GALVANIC COUPLING OF DIRECT CURRENTS IN TRANSMISSION GRIDS AND ITS EFFECTS ON POWER TRANSFORMERS

Michael Beltle[1*], Michael Schühle[1] and Stefan Tenbohlen[1]
[1]University of Stuttgart, Pfaffenwaldring 47 D-70569 Stuttgart, Germany
*Email: michael.beltle@ieh.uni-stuttgart.de

Abstract: Different stress factors impact power transformers during service. In most cases, the effects of additional direct current (DC) components are not taken into consideration. Nevertheless, this contribution considers DC or quasi-DC components which occur in the German transmission grid (400 kV level). Current measurements are therefore performed at several grounded star points of grid coupling power transformers using a customized current monitoring system. At a first glance, DC levels in the range of several Amperes can be observed. The subsequent detailed analysis allows discriminating different superimposing DC sources contributing to star points' direct currents. The correlation of current measurements at different locations with the actual grid topology and switching operations enables the identification and localization of different sources. Additional comparisons to temporal changes within the earth's magnetic field provide information about the impact of geomagnetically induced currents (GIC).

The effects of observed direct currents on power transformers are determined by an evaluation of mechanical oscillations of affected transformers. The effects are linked to the transformer's magnetic equivalent circuit and derived from half wave saturation effects of the magnetic hysteresis loop. A large-scaled laboratory setup which consists of two connected 380 kV / 110 kV, 350 MVA 5-limb power transformers is used to emulate DC effects and mechanical oscillations. Comparisons to field measurements are used to verify the model theory and the setup. In this context, the ability of low cost vibration measurement systems to detect direct currents in power transformers is also evaluated.

1 INTRODUCTION

In most cases the influence of direct currents (DC) on power transformers is not an issue during normal grid operation. Nevertheless, there have been investigations since the early forties of the last century [1] and in recent years [2], [3]. As literature shows, direct currents effect power transformers by changing the magnetic operational point (see chapter 1.1) which causes saturation effects in the magnetic core. Thereby, additional harmonic currents can be created. Hence, DC can also influence the entire power grid. In many investigations, geomagnetically induced currents (GIC) represent the dominant DC source [4]. GIC occur on in transmission grids in Central Europe mostly on a small scale [5]. Such temporary natural sources can be superimposed by constant man-made sources. In the current scenario, a new 350 MVA grid coupling power transformer (5-limb, 380 kV/ 110 kV) was showing unusual noise emissions after its start of operation. Therefore, star point currents of the asset were measured and revealed a DC component in the range of I_{DC} = 1 A. As an interim solution the transformer's star point was disconnected from ground. This does not represent a general solution for the entire grid. In order to provide a detailed analysis of the DC components, its origins and the resulting effects are considered in the following.

1.1 Magnetic effects in the transformer's core

If a DC component I_{DC} is injected into a coil Ampere's Law causes a direct magnetic force Θ_{DC}. Due to the dependency of the magnetic field on Θ (and the number of windings n) Θ_{DC} leads to a shift of the working point within the magnetic characteristic curve (B-H curve) and a constant magnetic flux ϕ_{DC} is generated. If an alternating voltage is superimposed additionally, the resulting alternating magnetic flux ϕ_{AC} superimposes ϕ_{DC}, see Figure 1 (left plot). If the coil is winded around a ferromagnetic core, saturation will occur at a certain magnetic flux density because the Weiss' Domains will be orientated along the external field, see the knee point in the characteristic magnetising curve at Figure 1 (right plot). During saturation the core material is ineffective and the inductivity of the setup is reduced to an air coil. Hence, the AC currents will increase quickly as soon as saturation is reached; see Figure 1 (lower plot). This DC driven effect only occurs in one of the period's half wave and is therefore known as half-wave-saturation. The core is the main cost driver in a transformer, core geometries are usually chosen which minimize the required material. Hence, the magnetic nominal flux density will be close to the knee point and already small DC components in the range of $I_{DC} \geq 100$ mA can be sufficient to cause saturation effects.

