Journal of Energy

VOLUME 63 | 2014

journal homepage: http://journalofenergy.com/

Helfried Passath
Siemens AG Österreich
Transformers Weiz
helfried.passath@siemens.com

Gerald Leber
Siemens AG Österreich
Transformers Weiz
gerald.leber@siemens.com

Peter Hamberger
Siemens AG Österreich
Transformers Linz
peter.hamberger@siemens.com

Florian Bachinger
Siemens AG Österreich
Transformers Linz
florian.bachinger@siemens.com

DIRECT CURRENT COMPENSATION – FIELD EXPERIENCE UNDER SERVICE CONDITIONS

SUMMARY

Modern grain oriented core steel used in power transformers has a very high magnetic conductivity. This advanced material makes the transformer susceptible even for small direct current (DC) in the power grid. Already minor DC increases the no-load noise and no-load losses of the transformer considerably. This effect is known as half-cycle saturation. In order to overcome these parasitic DC an active compensation method called “DC compensation” (DCC) was recently developed by Siemens [1].

The question about the origin of the DC is not fully answered yet. However the following sources have been already identified: power electronics, renewable power generation (wind, solar), HVDC transmission lines and DC operated railroad or subway systems. The parasitic direct currents can flow over the power lines to ground or asymmetrically in the power line phases only.

In this paper field data, a four-month DC load profile, of single-phase core type transformers, equipped with active DC compensation, are shown. The discussed unit, a bank of three single-phase autotransformers, is in service mainly exposed to DC flowing from the overhead lines through the windings to the common neutral. DC magnitude varies from 0.05 A to about 0.2 A DC per phase throughout the day. From factory tests we know that only 0.2 A DC causes a noise increase of 5.6 dB(A) compared to the noise level without any DC compensation. This might cause troubles at the substation when noise has to be below a guaranteed level.

Data analysis of the field data shows that the DC throughout the day follows a clear profile with its highest level during midnight and lunch time. This might indicate a correlation to the load and / or switching operations in the grid to adjust to the actual needed load.

However, the DC compensation equipment fully eliminates the direct flux in the core and thus the DC caused increase in noise.

Key words: Transformer – Direct current – DC bias – Saturation – Noise – No-load loss – Renewable power generation

1. INTRODUCTION

Modern power transformers use highly efficient grain oriented electrical core steel. The cores are manufactured by using most advanced core stacking techniques. These transformers are usually operated at low core flux densities and low excitation currents in order to achieve low no-load noise and no-load losses.

By using these optimization strategies excitation currents are small and therefore even small direct currents are influencing these transformers in a negative way [2]. Half cycle saturation may occur already when DC in the range of a few hundred milli-amps (mA) to a few amps (A) is applied. This results in a considerable increase of the no-load noise level and no-load losses. Reactive power consumption is increased as well. So far the origins of these small DC have not been completely investigated. However the following sources have been already identified: power electronics, renewable power generation (wind, solar), HVDC transmission lines [4] and DC operated railroad or subway systems. The direct currents may also be geo-magnetically induced (GICs). The case of GIC has been analyzed e.g. in [6], [7], [8] and [9]. The parasitic direct currents can flow between the power lines and ground or asymmetrically in the power line phases only. Three-phase three limb cores are relatively insensitive to symmetric direct currents but react strongly to DC asymmetries between the phases. This is the case for example for static VAr compensation (SVC). Transformers with high magnetic conductivity paths for zero sequence flux, like single phase and three phase five limb core transformers are most sensitive to the DC magnetization in any case.

An active compensation method was developed to overcome the problems with parasitic DC [1]. This paper shows four month of DC load field data of a bank of three single-phase autotransformers equipped with DC compensation (DCC) and gives another possible explanation of the cause of the DC.

2. INVESTIGATED TRANSFORMERS

A bank of three single phase autotransformer intertie transformers and one spare with a guaranteed noise level of 69 dB(A) with a specified DC level of 2 A per phase (table I) was delivered to a substation in the USA. All transformers have been equipped with DC compensation.

Table I – Transformer ratings

	unit	Transformer (single phase)
Rated power	MVA	134.4 / 134.4 / 44.8
Rated voltage	kV	230/√3 / 120/√3 / 13.2
Frequency	Hz	60
Core type (limbs-return limbs)		1-2

Since the transformers are single phase units, they are very sensitive to DC. Factory acceptance tests with DC in the range from 0 to 3.6 A DC have been carried out. The test setup was a back to back test configuration according figure 1. The transformers have been excited through the tertiary windings at the maximum tap position at both transformers. This setup allows injecting DC into the HV winding with an off the shelf DC source. DC was measured by current probes and shunts. The Resistor R_v is for grounding the second transformer in case of malfunctioning of the current source.

