Geomagnetically induced currents and space weather - A review of current and future research in Austria

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***Abstract*—Conductive grounded electrical power transmission networks offer a low resistance path for currents induced in the ground. High latitude regions or those with low earth conductivity are especially affected by geomagnetically induced currents (GICs), which are caused by space weather events. Induced currents can cause damages of assets or system outages. Austria, as part of the European Alps with low conductive areas, tends to have a higher risk of induced currents in the electrical power transmission network, therefore, the effect of space weather in the power system has been investigated. Two independent models of GICs in Austria were set up and verified through comparison to ongoing transformer neutral point current measurements. Further research fields, such as space weather prediction, power transformers under dc bias and countermeasures for system operation are outlined.**

***Index Terms*—Geomagnetism, Geophysics, Monitoring, Power System Measurements, Power System Simulation**

Introduction

Space weather can influence technological infrastructure on Earth. Geomagnetic variations of the magnetic field can cause currents induced at the Earth's surface. Conductive grounded connected infrastructure with a geographically wide extension, such as the electrical power transmission network, offer low resistivity paths for induced currents, leading to outages or damages in the network [1], [2].

To better understand the effects in the power transmission network, simulation and measurements have been performed in Austria as well as other countries. Geographical areas with low earth conductivity, such as the European Alps, tend to have a higher risk of significant currents from space weather, which enter the technological infrastructure systems [3]. Therefore, research in the field of GICs is also carried out in Austria and other lower latitude countries [4].

In the TU Graz and ZAMG (Zentralanstalt fuer Meteorologie und Geodynamik), two independent GIC simulation models were set up and compared with transformer neutral current measurements in the Austrian power transmission network. Induced currents up to 15 A could be measured and simulated. This paper summarises the research conducted in Austria until today and outlines the questions and research fields for tomorrow.

Space Weather

A. Magnetosphere and earth magnetic field

The Earth's magnetic field is formed by an inner and outer magnetic field. The inner part is formed by the Earth's core while the outer magnetic field is influenced by space weather, which describes the effect from space at the Earth near region. The outer magnetic field dominates the magnetosphere, which can reach out into space from approximately ten times to hundred times the earth radius. In the Earth's magnetosphere, multiple current systems interact and form the outer magnetic earth field. Even up till today, the overall current system is not fully understood [5]. Fig. 1 depicts the current system dominating in the polar regions of the Earth.

The Birkeland currents in region 1 and 2 in Fig. 1 are between the north and south pole and are connected via the Pedersen currents. The Pedersen currents drive the Hall currents, due to the Hall effect [6]. The Birkeland currents also form the Van Allen belt, which surrounds the earth. In the equatorial region of the Van Allen belt, the ring current flows in east-to-west direction. This ring current leads to the largest geomagnetic effects in mid-latitude regions such as Austria. The various current systems are constantly affected by the solar wind originating from the sun. A low energetic solar wind causes little current variations in amplitude over time. Solar ejections with a great amount of energy from the outer region are called solar storms or coronal mass ejections - CMEs. It is suspected that CMEs are due to magnetic reconnections of the Sun's magnetic field lines. These CMEs can reach Earth orbit distance in one to three days and can cause current variations and subsequently geomagnetic disturbances, GMD. The CME occurrence correlates with the solar maxima, which last from two to four years during the magnetic pole reversal of the sun,

978-1-7281-3349-2 /19/$31.00

every eleven years. A review of the current system in the earth magnetosphere can be found in [7].

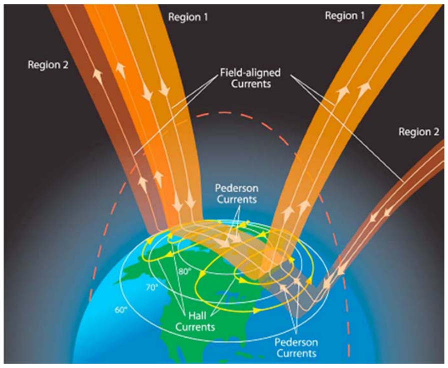

Fig. 1. Schematic of magnetospheric and ionospheric current system [5].