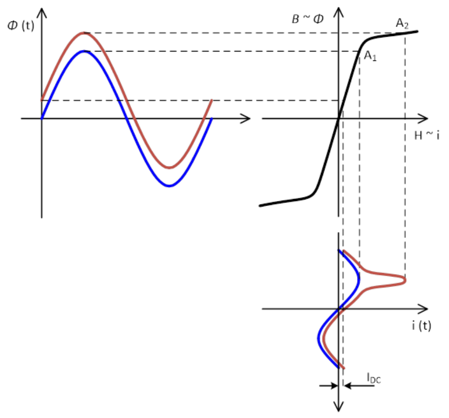

Figure 1: Magnetic core behavior during AC condition with superimposed DC

2 MEASUREMENT EQUIPMENT

2.1 Measurement of star point currents

Currents in grounded star points are measured using a custom made monitoring system. The measurement unit is connected to the star point outlet of the transformer using a manual grounding rod. The second connector of the system is attached to earth, see Figure 2.

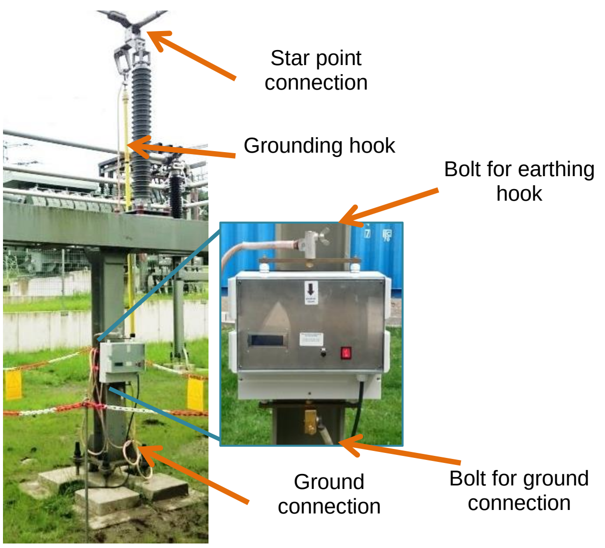

Figure 2: Current measurement at a grid coupling transformer star point

The system is installed when the automatic star point grounding system is still inserted which allows the application at online power transformers. After installation the automatic star point grounding is opened and all star point currents commutate to the measurement path of the monitoring system. Diameters of all conductors are dimensioned in order to withstand short circuit currents (15 kA). The system uses closed-loop hall effect current sensors being able to measure current (AC and DC) in the range of ± 20 A. Signals can be recorded continuously or using predefined measurement intervals with a sample rate up to 1 MSample / sec. In most cases a direct access to the system in service is not allowed due to security policies. Thus, a remote WLAN access is implemented providing data access and remote service from a safe distance.

2.2 Measurement of mechanical oscillations and influences of direct currents

In order to measure mechanical vibrations of power transformers accelerometers are installed on the tank surface. This method is suited for field measurements as well as for laboratory setups. The used sensors measure the orthogonal force of the tank wall movement. The time domain signals are converted into frequency domain using Fast Fourier Transformation (FFT). Two exemplary frequency spectrums are shown in Figure 3. The black plot is a reference measurement of mechanical oscillations at no-load condition without superimposed DC components. The spectrum is characteristic for transformers and consists of the basic mechanic frequency, in this case f_{mech} = 100 Hz and its harmonics. The basic mechanic frequency is always the doubled frequency of the applied voltage source due to magnetostriction [6]. The orange spectrum is caused by a superimposed DC current which impacts the operation of the magnetic core material. In the mechanical spectrum additional frequencies are added: the lowest mechanical frequency now is equal to the electric frequency (here f_{mech} = 50 Hz). Also, harmonics of the new frequency occur in the spectrum. This effect can be observed at both, 3-limb and 5-limb transformers. In general, 5-limb transformers are more susceptible if DC components are distributed symmetrically of all three phases [6]. Assuming the ohmic components of transformer windings and line phases are roughly comparable, a symmetric DC distribution is the most likely case. All transformers considered in the following field measurements are 5-limb transformers. Therefore, it is likely for all occurring DC components to have a high effect on these grid coupling power transformers.

