Chapter 1

Introduction

1.1 Summary of previous studies in Finland

Geomagnetically induced currents (GIC) flowing in electric power transmission systems, pipelines, telecommunication cables and railway systems are the ground end of the complicated space weather chain starting from the Sun. Generally, GIC are a source of problems to the system, and particularly prone to GIC harm are systems located in high-latitude areas, like Fennoscandia and North America, where geomagnetic storms are the largest and most frequent.

A motivation to start an active research of GIC in the Finnish high-voltage power system in 1977 was obviously obtained from reports about GIC problems in North America during a large magnetic storm in August 1972 (*Anderson et al.*, 1974; *Boteler and Jansen Van Beek*, 1999). Because Finland is located at a high latitude studying GIC was well established. Another good reason for starting GIC investigations in Finland at the latter part of the 1970's was the rapid growth of the 400 kV grid in those times including the loops in southern and central Finland. In the first years the Finnish GIC research mostly consisted only of GIC recordings in the earthing wire of the Huutokoski 400 kV transformer (*Pirjola*, 1983). GIC research in the Finnish power system that already covers more than two eleven-year sunspot cycles, has always been done as a close collaboration between the Finnish power industry and the Finnish Meteorological Institute (FMI). Previous studies were made in collaboration with Imatran Voima Oy, IVO. However, observations of GIC at different times are not necessarily comparable because great changes have occurred in the power system configuration.

In spite of temporary GIC recordings at some other 400 kV sites as well, Huutokoski was the main recording station until the measurements were stopped there in the first years of the 1990's. The reason for the stopping were the very small GIC values recorded, which in turn resulted partly from the large resistance of the neutral point reactor installed at Huutokoski in the middle of the 1980's and partly from the location of Huutokoski in the configuration of today's 400 kV system.

Modelling efforts to calculate GIC in the Finnish 400 kV system were started in the beginning of the 1980's. The calculation of GIC in any network is divided into two steps containing the modelling of the geoelectric field at the earth's surface and the computation of GIC driven by this field. *Lehtinen and Pirjola* (1985) presented exact matrix formulas for the latter step when a discretely-earthed network is considered. The former step is a complicated geophysical problem which requires knowledge or assumptions about ionospheric-magnetospheric currents and about the earth's conductivity structure. *Häkkinen and Pirjola* (1986) presented formulas for the surface electric and magnetic fields created by a general current system above a layered earth. The formulas are, however, complicated and thus laborious to be used in practical numerical computations (*Pirjola and Häkkinen*, 1991). Recently, the complex image method (CIM) suitable for time-critical calculations was extended to the determination of the fields at the surface of a layered earth due to a general ionospheric current system with vertical currents implying a coupling to the magnetosphere (*Pirjola and Viljanen*, 1998).

To get more accurate information about the occurrence of GIC in the Finnish 400 kV power system, IVO ordered a study from FMI in the middle of the 1980's. Using time derivatives of the geomagnetic field recorded at the Nurmijärvi and Sodankylä Geophysical Observatories and the plane wave model for calculating the geoelectric field, it was possible to derive GIC statistics for each site of the Finnish 400 kV system (*Pirjola*, 1985). The magnetic data applied did not contain very large magnetic storms, so their GIC effects were roughly estimated separately.

Several approximations had to be made in the first statistical GIC study. Therefore a supplementary investigation was made by *Pirjola* (1986). A special emphasis was paid to the fact that the plane wave assumption is often not a good approximation at high latitudes while a localized electrojet system plays an important role. Furthermore, additional geomagnetic data were used in the new study in 1986. It was also realized that GIC statistics are highly dependent on the power system configuration, so new computations were made for an updated configuration and also regarding planned future changes of the system.

A significant factor affecting the problems which GIC may cause is the duration of a large GIC at a transformer. This was not included in the previous studies but it was considered in the next investigation (*Viljanen*, 1987; *Viljanen and Pirjola*, 1989). The statistics were improved also when a more accurate coupling to GIC measurements at Huutokoski was included and the calculations were based on the geomagnetic K index at Nurmijärvi.

