POWER AND PIPELINES (GROUND SYSTEMS)

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ABSTRACT

Geomagnetically induced currents (GIC) in technological systems, such as electric power transmission systems, oil and gas pipelines, telecommunication cables and railway equipment, are a manifestation of space weather at the earth's surface. In power systems, GIC cause saturation of transformers, which may lead to problems in the operation of the system, and even to a collapse of the whole system and to permanent damages of transformers. The best-known GIC effect occurred in March 1989 when the Québec province in Canada suffered from an electric black-out for about nine hours. The corrosion rate may be increased in pipelines when GIC flows from the pipe into the soil, and the associated voltages can disturb pipeline surveys and the cathodic protection. This paper summarizes GIC effects on power systems and pipelines. GIC research associated with the Finnish high-voltage power system is discussed. GIC measurement data on a natural gas pipeline and Sweden is presented. The electric field observed at the earth's surface during a geomagnetic disturbance is the key quantity for the calculation of GIC magnitudes. It depends on currents in the ionosphere and on currents flowing within the earth. The theoretical modelling of the electric field is discussed in this paper. Particular attention is paid to the complex image method, which permits accurate and fast computations of the electric field and which is thus suitable for time-critical applications like GIC forecasting.

1. INTRODUCTION

During a space weather storm electric currents flowing in the magnetosphere and ionosphere change rapidly. The variations produce temporal changes in the geomagnetic field. The changes are known as (geo)magnetic disturbances or storms. According to Faraday's law of induction, magnetic disturbances are accompanied by an electric field, which drives currents within the conducting earth. These currents affect the magnetic disturbance and the (geo)electric field occurring at the earth's surface, too. The electric field also creates currents in man-made conductor systems, such as electric power transmission networks, oil and gas pipelines, telecommunication cables and railway equipment, in which they are called geomagnetically induced currents (GIC). Inconveniences to the system may result from GIC. Large GIC occur most frequently in the auroral regions, in particular in North America and Fennoscandia. The increasing number of technological systems vulnerable by GIC and the approaching sunspot maximum with a higher geomagnetic activity make GIC research very actual and important now.

The earliest GIC observations were made in the first telegraph systems about 150 years ago (*Boteler et al*., 1998). GIC phenomena have been widely investigated for tens of years (e.g. *Albertson et al*, 1974; *Campbell*, 1978; *Root*, 1979; *Elovaara et al.*, 1992; *Viljanen and Pirjola*, 1994a; *Kappenman*, 1996; *Petschek and Feero*, 1997). The largest GIC problems occur in power systems, in which the first GIC observations were made in 1940 (*Davidson*, 1940). The importance of GIC was emphasized by the inconveniences that occurred in North American power systems on March 13, 1989 (*Kappenman and Albertson*, 1990; *Bolduc and Langlois*, 1995). The most significant was a province-wide electric black-out in Québec, Canada, for about nine hours. A transformer was destroyed in the USA during this storm.

Today's activities in space weather research largely concern satellite observations of the solar wind, and an aim is to develop methods of forecasting space weather storms and GIC in technological systems. An important purpose of this paper is to demonstrate that a reliable quantitative GIC forecasting necessarily requires an accurate and fast determination of the geoelectric field at the earth's surface.

2. GIC EFFECTS ON POWER SYSTEMS

As compared to the 50 or 60 Hz frequency used in electric power transmission, geomagnetic variations are slow with typical frequencies in the mHz range. Therefore GIC, when flowing through a transformer, affects as a dc current. In normal conditions the ac exciting current needed to provide the magnetic flux for the voltage transformation in a power transformer is only a few amperes, and the transformer operates within the range where the dependence of the exciting current on the voltage is linear (*Kappenman and Albertson*, 1990). However, the presence of GIC implies an offset of the operation curve resulting in saturation of the transformer during one half of the ac cycle and in an extremely large non-linear exciting current (even some hundreds of amperes). The exciting current is asymmetric with respect to the ac half-cycles and is thus distorted by even and odd harmonics, which in turn may cause relaying problems in the system.

The increased exciting current also produces large reactive power losses in the transformer contributing to a serious voltage drop. The harmonics and the reactive power demands also affect the transformer itself. The noise level is increased, and due to the saturation of the core, the magnetic flux goes through other parts of the transformer possibly resulting in overheating. The hot spots may permanently damage the insulators and cause gassing of transformer oil resulting in serious internal failures.