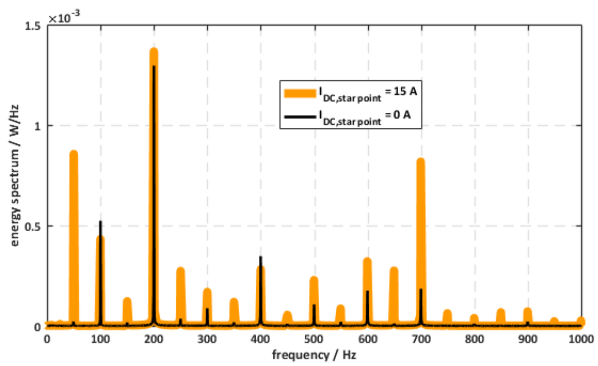

Figure 3: Comparison between mechanical oscillations at no-load (reference in black) and with superimposed $I_{DC,\ star\ point}$ = 15 A. (orange)

3 FIELD MEASUREMENTS

3.1 Long-term multi spot measurements

Three of the measurement systems introduced in chapter 2.1 are installed at distributed, grounded star points of grid coupling transformers. All measurement locations lie within the same grid area; they are connected by overhead lines in a series connection, where star point 1 is in between star points 2 and 3 (line distance from 1 to 2 is 60 km, and from 1 to 3 is 46 km). Figure 4 shows the daily trend of DC components of each star-point during 30 days of continuous measurement as well as the average curve of all 30 days. All measured DC components are negative, which means that the DC is flowing from ground into the star point through the transformer into the transmission lines. Hence, the point where the DC leaves the transmission grid is not captured in this field measurement.

3.2 Average DC behavior

The average daily trends of star points 1 and 2 in Figure 4 show opposing behavior because DC components commutate between them. There is no comparable interaction to star point 3 despite its closer to star point 1. Star point 3 also shows a slight oscillation with a 30 minute period which cannot be observed at the other measurements. This is an indication that several different decoupled sources could be active in the area. The high average currents at star points 1 and 2 indicate the main cause of DC and could be a continuously active industrial source, e.g. a cathodic corrosion protection system. The potential difference between the sacrificial anode and the protected structure causes a DC. Depending on the given parameters like ohmic ground resistances this DC can partly run through parallel paths given by the local transmission grid.

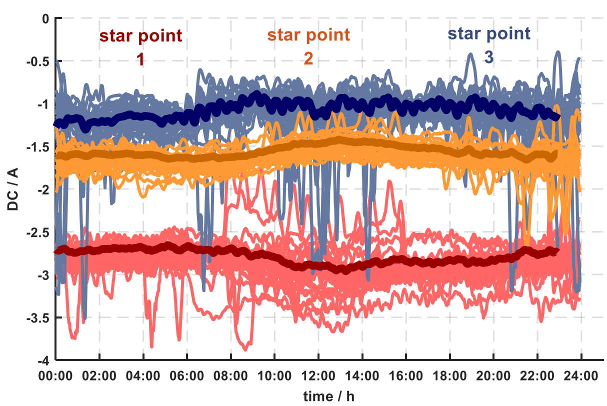

Figure 4: DC components at three different locations at 30 consecutive days. Thick lines represent the average intraday current of each star point.

Assuming that the path with the lowest ohmic resistance provides the highest current and is nearest to the source, star point 1 would be closest to the source. A detailed evaluation of this assumption is provided in chapter 3.4.

