical DC.

This paper details the effects of DC on single-phase and three-phase three-limb ‘low-noise’ transformers which incorporate premium grain-oriented core materials, assessed from both test laboratory and field data. It has been found that even small amounts of DC bias leads to noise level increases of more than 10 dB(A).

A system developed by Siemens AG, referred to as ‘DC Compensation’ (DCC), allows for the elimination of DC effects on power transformers through active compensation. The system, detailed within this paper, compensates for the DC flux offset in the core of the transformer without impacting the wider power grid. In addition to detailing the theoretical understanding of DC Compensation system, this paper will also illustrate its effectiveness.

KEYWORDS

Transformer, direct current, DC bias, DC compensation, noise

I. INTRODUCTION

Noise emissions and losses are two topics that have been extensively researched and progressed in the development of power transformers. However, the recent increase of direct currents (DC) in the power grid has negatively affected both the acoustic characteristics and efficiency of modern transformers. This is the result of the highly efficient grain-oriented electrical steel used to manufacture modern power transformer cores, which makes them susceptible to even minor DC biases in the grid.

Since the magnetizing current for modern transformers is very low, the addition of even a small direct current is sufficient to cause half-cycle saturation of the core. This half-cycle saturation, not accounted for in the design of transformers, results in the reduced performance of optimized transformers and significantly increased noise levels.

Aside from the undesirable effects, small amounts of DC in the grid are not damaging to the physical condition of the transformer. This is in contrast to significant DC events like geomagnetically induced currents (GIC), which have the potential to cause irreparable damage to transformers and therefore may result in widespread black-outs [1], [2], [3].

The origins of low levels of DC in the grid are still not fully understood. Sources that have been documented to date include: HVDC transmission lines; power electronics for railroad and subway systems; and converter electronics from renewable power generation equipment, such as wind power or photovoltaics [4a]. However, even if all sources will be identified, it may not be possible eliminate them. This is obvious when considering a HVDC transmission system [5] or a static VAR compensator. Therefore, the provision of countermeasures to offset the effects of DC on modern transformers appears as the only feasible solution.

In this paper a new measure developed by Siemens AG, known as the ‘Direct Current Compensation (DCC) system’, will be introduced and explained [6][7]. In addition to test lab results, field data from single phase transformers located in California will be shown.

II. EFFECTS OF DC ON TRANSFORMERS

This section of the paper details the effects of DC on transformers. Specifically, the noise characteristics, no-load losses and reactive power consumption are investigated. Two transformer types have been in also been investigated in order to show the effects of DC on different core designs.

A. *Specifications of the Transformers Investigated*

The two transformers analyzed within this investigation included a single phase unit (‘Transformer 1’) and a three-phase, three-limb transformer (Transformer 2). The technical specifications relating to each of these transformers are shown in Table I.

TABLE I. TECHNICAL DATA OF TRANSFORMERS INVESTIGATED

	unit	**Transformer 1 (single phase)**	**Transformer 2 (three limb)**
Rated power	MVA	134.4 / 134.4 / 44.8	100
Rated voltage	kV	$230/\sqrt{3} \pm 2x5/\sqrt{3}$ / $120/\sqrt{3} - 1x5/\sqrt{3}$ / 13.2	132.0 / 30.4
Frequency	Hz	60	50
Core type (limbs-return limbs)		1-2	3-0
Rated flux density	T	1.717	1.561
Magnetization (H) for rated flux density (peak value)	A/m	44.7	27.5

To test the influence of DC on transformers examined during this study a back-to-back setup was utilized. In this arrangement the HV terminals of two identical transformers were connected together and a controllable DC source was put between the neutral terminals. Such a setup allows the DC to close its path through the main windings of the two transformers. For the AC magnetization, both transformers were energized via the tertiary winding. A schematic of the back-to-back setup employed in this investigation is shown in Fig. 1.

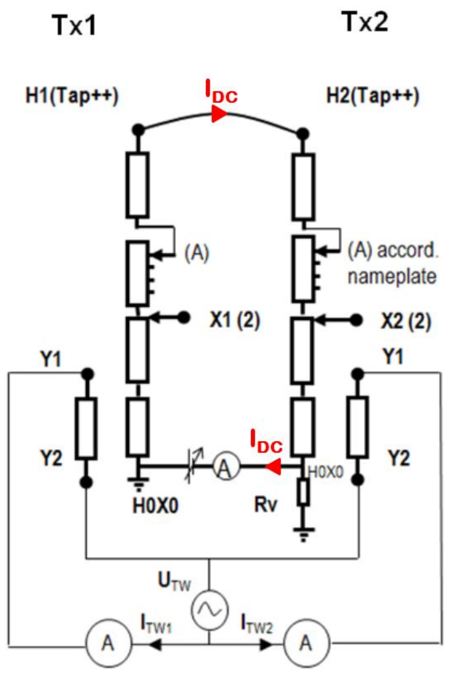

FIG. 1 BACK-TO-BACK TEST SETUP.