B. *Space weather prediction*

Due to the potentially damaging effects of space weather, the modelling and prediction of space weather phenomena has been an important issue for a long time [8]. A recent example of a larger project with this aim is the Solar Shield project [9], although there have been smaller attempts in the direction of space weather prediction and as a result GIC forecasting such as in [10] and [11]. Methods for predicting space weather at the Earth are based on two different approaches: some are based on solar images with models predicting the propagation of CMEs through the interstellar medium using physical or empirical models (allowing for predictions of hours to days), while others take solar wind measurements at the Lagrange-1 (L1) point (which has a lead time of 30 - 60 minutes). CME propagation models have a long lead time but high inaccuracy due to the turbulent nature of the solar wind, while models using L1 data have relatively good predictive abilities but a very short lead-time.

A preliminary study of event prediction was carried out for Austria in [12]. This work will be expanded on with more advanced machine learning methods as part of a project (PREDSTORM) to provide comprehensive predictions of space weather effects at the Earth. This will be done with deep learning using a recurrent neural network similar to the one described in [13] by training the network on solar wind data at the L1 point to output GICs measured in substations in Austria. In the future it will be coupled to more advanced CME propagation models to give a longer lead time.

Modelling, Simulation and Analysis of GICs

A. *Modelling and simulation approach*

Two independent models to simulate GICs in the Austrian power transmission network have been developed and investigated. The main characteristics of these models are listed in tab. I.

In the simulations, the following geophysical and engineering steps are conducted.

First. Calculate the equivalent surface impedance of the ground by considering the reflected and transmitted electromagnetic waves (in this case geomagnetic variations measured at the Conrad Observatory/WIC) according to Snell's law.

TABLE I. Modelling and Simulation Methods

	ZAMG [14]	**TU Graz [15]**
Earth conductivity model	2-D thin sheet + 1-D half space	1-D layered
Geoelectric field calculation	thinsheet approximation	plane-wave
Current calculation	Lehtinen-Pirjola	Nodal Admittance
Programming language	Python	Matlab
Magnetic field data	WIC	WIC

Second. The given line resistance is recalculated by calculating the geographical distance between the substations and multiplying the distance with the line resistance per km. The number of conductor phases are considered as a parallel circuit with the same line resistance [16].

Third. The different types of transformers are modelled according to [16].

Fourth. If the actual network parameters are not available or missing, the values from tab. II are used, which are also recommended in literature [17], [18].

Further information on the process of current induction on earth can be found in [19].

TABLE II. General Network Parameters

	Voltage level	
	230 kV	**400 kV**
Line res. R_L	0.06 Ω/km per phase	0.02 Ω/km per phase
Winding res. R_W	0.06 Ω/km per phase	0.2 Ω/km per phase
Grounding res. R_G	0.2 Ω	

The code for calculating currents in a network from a given geoelectric field from [14] is available at https://github.com/geomagpy/GEOMAGICA.

B. *Analysis of simulation results*

Substation sensitivity. Substations connected to transmission lines in the east/west direction are sensitive to an electric field in east/west or a magnetic field in north/south direction. Substations connected to transmission lines in north/south are sensitive to an electric field in north/south direction or a magnetic field in east/west direction. Fig. 2 indicates the level of GIC and the most sensitive geoelectric field orientation for each substation [15].

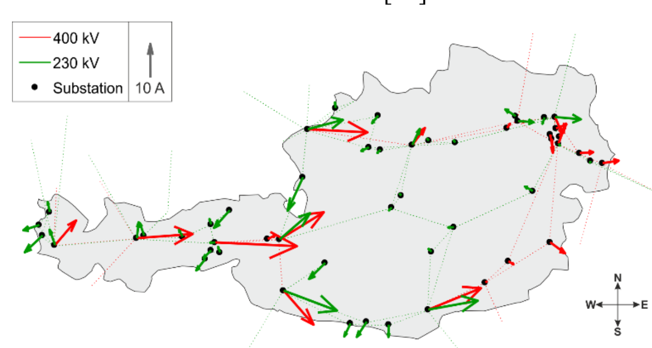

Fig. 2. Sensitivity map of the Austrian power transmission network. Quiver direction indicates most sensitive geoelectric field orientation [15].