3.3 Transient DC behavior

Permanent DC components are occasionally superimposed by short-time changes. Figure 5 (upper plot) shows an exemplary DC change within less than an hour which occurred several times within the considered 30 days. In many cases, this behavior can be linked to previously discussed geomagnetically induced currents. In order to evaluate this thesis, the observed short-time DC changes are correlated with changes of the earth's magnetic field in this area. Therefore, data is used from the Intermagnet project [7] which provides magnetic field data from observatories all around the world.
Events within the 30 days period are taken into account if one component of the earth's magnetic field density changes at least about ΔB_{min}> 50 nT. 11 events can be identified. Figure 5 shows one of these events. The DC in star point 3 temporarily increases about ΔI_{DC} = 2.5 A. Also the other star points are impacted but with smaller amplitudes (ΔI_{DC} ≈ 0.5 A). All events result in comparable DC trends. The individual effect on single star points depends on the changes of the individual magnetic field components, their orientation relative to the induction loops provided by the overhead lines and the ohmic resistance of the ground in the area [5]. In conclusion, most transient events of this field test with significant changes of the DC component (ΔI_{DC} > 0.5 A) can be linked to GIC. However, all recorded transient sources represent a minor compared to the averaged DC effect. The stable sources contributing to the average DC behavior will be identified and localized in the next chapter.

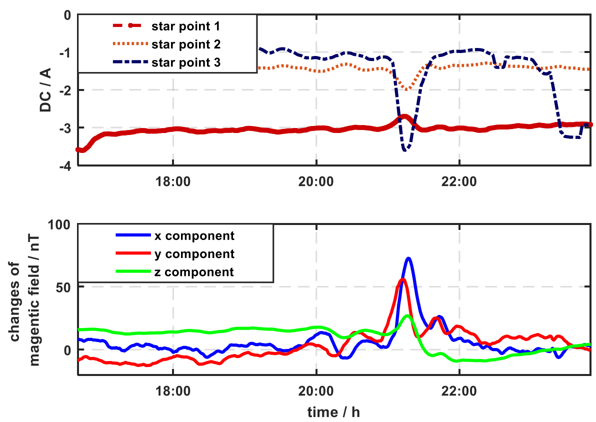

Figure 5: Geomagnetic influences
upper plot: direct current in 3 star points
lower plot: alternating components of earth's magnetic field vector.

3.4 Source Identification

This chapter considers sources of statistical importance. As deducted in chapter 3.2, one main source is likely to be near star point 1. In order to support this thesis by measurements, the interconnections between star points are now alternated by different switching operations. In particular, the direct connection between star points 1 and 3 are opened and closed several times over a period of 9 days. Figure 6 shows the resulting DC distribution. Every time the interconnection is open the DC at star point 3 decreases to approx. zero. At the same time a comparable amount of current commutates to star point 1 which supports the thesis that the main source is nearby star point 1: the source injects DC into the earth. The return path is provided partly by the transmission grid. If star point 3 is disconnected, currents rise in the remaining part of the current divider circuit, which is provided by star point 1.

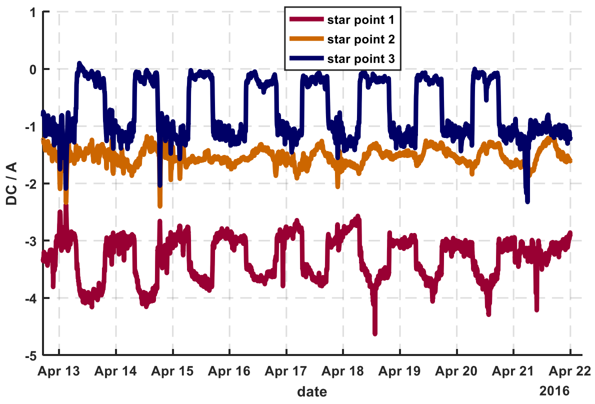

Figure 6: Direct currents at switching operations of the transmission line between star points 1 and 3