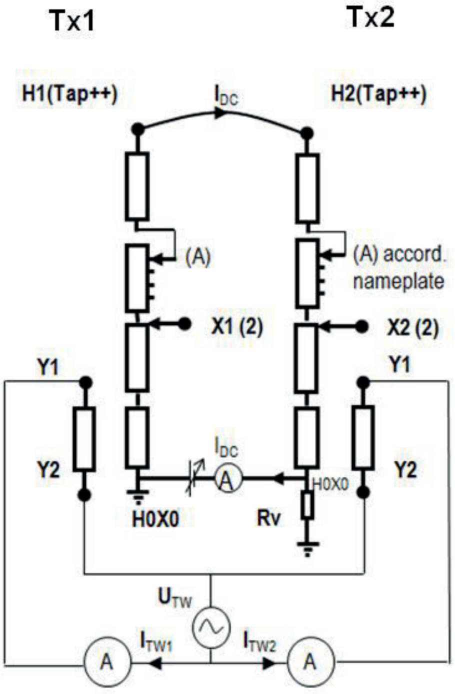

Figure 1- Back to back test setup

2.1. Effects of DC on the unit

The effects of DC on transformers are well known [2], [3] and [5]. In this paper we will focus only on the noise rise and the no-load losses rise since problems with eddy currents and therefore overheating in metallic parts nearby the core occur only at much higher DC levels like GIC.

2.1.1. No-load losses

An unwanted effect of DC is the increase of the no-load losses. For these transformers the increase was almost 30% at 2 A (DC compensation switched off) which is quite significant. The loss increase at higher DC levels flattens since the core is driven into the non-linear range of the B-H curve (figure 2).

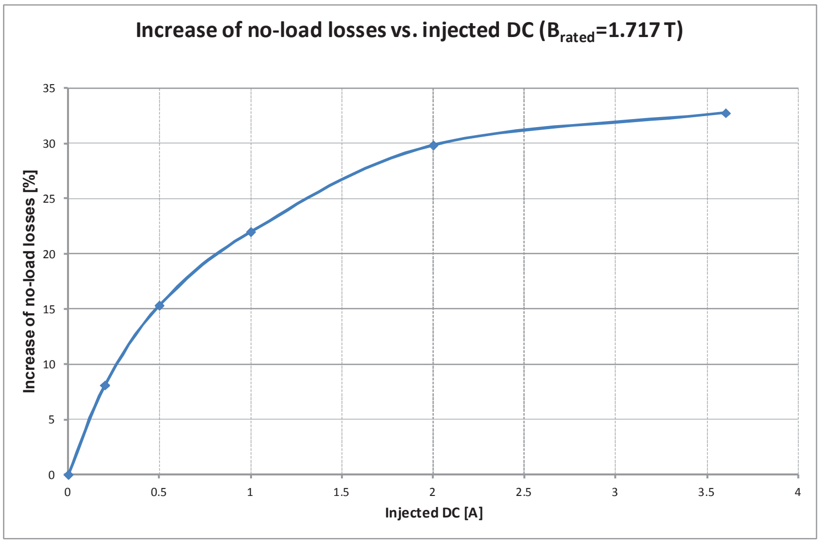

Figure 2 - Increase of no-load losses without DC compensation

2.1.2. Noise rise

In figure 3 the noise rise of the DC magnetized transformers is shown. At the specified DC level of 2 A the noise rise is more than 10 dB(A). Since the rated AC flux density of the unit is 1.717 T, the increase is lower than at transformers operated at lower AC flux density levels where the increase can be even above 20 dB(A) [3]. In figure 4 the transformer noise with DC load with and without DC compensation is shown. Without any compensation measures, the noise would be above the guaranteed level at approximately 100 mA DC. With active DC compensation the noise level is well below the guaranteed level in the entire specified DC range.