B. Noise

The most undesirable effect on transformers from small magnitude DC is the increase of the no-load noise. This is especially true if substations located are close to inhabited areas. Fig. 2 illustrates the increase of the no-load noise as a function of DC magnetization at differing flux density levels. It should be noted that in order to have results from both Transformer 1 and Transformer 2 in a single diagram the DC was normalized with respect to the number of turns and the magnetic length to the magnetization.

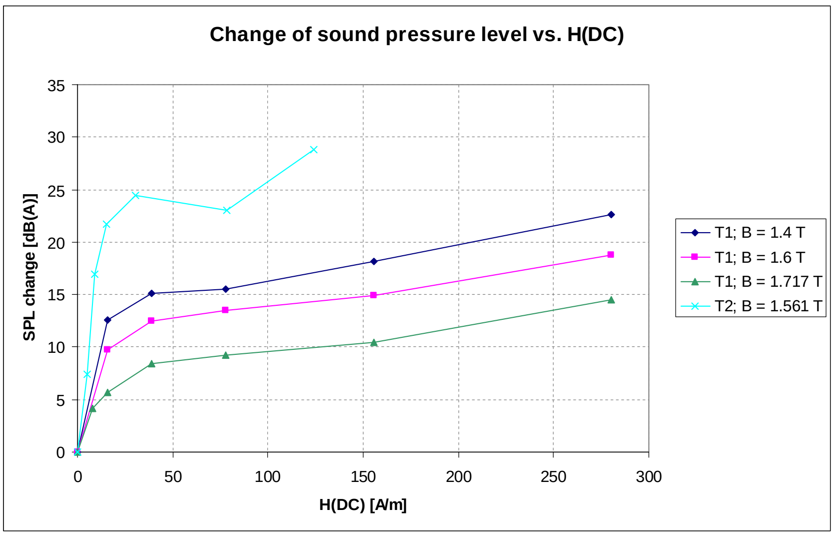

FIG. 2 CHANGE OF SOUND PRESSURE LEVEL AS A FUNCTION DC MAGNETIZATION.

The most notable result illustrated in Fig. 2 is that under DC magnetization the noise level is inversely related to the rated induction level. Therefore, it was seen that higher noise levels were experienced at lower rated inductions. This trends matches exactly with the shape of the B-H curve of the core material.

A second important result observed during acoustic testing was the frequency spectrum of the noise. With pure AC magnetization, only the even harmonics of the 50/60 hertz electrical base frequency occur in the noise spectrum, being 100/120, 200/240, 300/360 Hz etc. However, in the case of AC and superimposed DC magnetization the transformer core is excited asymmetrically. This adds odd multiples of the electrical frequency to the spectrum. In Fig. 3 the third octave bands of the no-load noise during testing of Transformer 2 are shown. It is clearly illustrated that a small value of superimposed DC magnetization can lead to a significant increase in the noise emissions.

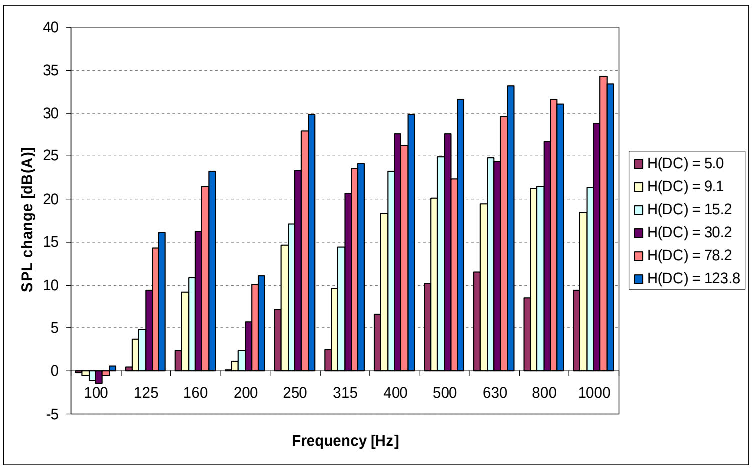

FIG 3. CHANGE OF SOUND PRESSURE LEVEL RESULTING FROM DC MAGNETIZATION (THIRD OCTAVE BANDS OF NO-LOAD NOISE OF TRANSFORMER 2).