A survey of different nearby industrial facilities reveals a local cathodic corrosion protection system of a power plant. The system uses depth electrodes (anodes are drilled about 100 m into the ground). Due to the size of the system the injected DC into ground is about I_{DC} = 300 A (continuously). Hence, a widespread distribution of DC through the depth electrodes is possible. For a short-time test the corrosion protection can be switched off. Figure 7 shows the DC components of star point 1 and 2 during this test (The line to star point 3 is open and DC is approx. zero). The absolute DC component at both star points is minimized when the corrosion protection is deactivated (Mai, 20th 10:30 h until 11:15 h). Remaining DC components are I_{DC} = 300 mA (star point 1) and I_{DC} = 450 mA (star point 2). After the protection system is back in service the DC components at both star points reach the same levels as before the test. Therefore, the assumption can be made that the main source contributing high, permanent DC to the local grid is the identified corrosion protection system. As DC components do not vanish completely during the test, the presence of additional superimposing sources is very likely. Further investigations will show if other corrosion protection systems installed in the same area do contribute to DC components in the transmission grid.

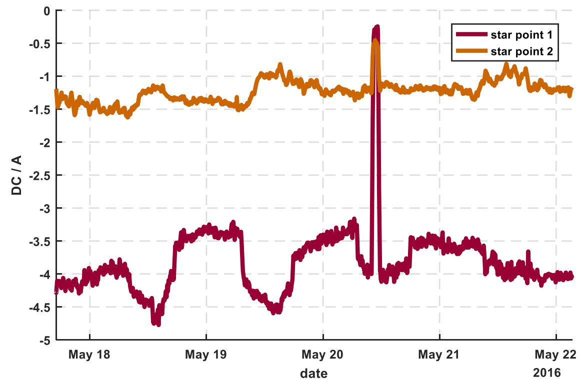

Figure 7: Direct current components during short time deactivation of a cathodic corrosion protection system.

3.5 Mechanical Oscillations

The mechanical oscillations of one of the affected transformers are recorded and correlated over time with the star points DC components. For a short-time test different configurations are tested. At first, the star point is not connected to ground. Hence, no DC flows through the transformer and recorded mechanical oscillations can be used as no-DC reference. Figure 8 (lower plot) shows the DC trend for this test. After 1 Minute the star point is closed and DC continuously rises. Additionally, two DC steps at 12.25 h and 13.30 h occur. At 12.25 h the star point of another (not monitored) 380 kV grid coupling transformer star point is disconnected from ground (distance approx. 10 km). DC commutates to the surveyed star point and DC increases about ΔI_{DC} = 250 mA.

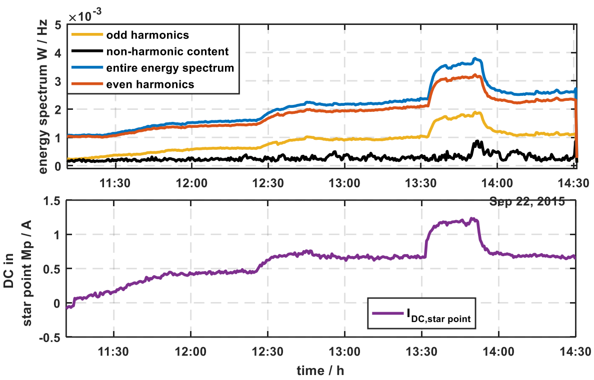

Figure 8: upper plot: harmonic components of mechanical oscillations
lower plot: star point DC $I_{DC,\ star\ point}$ (absolute values)