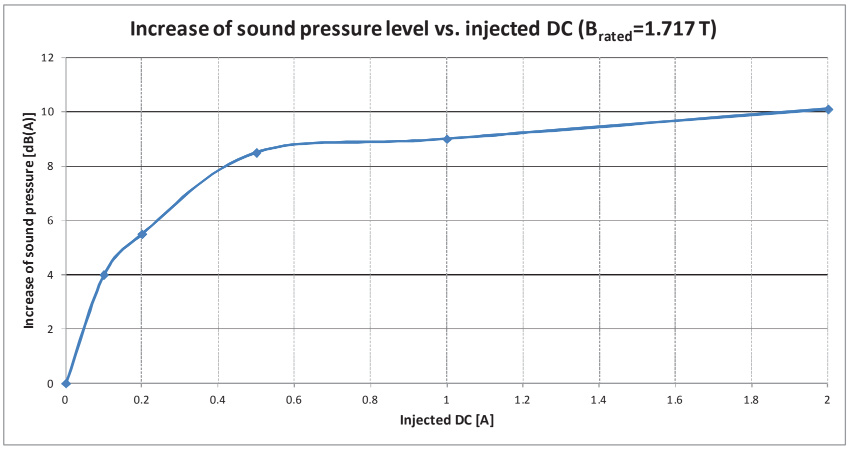

Figure 3 - Measured noise rise in relation to the injected DC

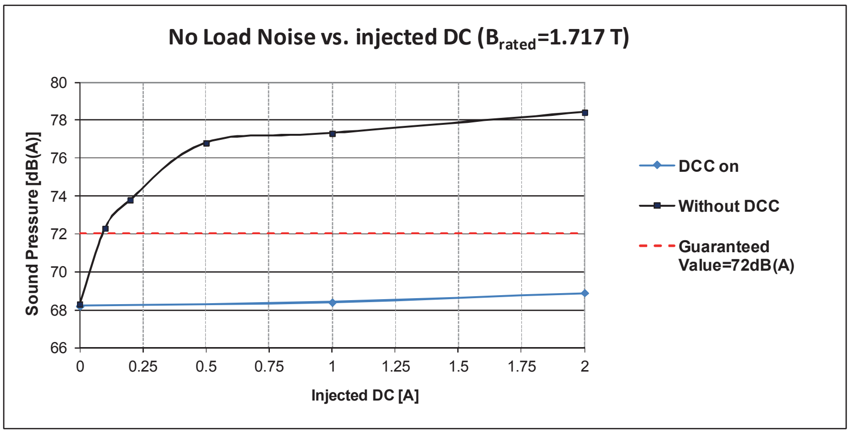

Figure 4 - Measured noise with DC and DC compensation

3. FIELD EXPERIENCE

As stated above the effects of DC on transformers are well known. So far the origin of the DC in the power grid is not fully investigated at the moment. Different sources have been identified but it is very difficult to identify the corresponding source of the DC for the considered transformers. The aim of this paper is to raise awareness of this problem at the manufacturers, customers and operators of transformers.

In this section a four month profile of the DC load of the 3 transformers equipped with DC compensation (table I) is presented. Data is available from 1st of September 2013 to the end of December 2013. In order to attenuate short spikes coming from switching operations in the grid, a moving average filter was applied to the raw data.

3.1. Analysis of field data

Figure 5 shows the (filtered) DC load from 3rd of September to the 6th of September. The shape of the profile is found in the entire four month data. The DC load is highest at around noon and higher than average in the night. In table II the average DC load in time and phases is shown. As from this table and figure 5 can be seen the DC in the transformer flows between the windings and the neutral and splits up almost symmetrically between the windings and therefore we concentrate in the following analysis on one phase (Phase A) only.

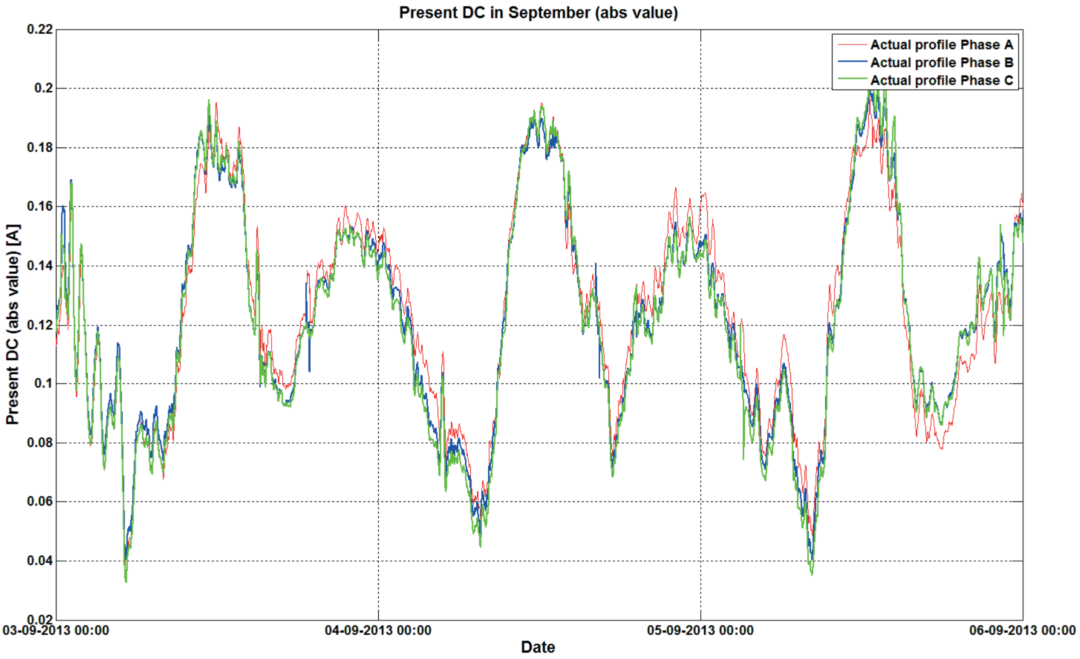

Figure 5 - Representative DC profile of September 2013

Table II – Average DC load

	unit	Phase A	Phase B	Phase C
September	A	0.123	0.12	0.119
October	A	0.118	0.118	0.118
November	A	0.113	0.112	0.115
December	A	0.095	0.103	0.105