C. *No-load losses*

As previously noted, DC in the grid is known to have an adverse effect on the efficiency of a power transformer. The increase in no-load losses due to superimposed DC magnetization of the transformer core, as measured on Transformer 1, is illustrated in Fig. 4. From Fig. 4 it can be seen that the increase in no-load load losses was approximately 30 % at a specified DC level of 2 amperes. The nonlinear relationship between the magnitude of DC and no-load losses is due to the nonlinearity of the core material's B-H curve.

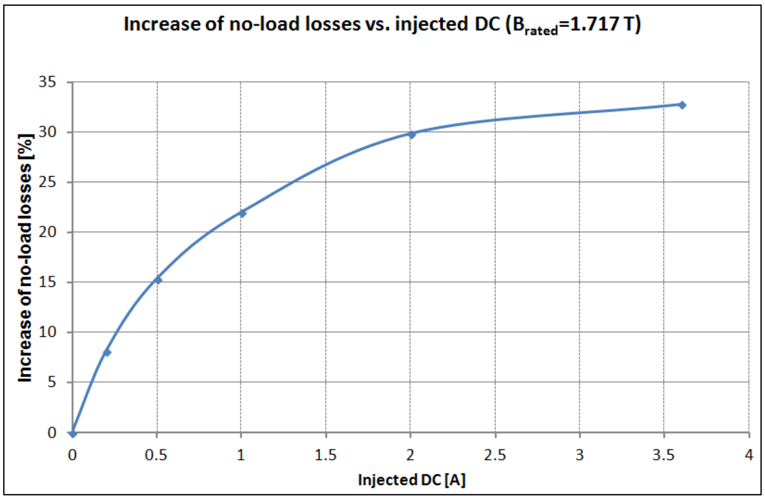

FIG 4. INCREASE IN THE NO-LOAD LOSSES OF TRANSFORMER 1 UNDER DC BIAS.

D. *Reactive power consumption*

Resulting from the non-linearity of the B-H-curve, the reactive power needed for magnetization of the core increases significantly with the presence of DC. This relationship between the reactive power consumption and the DC flux density is shown in Fig. 5.

However, in the measured range of DC, the reactive power is still small in comparison to the rated power of the transformer. In case of large DC, like geomagnetically induced currents, the increased reactive power consumption may lead fatal damage of the transformer and subsequent black-outs.

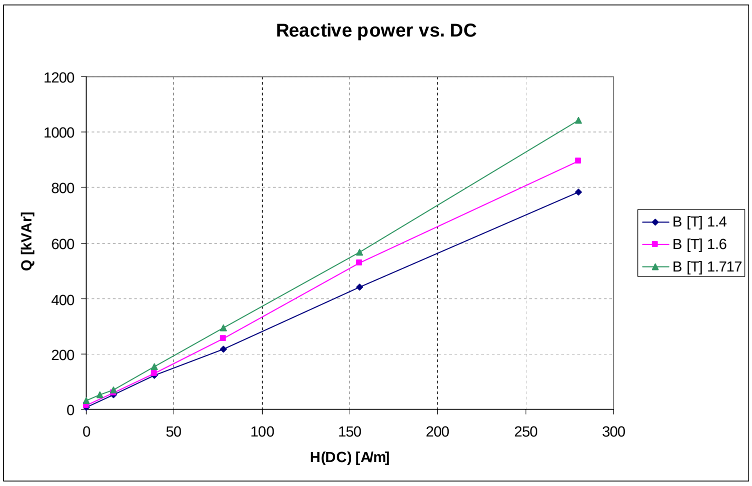

FIG 5. REACTIVE POWER CONSUMPTION AS A FUNCTION OF DC MAGNETIZATION AT DIFFERENT INDUCTION LEVELS FOR TRANSFORMER 1.

III. OFFSETTING THE DC RELATED EFFECTS

Many passive counter-measures to deal with the undesirable effects on transformers from DC in the grid are available. Two of the most common passive counter-measures include sound enclosures and DC blockers; however, these solutions are not ideal as sound enclosures are very expensive and DC blockers have a significant impact on the grid. Several other passive measures have also been proposed.