At 13.30 h the star point of a step-up generator unit (distance approx. 2 km) is disconnected from ground. Currents commutate again to this star point increasing DC by ΔI_{DC} = 500 mA. After 20 minutes the star point is reconnected and DC commutates back to the step-up unit.
The upper plot of Figure 8 shows the levels of the mechanical oscillations. The signal power density of odd harmonics (50 Hz, 150 Hz, etc.) can be correlated with the DC over time. At the beginning of the test DC is zero and so are odd harmonics (in the same range as noise, only about 3% of entire signal power density). By rising DC, both odd and even harmonics rise. In general, the mechanic oscillations follow the DC curve. Especially the DC steps are also detectable within the oscillations. At the DC peak, odd harmonics contribute about 25% to the entire signal power density. Using odd harmonics is advantageous because these oscillations do not occur at normal transformer operations but are especially caused by DC. Even harmonics are less selective and can be influenced by other parameters, mainly the transit power and the oil temperature of the transformer. In conclusion, it is possible to use odd harmonics of mechanical oscillations as DC detector. This might be a suited alternative method, if the direct measurement of star point currents is not possible.

4 LARGE SCALED LABORATORY SETUP

The effects observed in field measurements are reproduced under controlled laboratory conditions. Therefore, a test setup consisting of two identical 350 MVA grid coupling transformers (5-limbs, 380 kV) is used. The transformers are of a similar design compared to those from the field. Both are connected in a back-to-back circuit, meaning their primary 380 kV phases are connected, see Figure 9. Hence, it is possible to drive a DC current through their primary star points without the issue of high potentials. One of the transformers is connected to a 3 phase voltage source on its secondary or tertiary winding. Both secondary windings are left open, so the entire setup operates in no load conditions.

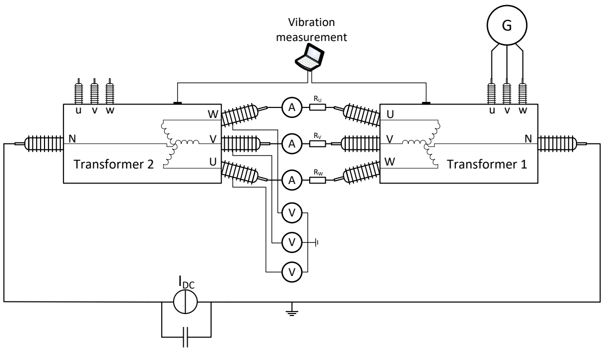

Figure 9: Laboratory setup using to 380 MVA grid coupling transformers in back-to-back connection

The voltage source provides the power to energize both transformers (only no-load losses have to be provided). All currents and voltages are measured (low and high voltage side) which provides information about the saturation effects. The high currents during saturation can be of interest in terms of grid stability because harmonic components of the reactive or non-active power [8] have to be provided in order to maintain the nominal voltage [9].

4.1 Mechanical oscillations during DC superimposition

Mechanical oscillations are measured on both tank walls similarly to the onsite measurements. Thus, the field test form chapter 3.5 can be evaluated using the lab setup. Figure 10 shows the rise of mechanical oscillations separated into odd (50 Hz, 150 Hz, etc) and even harmonics (100 Hz, 200 Hz, etc.) at rising DC in the test setup. Both components are increased constantly with rising DC until a knee point is reached with approx. 10 dB / A_{DC}. Hence, even very small DC components lead to a significant rise of mechanical oscillations. At even DC levels above the knee point only the even harmonics show further gain but with lower gradient, odd harmonics stagnate. Reasons to this particular behavior are part of current research.
In general, the reproducible gain of odd harmonics can be used as indicator for the presence of DC components in power transformers because they are exclusively caused by DC driven half wave saturation. The gain of even harmonics (usual mechanic oscillations and transformer noises) is not suited for this correlation because other influences superimpose with DC, e.g. load conditions and temperature.