Out of the obtained data, for each investigated month an average day profile has been calculated and correlated to the actual day profile. With this method it shall be proven that the DC in parts of the US grid and probably in the entire grid of the USA follows a clear profile which doesn't change significantly over time. The correlation was obtained by using the corrcoef function of Matlab® (MathWorks®). In order to get the quality of the correlation the coefficient of determination was calculated. This coefficient can be easily determined by the square of the correlation coefficient (R) and is called R^2 and is in the range between 0 and 1. Although different limits for this value are given in the literature, a value above 0.4 or better 0.5 should be taken into account. When the value of R^2 is 1, the data (in this case the average DC profile) fits perfectly with the actual DC profile. As a second test the hypothesis of no correlation was checked and was in all cases well below the 0.05 significance level.

Figures 6-11 show the coefficient of determination as described above. Unfortunately some days are missing due to problems with the remote data transmission system. For several periods this coefficient is above 0.4 which states that the actual daily profile doesn't change a lot in comparison to the average profile. In periods with low correlation it might be interesting to check the GIC activity and or load conditions since these artifacts have a duration of several minutes up to a couple of hours. The periods of poor correlation also indicate the difficulty in determining all the sources of the parasitic DC.

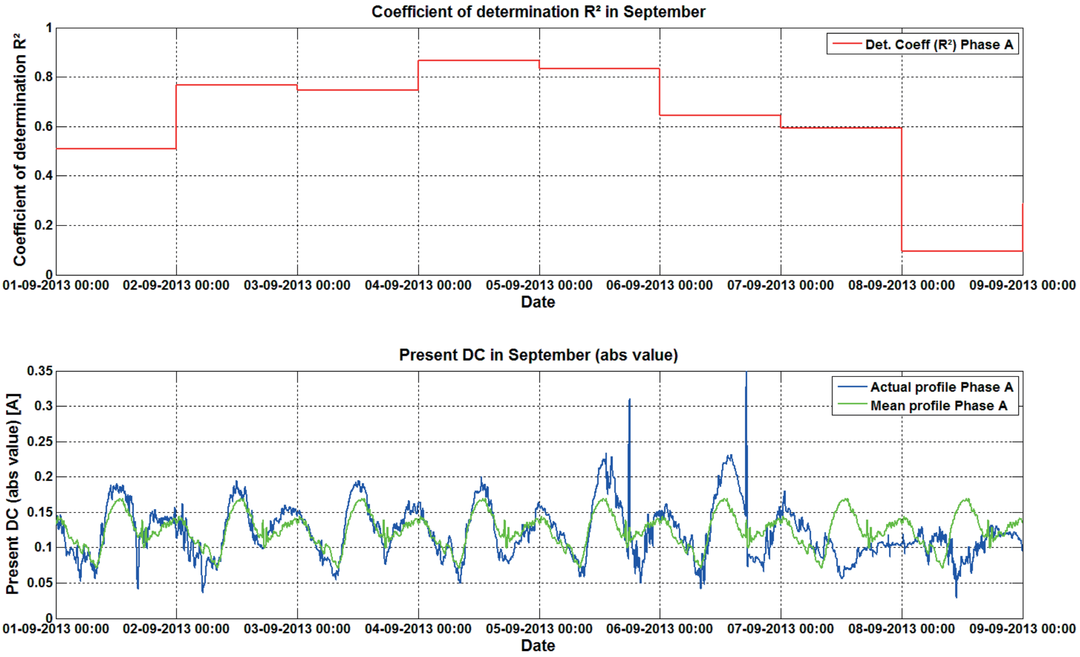

Figure 6 - Coefficient of determination and DC Profiles for September (Part 1)