An alternative to the passive solutions available is an innovative active method, referred to as DC Compensation. The system, developed by Siemens AG, is able to eliminate the effects of DC on the transformer core by injecting the same number of DC ampereturns with the opposite sign in a so called compensation winding. This approach results in the DC not being blocked but instead the resulting DC flux in the core is compensated. By doing so, none of the adverse effects arising from DC in the grid, as detailed in Section II of this paper, occur. Fig. 6 shows the principle concept behind the DC Compensation system. As illustrated, the system consists of a digital control loop in order to adapt to different DC levels over time. The controller calculates the needed amount of DC counter ampereturns and injects the corresponding DC into the compensation winding.

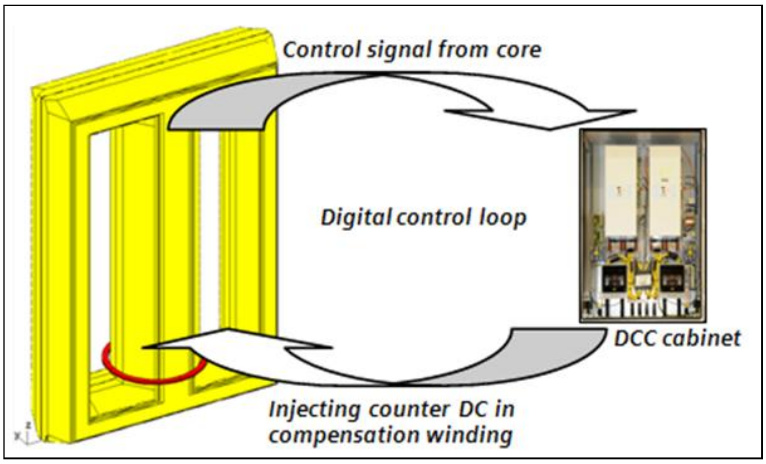

FIG 6. PRINCIPLE CONCEPT OF THE DC COMPENSATION.

The significant advantage of the DC Compensation system is that the DC in the grid is not blocked but its effects on the transformer are instead offset. Therefore adverse effects are not suffered by the grid or the transformer. The principle of the controlled injection of counter DC ampereturns is relatively simple; however, the technological challenge is to measure small amount of direct current (in the range of mili-amperes to a few amperes) in high load currents of approximately 1000 amperes. For this a sophisticated solution has been developed that requires no electronic components being placed inside the tank. The electronics employed to analyze the sensor signal and calculate the DC load are instead mounted in a cabinet and fitted on the tank as shown in Fig. 7. Through testing and validation the measurement system developed has proven to be accurate and reliable.

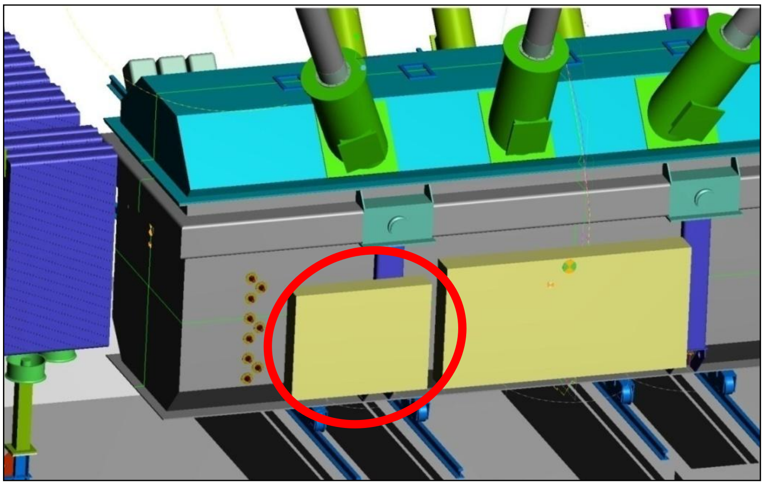

FIG 7. DC COMPENSATION CABINET (MARKED WITH RED CIRCLE) MOUNTED ON THE TANK.

IV. PERFORMANCE OF THE DC COMPENSATION SYSTEM

A. *Factory acceptance tests for Transformer 1*

The factory acceptance tests on Transformer 1 were performed with two identical transformers in a back-to-back configuration – refer to Figure 1 for a schematic of this setup. It should also be noted that during testing the transformers were operated in the same tap position. This allowed for the injection of a direct current into the neutral point of the transformers with an off-the-shelf DC source as this device does not see any of the induced voltages in the transformer. Fig. 8 illustrates the results from the factory noise acceptance tests. The measurements indicate that approximately 100 miliamperes of superimposed DC are sufficient to exceed the guaranteed noise levels of Transformer 1 if no counter measure is applied. It is also evident in Fig. 8 that the DC Compensation system reduces the total sound pressure level to well below the guaranteed level of 72 dB(A) up to the specified DC range of 2 amperes.