The most famous GIC failure occurred in the Hydro-Québec power system on March 13, 1989, at 2.45 a.m. local time (*Kappenman and Albertson*, 1990; *Bolduc and Langlois*, 1995). The problems started when harmonics created by GIC flowed into static voltampere reactive compensators, which provide a rapid voltage regulation and thus ensure the system stability. Due to the harmonics, the protective systems tripped seven compensators and a generated power of 9500 MW, i. e. 44 % of Québec's total power consumption at the particular time, was left without voltage regulation. Combined with increased reactive power demands, it resulted in serious voltage problems. The consequence was that a 735 kV line was tripped interrupting the 9500 MW generation entirely. The frequency and the voltage fell throughout the rest of the system, and there was a great imbalance between the load connected to the Hydro-Québec system and the generated power available. All this caused that the whole network collapsed and most of Québec lost power. In total, 21500 MW of load and generation was lost. These cascading phenomena occurred in some tens of seconds, and the time between the onset of the magnetic storm and the collapse of the network was about one and a half minutes. After nine hours 17 % of the load were still out of service. The March 1989 storm created a GIC investigation in the Hydro-Québec system and corrective measures against GIC have been taken (*Bolduc and Langlois*, 1995; *Bolduc et al.,* 1998).

During the same March 1989 storm, overheating destroyed a transformer in New Jersey, USA, causing a cost of several million US dollars together with replacement energy costs of about 400 kUSD per day (*Kappenman and Albertson*, 1990). It has been estimated that the total costs of a GIC failure in the northeastern USA during a slightly more severe storm than that of March 1989 would be 3–6 billion USD (*Kappenman*, 1996).

3. GIC IN THE FINNISH HIGH VOLTAGE POWER SYSTEM

The Finnish high-voltage power system shown in Fig. 1 has never suffered from noticeable GIC inconveniences. This is probably mostly due to the large margins used in the design of the power transformers. Also the relay tripping systems are not very sensitive to GIC effects. However, because of the vicinity of the auroral region, active GIC research has been carried out in Finland for more than 20 years, which has contained both GIC recordings and theoretical modelling (*Elovaara et al.*, 1992; *Viljanen and Pirjola*, 1994a).

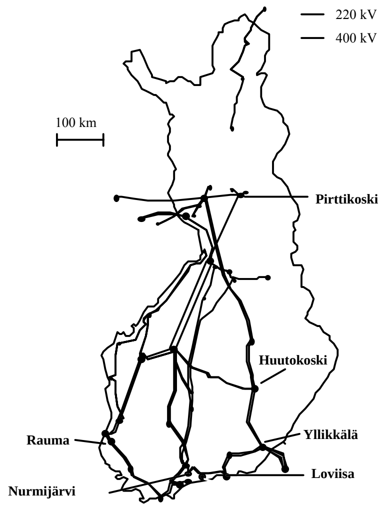

Fig. 1. Finnish 400 kV (thick lines) and 220 kV (thin lines) electric power transmission system.

Fig. 2 depicts the largest GIC (≈ 200A as a one-minute mean value) ever measured in Finland. It occurred in the earthing wire of the neutral point of the Rauma 400 kV transformer on March 24, 1991. Simultaneous recordings of the north component of the geomagnetic field and its time derivative at the Nurmijärvi Geophysical Observatory in southern Finland are also shown. GIC clearly follows the behaviour of the time derivative rather than the geomagnetic field itself (*Viljanen*, 1998).

In 1991 to 1992 a special GIC project was carried out in Finland (*Mäkinen*, 1993; *Viljanen and Pirjola*, 1995). GIC were measured in the neutral wires of four 400 kV transformers, and using a magnetometer, GIC flowing in a 400 kV transmission line was also recorded. Combining the GIC data with geomagnetic recordings and theoretical model calculations, it was possible to derive statistics of GIC occurrence (probability and duration) at each site of the Finnish 400 and 220 kV systems.