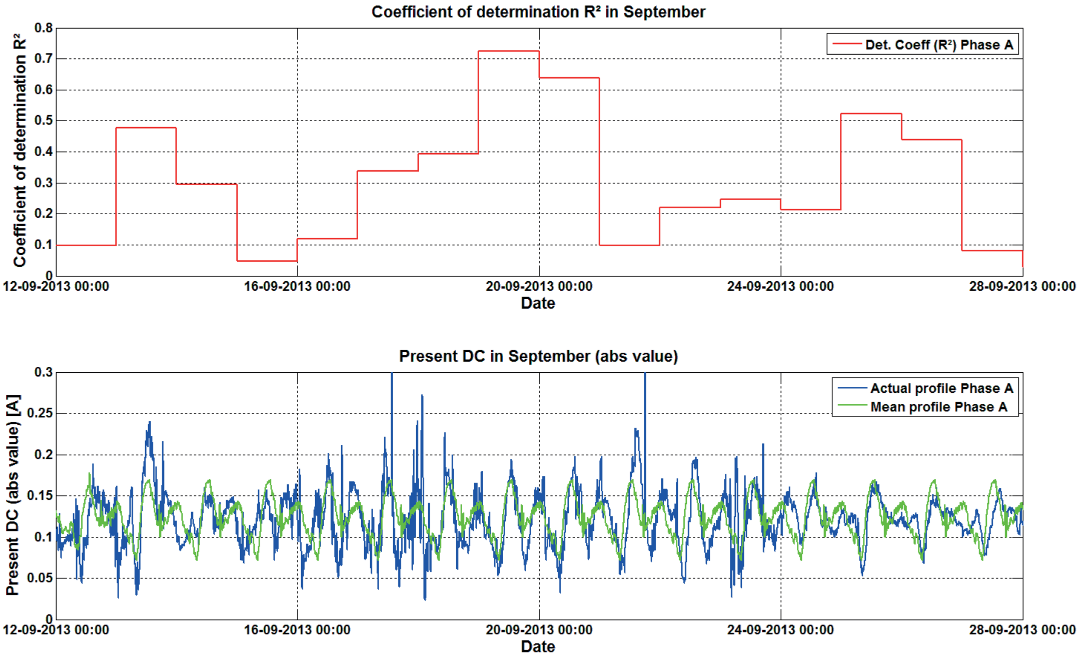

Figure 7 - Coefficient of determination and DC Profiles for September (Part 2)

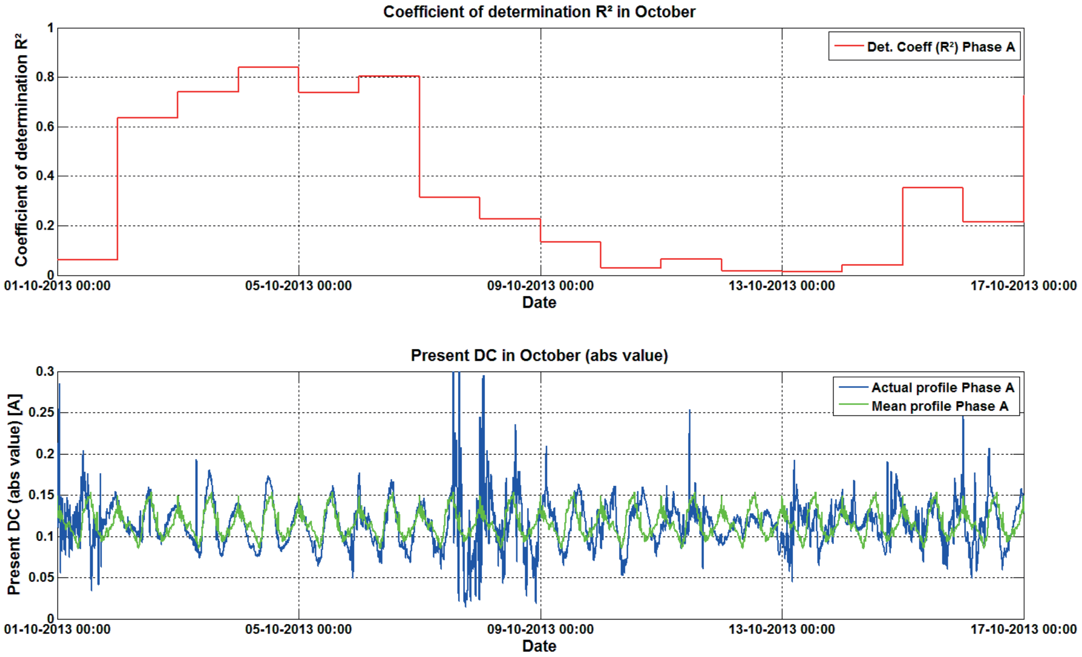

Figure 8 - Coefficient of determination and DC Profiles for October (Part 1)