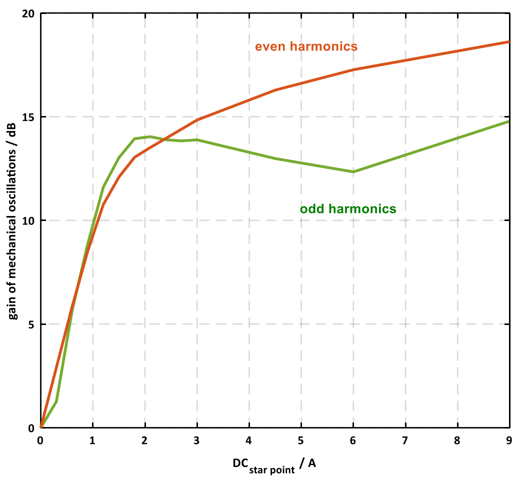

Figure 10: Gain of mechanical oscillations at rising DC separated into even and odd harmonic content. (Relative gain with reference to no-load / no DC condition)

5 CONCLUSION

The presented long-term measurements allow the discrimination of different DC sources impacting grid coupling power transformers in the transmission grid. DC can either be measured directly using current monitoring in the star point of affected transformers or indirectly by measuring mechanical oscillations on the tank wall. The indirect method is more easily to apply and cheaper which enables a quick check of an entire transformer fleet for DC. The causing DC components can be derived from oscillations measurements if the transformers behavior under DC is known either by laboratory measurements or by simulations in the future. .

In the actual field measurements two different type of DC sources can be distinguished. Geomagnetically induced currents (GIC) cause short- time (quasi) DC components in the range of several amperes. These events last for several hours. . These effects can be identified by correlating data from the earth's magnetic field with current measurements.

Industrial sources can cause a constant DC (with some fluctuations). Distributed synchronous measurements ideally combined with switching operations in the affected grid area allow a rough localisation of potential sources because star points close to the sources show highest DC in the field test. In the actual case a cathodic corrosion protection system can be identified as the main source for constant DC components.

An effective countermeasure in order to minimize the effect of DC on power transformers (considering non-active power consumption and mechanical oscillations / noise) is to disconnect their star points from ground. In general, this is not always possible. It depends on the short circuit treatment of the transmission grid. Future approaches, which are currently evaluated, consider capacitive (DC-block) groundings of star points.

References

[1] W.F. Davidson, „Einwirkungen des magnetischen Sturmes vom 24. März 1940 auf Hochspannungsanlagen," *Elektrotechnische Zeitschrift,* Bd. 5, pp. 99-100, 30. Januar 1941.

[2] Saifur Rahman et al, IEEE Electrification Magazine Solar Storms and Power Grids, New York: IEEE, 2015.

[3] M. Beltle, M. Schuehle, S. Tenbohlen, „Influences of direct currents on power transformers caused by AC-HVDC interactions in hybrid grids," in *ISH 2015*, Pilsen, Czech Rebublic, 2015.

[4] M. Heindl. M. Beltle, M. Reuter, D.Schneider, S. Tenbohlen, D. Oyedokun. T. Gaunt, „Investigation of GIC related Effects on Power Transformers using Modern Diagnostic Methods," in *International Symposium on High Voltage Engineering*, Hannover, 2011.

[5] T. Halbedl, H. Renner, G. Achleitner, „Einfluss des Geomagnetismus auf das österreichische Hochspannungsnetz," in *VDE-ETG Schutz- und Leittechnik*, Berlin, 2016.

[6] M. Beltle, S. Tenbohlen, „ Diagnostic Interpretation of Mechanical Oscillations of Power Transformers," in *ISH*, Pilsen Czech Republic, 2015.

[7] „Intermagnet," [Online]. Available: www.intermagnet.org.

[8] IEEE Power & Energy Society - Power System Instrumentation and Measurements Committee, IEEE Standard 1459-2010: Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions, New York: IEEE, 2010.

[9] M. Beltle, M. Schühle, S. Tenbohlen und U. Sundermann, „Das Verhalten von Leistungstransformatoren bei Beanspruchung mit Gleichströmen," in *Hochspannungssymposium Stuttgart*, Stuttgart, 2016.