Earth impedance influence

By increasing the degree of detail of the earth conductivity model, the GIC simulations results show a higher level of correlation to the measurements [21]. In [20] four surface conductivity models were compared. The most detailed model shows the highest correlation with the measurements.

C. Network configuration and expansion

The network configuration was changed and GIC were calculated for the new network configuration. The following effects were observed [20], [22]:

- the severance of long transmission lines leads to an increase of GIC;
- nodes with a high number of connections (> 2) experience higher GIC for a network configuration change;
- node with short average distances to other nodes experience lower GIC for a network configuration change;
- nodes are more greatly affected by transformer outages if they are direct connected via conductor(s);
- a clear influence of the transmission line direction could not be pointed out;
- neglecting connections to surrounding areas and countries led to a decreased correlation between measurement and simulation.

D. Low frequent current, LFC, sources

Due to an observed dc offset in the measurements, an investigation into the source was conducted and a first assumption therefore was a so-called photoelectric effect from solar radiation on the ground. However, the influence on the current measurement system by the photoelectric effect could not be confirmed by comparing current measurements from sunny and cloudy days.

Current measurements show a high correlation with the operating hours of the subway transportation system in Vienna. During operation hours the measured currents increase. Because the subway system uses dc as supply voltage, it is reasonable to consider stray currents entering the electrical transmission system via the transformer neutral points [15].

Influence of "400 kV-ring". In Austria a network expansion is planned, known as the "400 kV-ring". This will include a 400 kV overhead line between the substations Tauern and St. Peter. Simulations including this future scenario show a lower level of GIC in most of the substations [15].

GIC MEASUREMENTS IN THE AUSTRIAN POWER NETWORK

A. Measurements and simulations

Transformer neutral point measurements of LFC are conducted at four substations, geographically distributed over Austria, as depicted in Fig. 3. The automated stand-alone measurement system uses a zero-flux transducer for current measurement and the measurement data is stored at a data logger with a sample rate of 1 S/s. For further data analysis the data is accessed via a virtual private network (VPN) connection and downloaded to a server. Continuous measurements are available from the year 2016 onwards.

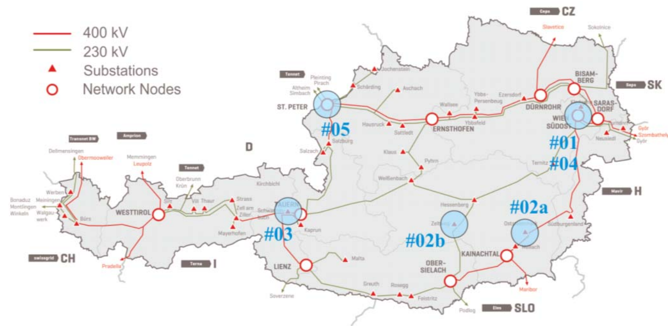

Fig. 3. Neutral point current measurement installations in the Austrian power network [15].

Tab. III. lists the transformer information and the observation period of the five measurement units.

In Fig. 4 the current measurement unit is depicted. Fig. 5 illustrates the measurement setup at one transformer neutral. The corresponding descriptions can be found in tab. IV. The radiator was added to provide more constant temperature in the measurement unit and to prevent moisture accumulation.