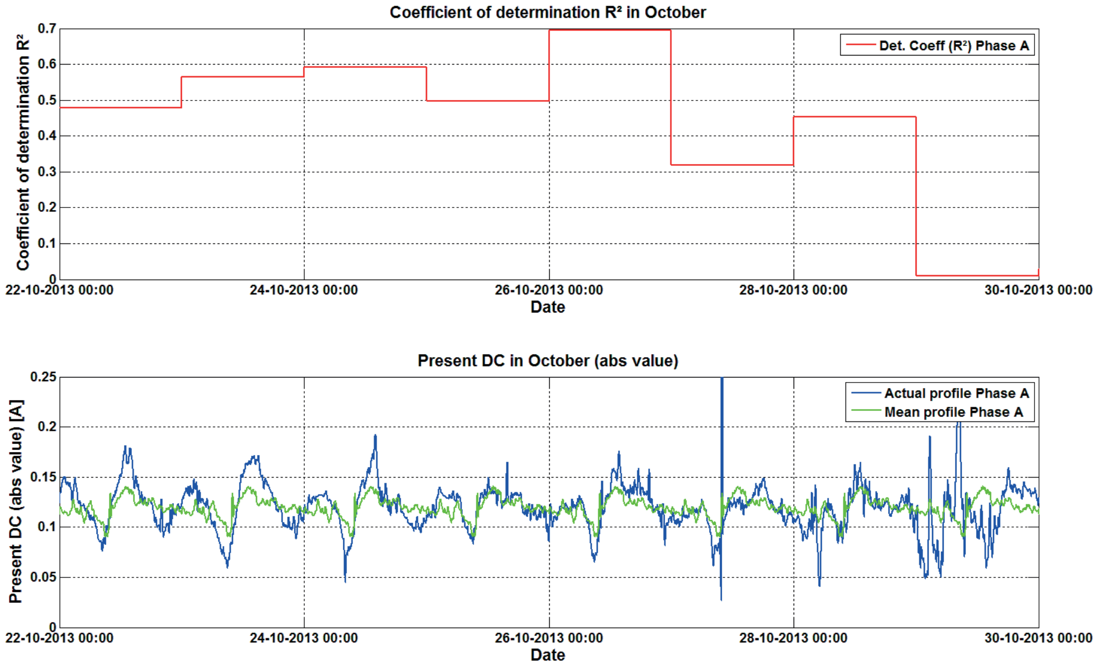

Figure 9 - Coefficient of determination and DC Profiles for October (Part 2)