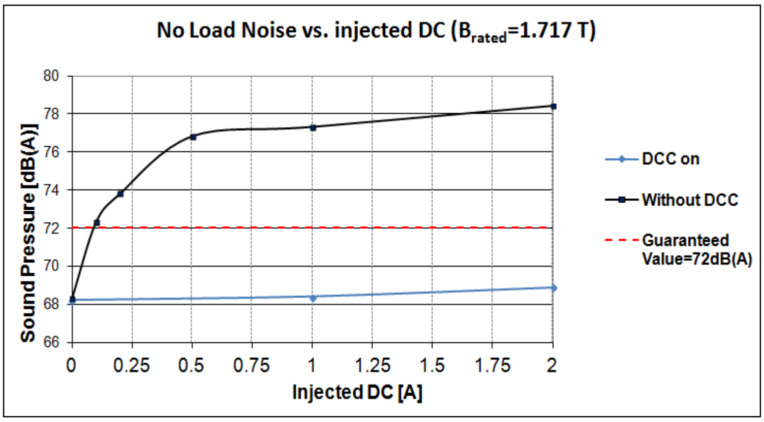

FIG 8. SOUND PRESSURE AT RATED INDUCTANCE AND DIFFERENT DC LEVELS FOR TRANSFORMER 1.

In addition to overall sound pressure levels, the sound pressure spectrum at different levels of DC was measured during the testing of Transformer 1. These results have been illustrated in Fig. 9. From the results the significant rise in noise levels at odd frequencies due to the asymmetric magnetization of the core is clearly seen.

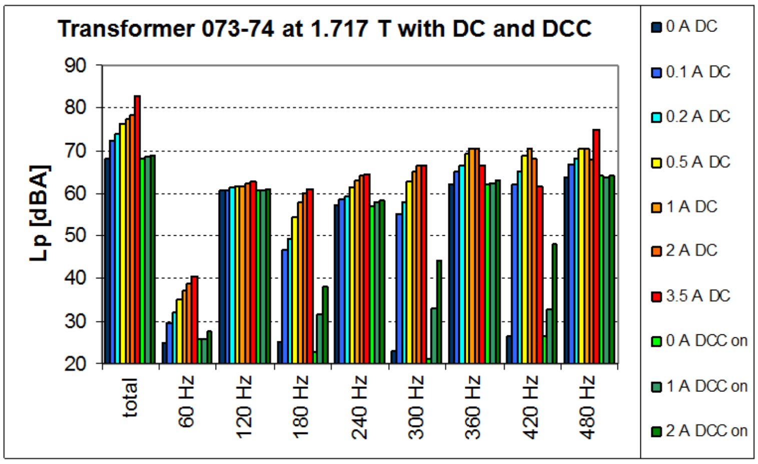

FIG 9. SPECTRUM OF SOUND PRESSURE LEVEL WITH DIFFERENT LEVELS OF DC AND DC COMPENSATION.

B. *Field experience under service conditions*

To understand the functionality of the DC Compensation system in the field the system has been fitted with internal memory capable of storing the conditions in which it operates. By analyzing this data, the DC load of the transformer can be reconstructed. A four month DC load profile of Transformer 1 was analyzed by Passath, Leber, Hamberger and Bachinger in *Direct Current Compensation – Field Experience Under Service Conditions* [6]. The most significant result from this study was that the DC followed a clear profile, which has been reproduced in Fig. 10. From the figure it is cleat that the highest values of DC in the grid appear at around midday and at midnight. This may indicate a correlation to the load or adjustments to the load in the power grid. Furthermore, according to the study by Passath et al., without DC Compensation the transformer's noise would have been above the guaranteed noise for level almost the entire period observed [9].