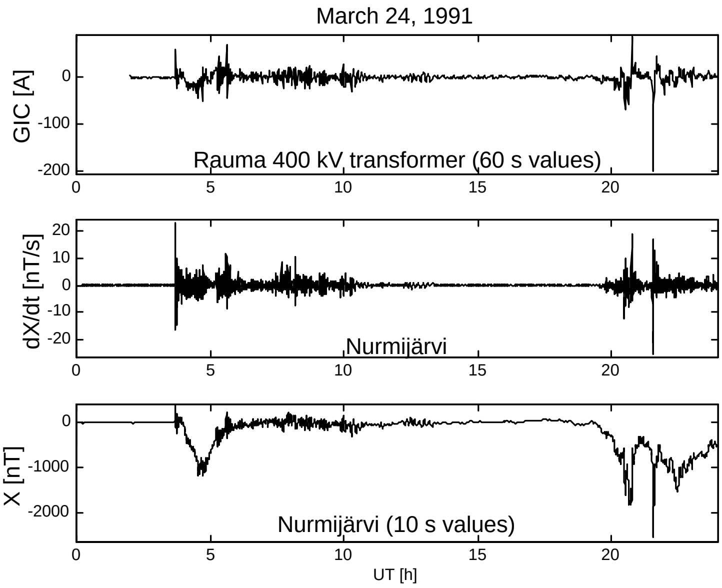

Fig. 2. GIC in the neutral wire of the Rauma 400 kV transformer in Finland during a magnetic storm on March 24, 1991. Simultaneous recordings of the north component of the geomagnetic field and its time derivative at the Nurmijärvi Geophysical Observatory, Finland, are also shown.

4. GIC EFFECTS ON PIPELINES

Metallic oil and gas pipelines buried in the ground are apt for corrosion (e.g. *Harde and Johansson*, 1996; *Osella et al.*, 1998; *Boteler*, 1998). To avoid the resulting harmful effects, pipelines are covered by an insulating coating, which should prevent an electric current flow from the pipe into the surrounding soil. The coating is, however, never perfect. Therefore a cathodic protection system is also applied o keep the pipeline in a negative potential with respect to the earth (about –0.85 V for steel pipelines).

If GIC flowed only along the pipeline it would not affect the pipe-to-soil voltage and would thus not have any corrosion consequences either. However, at inhomogeneities of the pipeline or of the surrounding earth, in particular near the ends ands bends of the pipeline, GIC can flow between the pipeline and the earth. The associated pipe-to-soil voltages may easily be a few volts (Fig. 3) thus greatly exceeding the cathodic protection voltage. The contribution of GIC to pipeline corrosion seems to be an open question since *Campbell* (1978) concludes it to be negligible but other authors, like *Henriksen at al.* (1978) and *Osella et al.* (1998), regard the increase of the corrosion rate due to GIC as significant. In any case, GIC disturb measurements of pipe-to-soil voltages and may make the recordings invalid and thus result in incorrect conclusions regarding corrosion protection (*Camitz et al.,* 1997).

Fig. 3 shows the clear and expected correlation between pipe-to-soil potentials and the time derivative of the geomagnetic field.

5. CALCULATION OF GIC

A theoretical calculation of GIC in a given network has two parts:

1° The horizontal geoelectric field at the earth's surface produced primarily by the ionospheric-magnetospheric currents and affected secondarily by the earth's conductivity structure is determined in the absence of the network. This can be done using Maxwell's equations by making suitable assumptions about the primary currents and the earth's conductivity.

2° Currents caused by the geoelectric field in the network are calculated using Ohm's and Kirchhoff's laws when the resistances and the geometrical structure of the network are known.

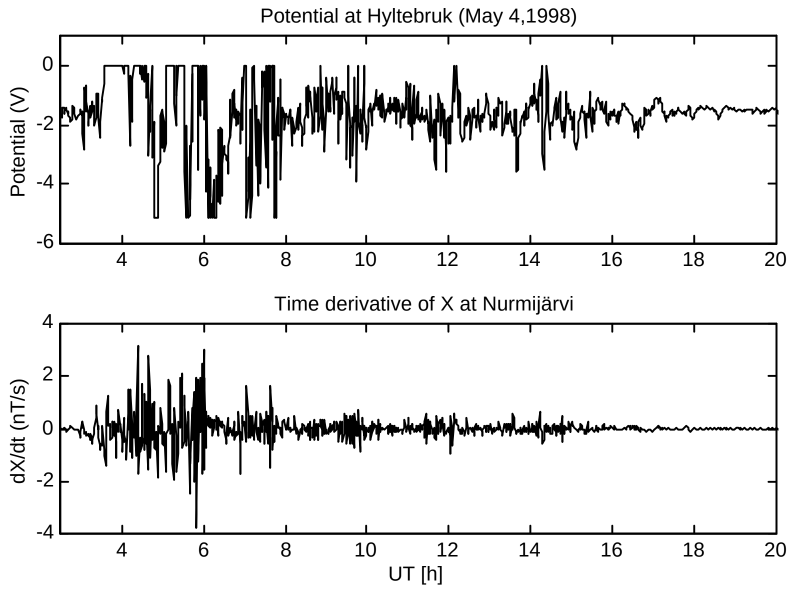

Fig. 3. Pipe-to-soil voltage measured on the Sydgas pipeline in southern Sweden during a magnetic storm on May 4, 1998. The measuring system cuts data less than –5 V or above zero. The time derivative of simultaneous recordings of the north component of the geomagnetic field at the Nurmijärvi Geophysical Observatory, Finland, is also shown.