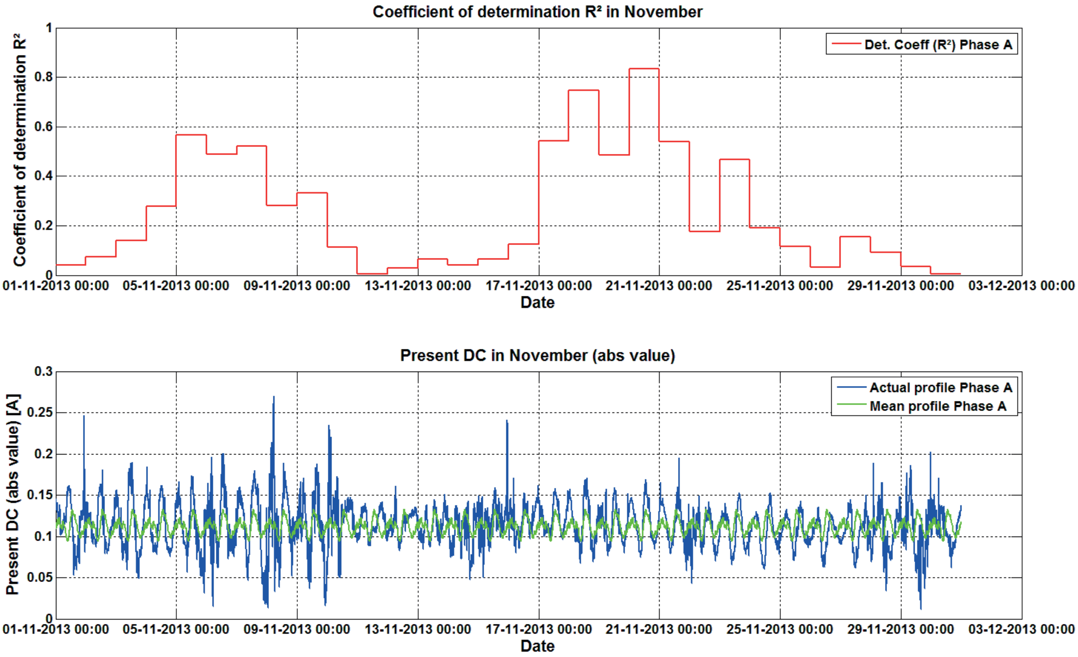

Figure 10 - Coefficient of determination and DC Profiles for November

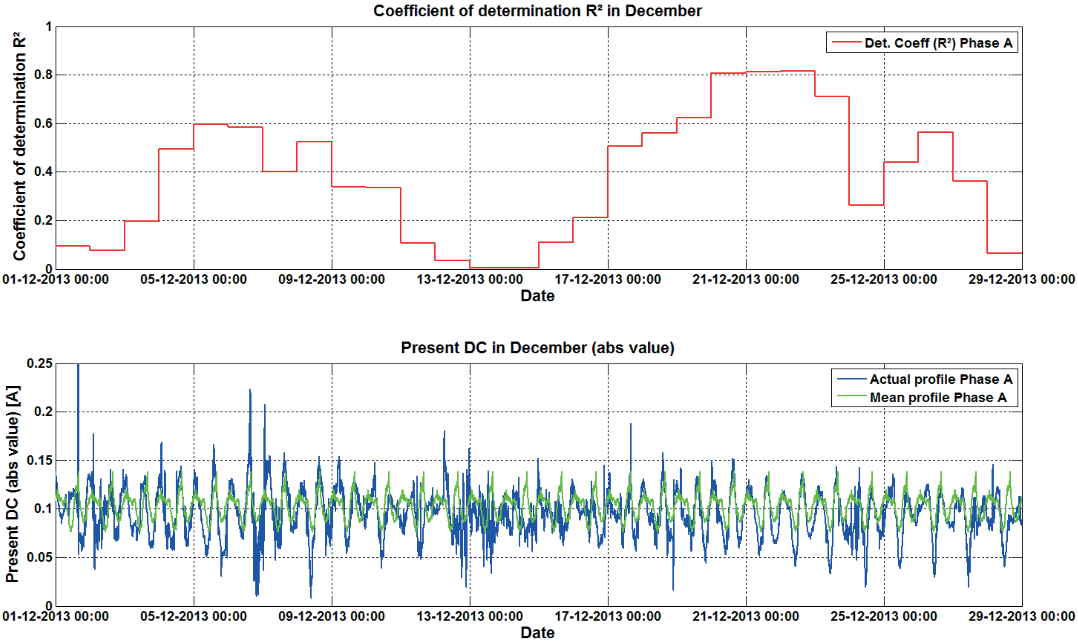

Figure 11- Coefficient of determination and DC Profiles for December

In figures 12 and 13 we compare DC profiles for July 2012 and September 2013. It can be seen that the DC load profile is quite the same although a year is between them and the shown profile of 2013 is an average one. The correlation shows a R² of 0.63 which is quite good.