TABLE III. FIELD MEASUREMENTS. BOLT WRITTEN VOLTAGES INDICATE MEASUREMENT POINT IN NETWORK

Client	*Transformer*		*Observation Period*	
	Voltage in kV	**Power in MVA**	**Start**	**End**
#01	**400**/230/30	600/600/150	Aug 2016	present
#02a	**400**/115/30	300/300/100	Nov 2016	Apr 2018
#02b	**230**/110/10	220/220/33	Apr 2018	present
#03	**400**/115/30	200/200/100	Apr 2017	present
#04	400/**230**/30	600/600/150	Aug 2017	present
#05	**400**/230/30	550/550/150	May 2017	Present

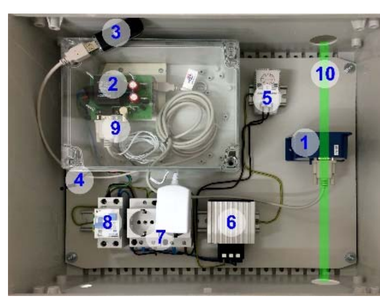

Fig. 4. Measurement unit.

Fig. 5. Field measurement setup.

Fig. 6 depicts the magnetic field components in x, geographical northwards, and y, geographical eastwards, direction and the corresponding current measurement. During the period marked in magenta the magnetic field change over time increased. An increase of current change rate could be measured during the same time interval. To validate the visual correlation, the cross-correlation of the measured data and also of the rate change in measurement data was calculated and listed in tab. V. The strong visual correlation could not be validated by the calculated cross-correlation. The reason for this is still under investigation.

TABLE IV. COMPONENT DESCRIPTION AND MEASUREMENT SETUP

1 – current probe	6 – radiator
2 – Data logger	7 – voltage supply
3 – GSM module	8 – automatic circuit breaker
4 – Temperature sensor	9 – data linkage cable
5 – Temperature regulator	10 – earthing cable
a – measurement enclosure	c – transformer neutral
b – earthing equipment	

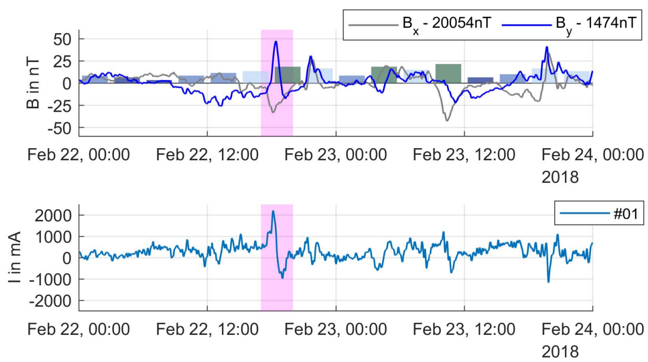

Fig. 6. Influence of the magnetic field on transformer neutral current measurements. Colored bars indicate geomagnetic activity index K_p [15].

TABLE V. CORRELATION BETWEEN MAGNETIC FIELD B AND MEASURED TRANSFORMER NEUTRAL CURRENT [15]

r_{xy}	B_x	B_y	$\mathrm{d}B_x/\mathrm{dt}$	$\mathrm{d}B_y/\mathrm{dt}$
$I_{\#01}$	-0.23	0.15	-	-
$\mathrm{d}I/\mathrm{dt}$	-	-	-0.45	-0.44

In Fig. 7 the simulation results are depicted together with the simulated values for measurement from client #01. A correlation of 0.83 between simulated and measured values could be calculated. High frequency changes in the measurement data set could not be modelled as well as low frequency changes, as depicted in Fig. 7.

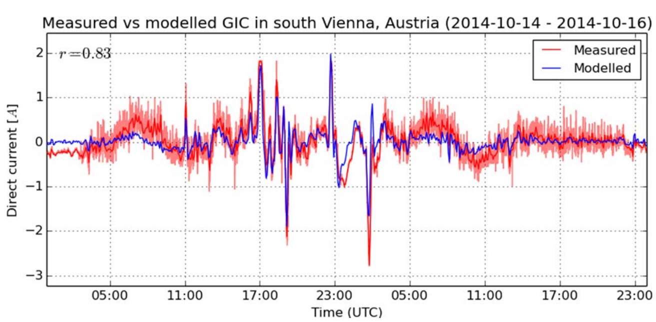

Fig. 7. Measured (#01) vs. modelled GIC in south Vienna during 14.-16. October 2016 with high correlation of 0.83 [23].