In general, the second part is easier to perform. *Lehtinen and Pirjola* (1985) present exact matrix equations for the currents flowing in different parts of a network of conductors earthed at separate points, provided the horizontal geoelectric field is known. They are applicable to the calculation of GIC in a high-voltage power system (e.g. *Pirjola and Lehtinen*, 1985; *Pirjola et al.*, 1998). The second part of a GIC calculation is different in the case of a pipeline because the leakage through the coating provides a continuous earthing for a buried pipeline. Recent investigations of the distributed-source transmission line (DSTL) theory offer a possibility of considering GIC in realistic pipeline systems (*Boteler*, 1997).

6. COMPLEX IMAGE METHOD IN GIC STUDIES

Häkkinen and Pirjola (1986) introduce a general model of the ionospheric electrojet system including geomagnetic-field-aligned currents, and exact formulas for the electric and magnetic fields at the surface of a layered earth are derived. The formulas are, however, complicated integrals whose numerical computation requires a lot of computer time. Consequently they are not suitable for time-critical applications like forecasting of GIC based on predicted ionospheric-magnetospheric currents.

In the complex image method (CIM) the earth is replaced by a perfect conductor lying at a complex depth, which depends on the earth's conductivity structure and on the frequency. It means that the secondary contribution of currents in the earth to the electric and magnetic fields at the earth's surface is obtained by setting an image of the primary ionospheric source at a complex mirror location. This further implies that the complicated integrals mentioned above are avoided, and the computations become fast. CIM is an approximate method originally introduced almost thirty years ago (*Wait and Spies*, 1969). *Boteler and Pirjola* (1998) prove the excellent accuracy and applicability of CIM in connection with GIC studies. They, however, only consider an infinitely long line current simulating an auroral electrojet. *Pirjola and Viljanen* (1998) extend the CIM concept to a horizontal line current of a finite length with vertical (field-aligned) currents at its ends (a "U"-shaped current) above the earth. The crucial point in their discussion is to show that a vertical current can be equivalently replaced by a radial horizontal current system when considering the total magnetic field and the total horizontal electric field at the earth's surface. This makes it possible to apply earlier CIM results for any horizontal ionospheric current distribution (*Thomson and Weaver*, 1975). Numerical examples presented by *Pirjola and Viljanen* (1998) show an excellent agreement between CIM results and exact calculations. CIM is formulated in the frequency domain but with FFT the fields and GIC can be calculated as functions of time as well. A reasonable time resolution is about one minute or less.

A superposition of U-currents permits the treatment of more complicated current systems. For calculating the electric field at the earth's surface and GIC in a network, a U-current can be specified at each site of an ionospheric grid having a typical element size of 50 km × 50 km.. The horizontal part of the U-current may have any orientation, and in the software we have developed it is decomposed into the eastward and northward components. The extension of CIM to more complicated current systems than an infinitely long line current is significant because *Viljanen* (1997) indicates that, from the viewpoint of GIC, currents other than an electrojet are also important.

An example in which GIC in the Finnish high-voltage power system (Fig. 1) due to real ionospheric currents are calculated based on CIM is presented in the following(*Pirjola et al*., 1998). For the earth's conductivity structure, we assume the "Southern Finland" layered model with layer thicknesses and resistivities 3, 6, 5, 7, 23, ∞ km and 5000, 500, 100, 10, 20, 1000 Ωm (*Viljanen and Pirjola*, 1994b). We have investigated different types of auroral substorm events (an electrojet, a Harang discontinuity, an omega band and a westward travelling surge (WTS)). The geoelectric field is calculated on a ground grid covering the power system. The size of the elements of this grid is also 50 km × 50 km, and their number is about some hundreds. According to our studies, WTS is the most important of the above-mentioned event types regarding GIC. In the following, we adopt a WTS model which is originally based on ground magnetometer and ionospheric radar data (*Amm*, 1995).

The standard coordinate system in which the *x* and *y* axes are northward and eastward, respectively, the earth's surface is the *xy* plane and the *z* axis is downward is used. Choosing the origin close to the centre of the overhead ionospheric current system, Fig. 4 depicts the ionospheric currents on a 50 km × 50 km grid at -350 km $\le x \le 350$ km, -650 km $\le y \le 650$ km and $z = -110$ km. The maximum current value in one filament is roughly 300 kA.