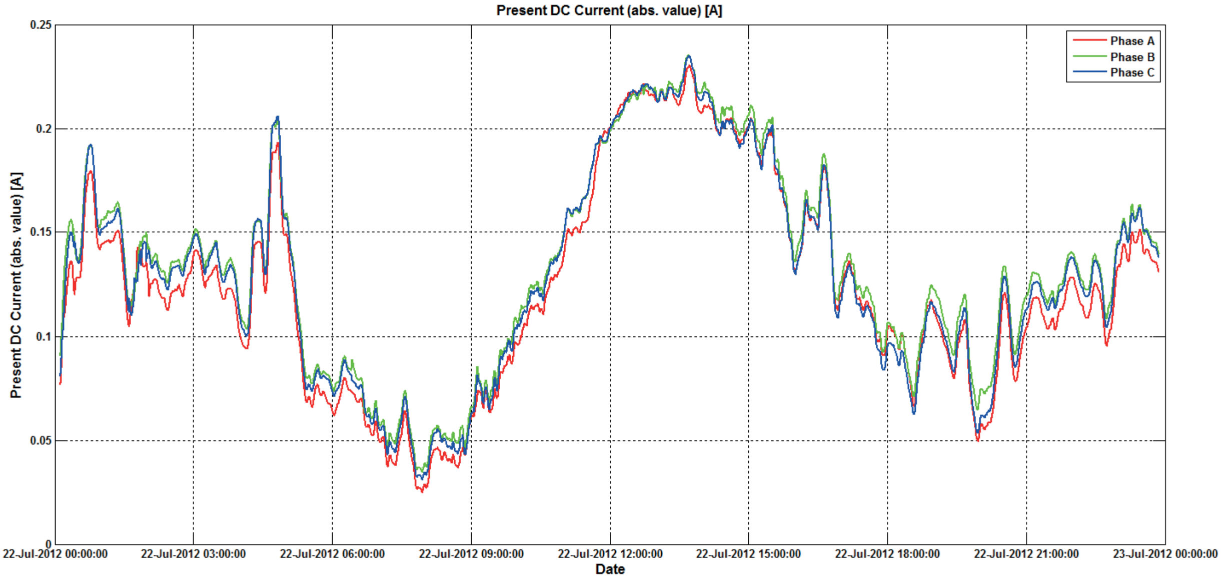

Figure 12 - DC profile of the 22nd July 2012

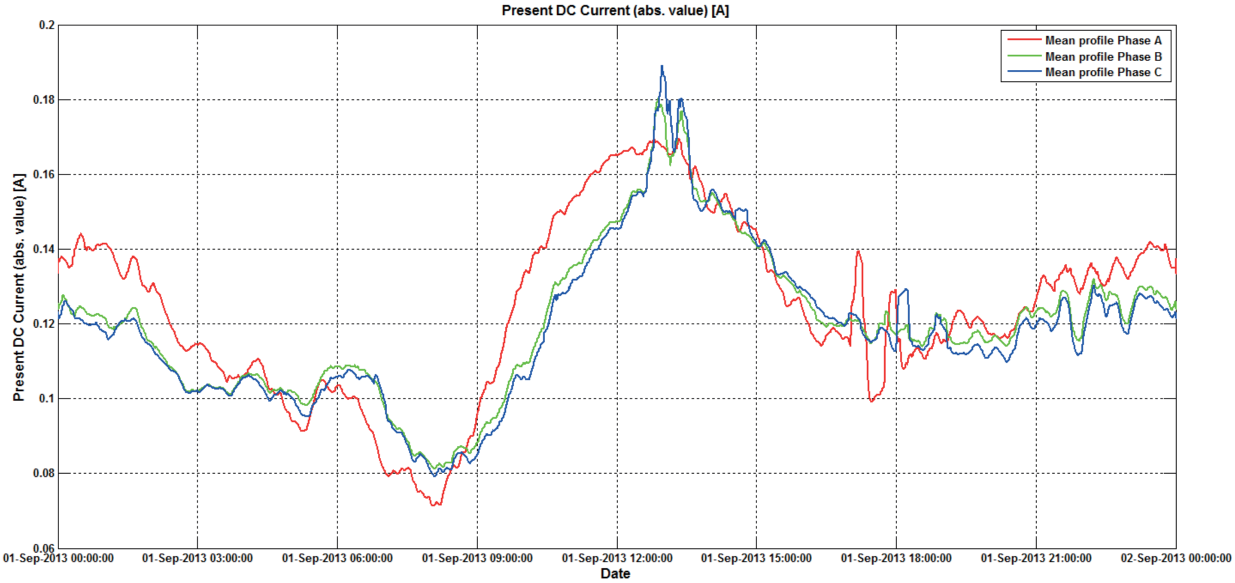

Figure 13 - Average DC profile of the first part of September 2013 data

4. CONCLUSION

Direct current was measured in an US power grid. The DC followed a clear profile as shown in figure 6-11. Due to this profile it might have a correlation to the load and or adjustments to the load (switching operations in the grid) .The DC was in average smaller in December than in September which might be as well an indication that the load has an influence on the DC since there might be for example less air-conditioning in use in the winter season.

The DC was mainly in the range from 0.05 to 0.2 A per phase which is the same range measured a year before. The shape of the profile didn't change as well (figure 12 and 13). According figure 4, without DC compensation the transformers noise would have been almost the entire four month period above the guaranteed noise level.

The coefficient of determination shows clearly that the followed profile doesn't change its shape significantly over time. Some poor correlation was found when artifacts are in the actual profile. Better correlation might have been achieved by a segmentation of the data for calculation of the average profile. However, beside the correlation, it can be seen that there is a good relationship between the average and actual day profile. It must be pointed out that these artifacts are probably caused by other unidentified DC sources that do not behave in a periodic way.

Customer should take the DC phenomenon in AC grids into account. No-load noise and no-load losses are increased. With the DC compensation equipment, the noise can be kept at the original level without DC and the increase of the no-load losses is not significant.

As a next step measurements in the European grid will be performed. If the profile in Europe follows more or less the same profile it would be another indication that the DC is correlated to the load. The renewable power generation shall also be considered when analyzing the DC since there are some indications that at some locations the wind power generation is responsible as well for the DC. So far as the DC cannot be turned off, countermeasures have to be considered when operating parasitic DC affected transformers.

5. REFERENCES

[1] F. Bachinger, A. Hackl, P. Hamberger, A. Leikermoser, G. Leber, H. Passath, M. Stoessl, "Direct current - effects and compensation", Proceedings of the CIGRE Session 2012 (Paris), no. A2-301(2012).

[2] H. Inoue, S. Okabe, "Magnetic properties of grain oriented electrical steel in model transformer", Journal of Applied Physics 115, 17A332 (2014); doi: 10.1063/1.4866846

[3] F. Bachinger, P. Hamberger, A. Leikermoser, G. Leber, H. Passath, "Direct current in transformers - experience, compensation", Paper PS1-34, CIGRE SC A2 & C4 JOINT COLLOQUIUM 2013 Zurich, Switzerland

[4] G. Mei, Y. Sun, Y. Liu. "Simulation on DC current distribution in AC power grid under HVDC ground-return-mode" (Journal of Electromagnetics Analysis and Applications, vol. 2, no. 7, 2010, p. 418 – 423).

[5] H. Pfützner, G. Shilyashki, F. Hofbauer, D. Sabic, E. Mulasalihovic, V. Galabov. "Effects of DC-bias on the loss distribution of a model transformer core" (Journal of Electrical Engineering, vol. 61, no. 7/s, 2010, p. 126 – 129).

[6] M.A.S. Masoum, P.S. Moses. "Influence of geomagnetically induced currents on three-phase power transformers" (Proceedings of the Australasian Universities Power Engineering Conference AUPEC 2008).

[7] P.R. Price. "Geomagnetically induced current effects on transformers" (IEEE Transactions on Power Delivery, vol. 17, 2002, p. 1002 – 1008).

[8] X. Dong, Y. Liu, J.G. Kappenman. "Comparative analysis of exciting current harmonics and reactive power consumption from GIC saturated transformers" (Proceedings of the IEEE Power Engineering Society Winter Conference 2011, p. 318 – 322).

[9] J. Kappenman. "Geomagnetic storms and their impacts on the U.S. power grid" (Meta-R-319, Metatech Corporation January 2010).