DISCUSSION

Both computation methods showed a good correlation between simulated and measured currents in the 400 kV level. The model from TU Graz has a lower correlation between measured and simulated currents in the 230 kV level. The two simulations differ in the used conductivity models and in the method of current calculation. The method can be excluded as a reason for the deviation [24]. The authors surmise the more detailed earth conductivity model used as possible reason for the deviation in simulation results.

Both simulations show a high correlation, r > 0.8, with the measurements. In both simulations the magnetic field, measured at the Conrad Observatory (WIC) is assumed to be uniform all over Austria. To improve to correlation values past studies used the spherical elementary current systems (SECS) method [25], [26], to interpolate the magnetic field of several magnetic field observatories. This method was tested in [20] but the lack of nearby observatories led to inadequate field modelling. Instead, data from nearby observatories was used and, depending on the location of the other observatories, the correlation value decreased or increased, but not significantly. In the western and southern parts of Austria in particular, there are few nearby observatories. Magnetic field measurements should be carried out in the western part of Austria to verify the quality of the assumption of a uniform magnetic field all over Austria, and this will be achieved with the setup of a new geomagnetic observatory near Innsbruck.

While currents can be modelled for past events with fairly good correlation, there is still a relative lack of information concerning upcoming and future events, which is of interest to mitigate possible damaging effects if there is a very strong incoming solar storm. This will be looked at with the development of a neural network to predict GICs in Austria from solar wind data.

LFC can cause an increase in power losses in the electrical power network. Therefore, economic effects such as the market price for electrical power should be taken into account for system operation. In [27] correlation between GMD and electric power market prices was investigated.

FURTHER WORK IN AUSTRIA

For further research in the field of low frequent currents in Austria the authors identify the following four fields of interest and tasks.

Field 1: Modelling, simulation and measurements

- comparison of different current measurement methods for cost-effective use of measurement units; systems under consideration are: magnetometer based systems [28] - [30], neutral point current measurement systems and measurement systems installed on the overhead transmission line,
- installation of more measurement units based on sensitivity analysis,
- extension of measurement unit with vibration sensor for identification of non-normal load situations of transformers,
- use of more detailed earth conductivity model,
- automated relevant event/data selection.

Field 2: Prediction of space weather and effects in power networks

- machine learning for space weather prediction,
- model other effects causing LFC and include them in simulation,
- reactive power demand calculation based on LFC in transformers.

Field 3: Countermeasures against LFC in power networks and utilities

- GIC risk management for transmission network including evaluation of protection relay setting with respect to harmonics,
- short and long term countermeasures,
- invasive and non-invasive countermeasures.

Field 4: Power transformers under LFC influence

- reactive power demand as a function of LFC,
- behavior of different transformer types such as auto-transformer or 3 and 5 leg transformer,
- influence of LFC during asymmetrical and symmetrical load situations.

Additional further research topics and questions from the NASA Living With a Star Institute Working Group are summarised in [31] and in [32].

CONCLUSION

Two independent simulations of GICs in Austria were setup and validated using ongoing measurements in the Austrian electrical power transmission network. Induced currents up to 15 A could be simulated and measured in the time from April 2016 till today, which is in the time span of decreasing sun activity in the sun cycle 24. Further research in the field of GICs will be conducted in Austria, focusing on space weather prediction, influence of GICs on the power network components and the impact in the overall power system. Further measurements of induced currents will be used to refine simulation models and to identify further sources of low frequency currents on earth. The research results will be used to investigate countermeasures to LFC and to develop a risk management concept for the power transmission network operator.

First countermeasures against LFC in the Austria transmission network are installed, using dc compensation technology in power transformers.

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