The largest effort in the GIC collaboration between IVO and FMI so far was a "GIC project" in 1991 to 1992 (*Elovaara et al.*, 1992; *Mäkinen*, 1993; *Viljanen and Pirjola*, 1995). GIC data were collected simultaneously at four 400 kV transformers (Huutokoski, Pirttikoski, Rauma, Yllikkälä) and in one 400 kV line (Nurmijärvi-Loviisa). The geophysical models used took into account both ground conductivity variations across the power system and different locations of an intense ionospheric electrojet current. The results obtained were derived by using A_k index statistics at Nurmijärvi since 1953. Besides, the 220 kV system to which the 400 kV network is in metallic connection at autotransformers was also considered in this study. It has been shown that the metallic connection to the Swedish system is not significant regarding GIC in Finland (*Pirjola and Viljanen*, 1991).

Since the "GIC project" theoretical modelling capabilities have been improved, thanks in particular to CIM. It has also become clear that the time derivative of the magnetic field and the electric field at the earth's surface are not only affected by an intense electrojet but more complex ionospheric current systems are of importance making the electric north and east components statistically approximately equal in magnitude, which a single electrojet model does not do (*Viljanen*, 1997). In addition to improvements in modelling techniques, a lot of new magnetic data collected in Fennoscandia are available. As a new aspect, the simultaneous occurrence of large GIC at several transformers is also considered now because such an information is necessary when estimating reactive power demands of the system.

The Finnish power system has not suffered from GIC problems. However, due to the location close to the auroral region the possibility of GIC should always be taken into account by maintaining an updated knowledge of the phenomenon, by continuing GIC recordings at some sites and by making new GIC calculations whenever major changes in the system occur. Now GIC recordings are carried out in the neutral conductors of the Pirttikoski, Rauma and Yllikkälä 400 kV transformers (see Fig. 1.1).

1.2 Outline of the 1999-2000 project

As indicated above, the main reasons for performing this study were the applicability of CIM to modelling complicated ionospheric situations, the availability of new geomagnetic data and the necessity to consider extreme geomagnetic disturbances and their effects on the Finnish power system. The new data comprise recordings of magnetic variations by the IMAGE array (*Viljanen and Häkkinen*, 1997) operating continuously since 1982 and measurements of the magnetic field in connection with the BEAR project during one and a half month in summer 1998 (*Korja et al.*, 1998).

Extreme events were studied using two different approaches:

1.) Measured geomagnetic data from the BEAR and IMAGE magnetometer networks in the area of the Finnish power grid were used with the plane wave method. The obtained geoelectric field was again put into the GIC model of the power system and both geoelectric field and obtained GIC distributions were studied. This is the main part of the work.

2.) Ionospheric current models obtained from other geophysical studies were applied to CIM, which gave the geoelectric field at the surface of the earth. Geoelectric field was then put into the GIC model of the Finnish power system and GIC of the system was obtained.

The aim of the both approach was to find the basic characteristics of the large GIC events and to sort out the geomagnetic conditions in which large GIC are possible. Also GIC data collected from the Nurmijärvi-Loviisa transmission line during the period June 1991 - May 1992 was used in the work to make similar interpretations. The geoelectric field given as time series in a grid covering Finland is the main product of the study and can be applied also for the future network configurations.

A side product of the work were statistics of GIC which can be used as a material for comparison with the earlier studies. Statistics were derived by calculating first GIC representing each K index value. Yearly statistics of K index were then used to give statistics of GIC.

The number of suitable data obtained in the GIC recordings carried out at Pirttikoski, Rauma and Yllikkälä since spring 1999 is not sufficient yet for comparisons with the derived theoretically-calculated results. The geomagnetic activity in 1999-2000 has been lower than expected, especially when compared to the former sunspot maximum in 1989.

The structure of this work is as follows:

The calculation of the geoelectric field is introduced in Chapter 2. The emphasis is focused on the plane wave method, with which we directly use magnetometer array data. Additionally, the use of the DC model of the power system is briefly reviewed.

Some intense events are investigated in Chapter 3 by the plane wave method with real input data. A short statistical review based on GIC recordings is also given.

GIC statistics are derived in Chapter 4 by starting with the event selection and then calculating GIC at each site of the power grid. The final result is the predicted yearly occurrence of GIC. For practical reasons, all results are not shown in this report. However, the calculated geoelectric field and GIC are stored in files available at the Finnish Meteorological Institute, so further analysis are easily performed.

In Chapter 5 the complex image method is applied to the Finnish power system. The model is first described briefly, and then it is used with realistic ionospheric current models.