The current pattern is assumed to move westwards above southern Finland with a propagation velocity of 1 km/s. The time step used is 60 s. The contour plots in Fig. 5 present the time behaviour of the electric north and east components E_x and E_y at $y = 0$ and at different values of *x*. The starting time 01^h00^m in the figures corresponds to the moment when the effects of the WTS begin to be seen at the points considered. Fig. 5 shows that E_x and E_y have an equal order of magnitude opposing the incorrect conclusion based on the consideration of a mere electrojet that the electric field would be mostly east-west oriented. The fact that a large horizontal electric field producing significant GIC may have any direction is also stressed by *Viljanen* (1997).

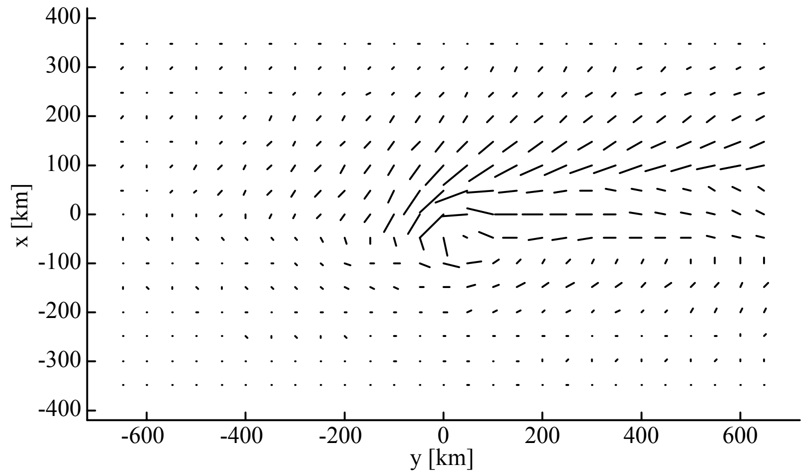

Fig. 4. Ionospheric current vectors associated with a WTS model.

Fig. 5. North component E_x (upper panel) and east component E_x [lower panel] of the electric field at the earth's surface at $y = 0$ as a function of time starting at 01^h00^m and at different values of *x* when the WTS current pattern shown in Fig. 4 moves at a westward velocity of 1 km/s across the area.

The electric field values presented in Fig. 5 permit the computation of GIC at each site of the Finnish 400 and 220 kV power system. Fig. 6 depicts the GIC flowing from the Rauma 400 kV transformer neutral into the earth (Fig. 1) The time is given in minutes starting at 00^h00^m. The peak value of the GIC is not more than about 10 A, which is much less than the largest GIC (200 A) recorded at Rauma (Section 3). We made additional calculations by changing the propagation velocity of the WTS to 5 km/s and 10 km/s thus making the time variations faster, which increases the electric field and GIC. The velocity equal to 10 km/s represents an extreme case, but GIC at Rauma still does not get larger values than about 25 A. It indicates that the event which created 200 A was of a very peculiar character. This is also supported by the fact that the second largest GIC measured at Rauma in 1991 to 1992 was 79 A, and 50 A were seldom exceeded (*Mäkinen*, 1993).

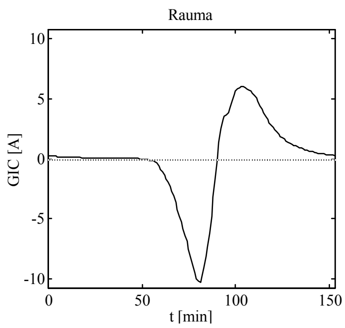

Fig. 6. GIC flowing at the Rauma 400 kV transformer due to the electric field shown in Fig. 5 as a function of time starting at 00^h00^m.

The CIM computations are performed applying MatLab and Tela (= Tensor Language developed by Pekka Janhunen, Finnish Meteorological Institute). Using an SGI Power Challenge computer or an efficient PC, it takes, for the WTS example, about 25 min CPU time to compute the electric and magnetic fields on a grid covering the Finnish power system and less than 1 min to calculate the resulting GIC.

7. CONCLUDING REMARKS

GIC in power systems and pipelines are the end of the long space weather chain starting from the sun. The key quantity for a GIC determination is the horizontal geoelectric field at the earth's surface. The electric field is primarily caused by ionospheric currents and secondarily affected by currents induced in the earth. Recent investigations of the complex image method (CIM) provide a great improvement in the calculation of the electric field since CIM is fast and accurate. The applicability of CIM in connection with GIC research is demonstrated by a numerical example, which concerns a westward travelling surge (WTS) event in the Finnish high-voltage power system.

From the practical point of view the largest GIC, which do not occur frequently, are the most interesting, and they are evidently associated with very exceptional ionospheric-magnetospheric situations. Our future work will concentrate on their analysis. The theoretical development should contain extensions of the CIM concept to laterally non-uniform earth structures.

8. ACKNOWLEDGEMENTS

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