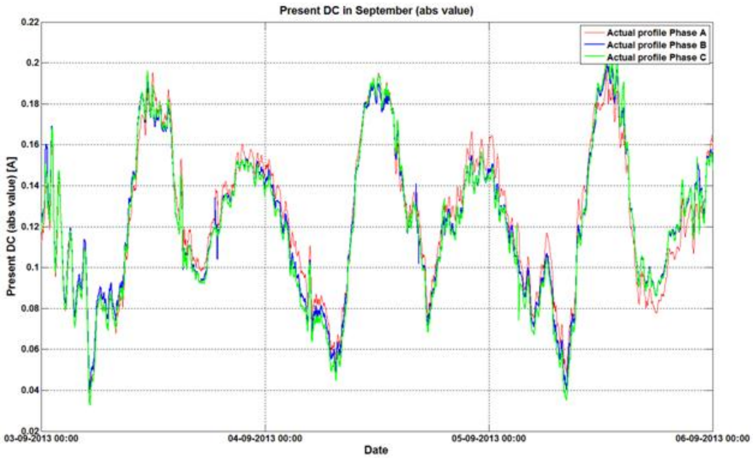

FIG 10. A 3-DAY DC PROFILE IN SEPTEMBER 2013.

A second result of note from DC load profile of Transformer 1 is that the profile seems to be relatively stable. Fig. 11 and Fig. 12 illustrated the DC profiles from 24 hour periods in July 2012 and September 2013. These figures show that the shape of the profile has stayed almost constant although more than a year lapsed between the measurements.

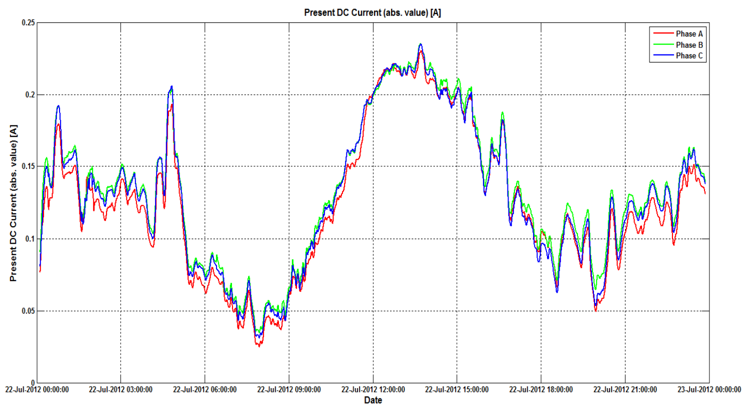

FIG 11. DC PROFILE FROM THE 22ND JULY 2012

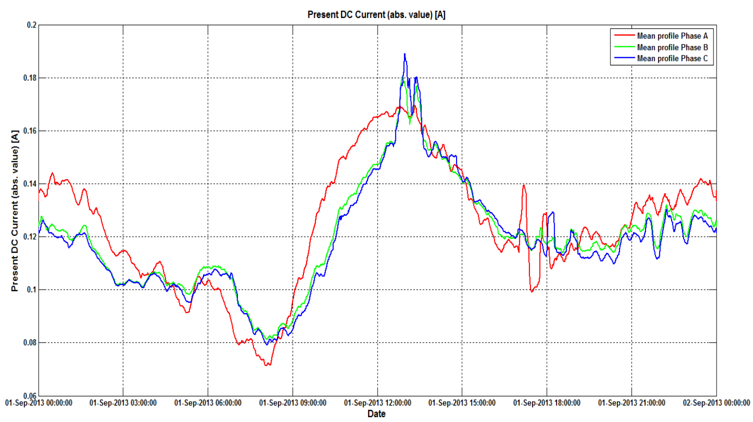

FIG 12. AVERAGE DC PROFILE OF THE FIRST 1ST SEPTEMBER 2013

V. CONCLUSION

Direct currents in the power grid negatively affect the performance of modern power transformers. Studies presented in this paper have illustrated that even small values of superimposed DC significantly increase the no-load losses, the noise emissions and the reactive power consumption of these devices.

In addition to the core shape, transformers designed with low induction levels, which result in lower losses and reduced noise levels under ideal conditions, are even more sensitive to DC. This is the result of the highly the efficient grain-oriented electrical steel is used in the manufacture of such transformer cores. Therefore, such transformers in service are not as silent as they are in the test lab where no DC is present. This presents a significant problem for customers that have ordered 'low-noise' transformers.

Gathered data illustrates that the DC Compensation system, developed by Siemens AG, is able to eliminate the effects of DC on the transformer. Furthermore, the method results in the DC not being blocked but instead the resulting DC flux in the core is compensated. By doing so, adverse effects are not suffered by the grid and no-load losses, noise emissions and the reactive power consumption of the transformer are restored levels measured with no DC present.

End of text

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