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Calculation of geomagnetically induced currents (GIC) in a high-voltage electric power transmission system and estimation of effects of overhead shield wires on GIC modelling

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Abstract

Geomagnetically induced currents (GIC) flowing in ground-based technological networks, such as electric power transmission grids, are the ground end of the space weather chain originating from the Sun. GIC constitute a possible source of problems to the system. Matrix formulas enabling the calculation of GIC in a power grid have been presented before. In this paper, we summarise the formulas and also express them in an alternative form that includes the (geo)voltages driving GIC during a space weather event more explicitly. An issue usually ignored in GIC modelling is the effect of overhead shield wires protecting a power grid and generally earthed at the towers. By numerical examples, it is shown in this paper that such neglect causes an insignificant error in comparison with other inaccuracies involved in GIC modelling and is thus really acceptable in practice.

Keywords: GIC; Geoelectric field; Power grid; Shield wires; Space weather

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1. Introduction

During a space weather storm, which is a result of solar activity, the magnetosphere–ionosphere system becomes disturbed with intense and rapidly changing currents (e.g., Lanzerotti et al., 1999). At the Earth's surface, varying space currents manifest themselves as disturbances or storms in the geomagnetic field. As expressed by Faraday's law of induction, a geoelectric field also exists in connection with a geomagnetic storm. The electric field produces currents, known as "geomagnetically induced currents" (GIC), in ground-based technological networks, such as high-voltage electric power transmission systems, oil and gas pipelines, telecommunication cables and railway equipment. GIC thus constitute the ground end of the complicated space weather chain originating from the Sun (e.g., Pirjola, 2000). In power grids, GIC can saturate transformers, which may cause different problems extending from harmonics in the electricity to a blackout of the whole system and permanent damage of transformers (e.g., Kappenman and Albertson, 1990; Kappenman,

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1996; Bolduc, 2002; Molinski, 2002; and references therein). In pipelines, GIC can create problems associated with corrosion. Telecommunication and railway equipment may experience unwanted voltages due to GIC possibly leading to failures. This paper deals with GIC in power systems.

A theoretical calculation of GIC in a technological system is convenient to be divided into two parts: (1) the determination of the horizontal geoelectric field (“geophysical part”), and (2) the computation of GIC produced by the electric field (“engineering part”) (e.g., Pirjola, 2002). The input of Part 1 includes information about the Earth’s conductivity structure and about ionospheric–magnetospheric currents or the magnetic field on the ground. Methods to carry out Part 1, which is independent of the technological system considered, have been discussed extensively and for a long time in the literature (e.g., Albertson and Van Baelen, 1970; Hermance and Peltier, 1970; Boteler and Pirjola, 1998a; Pirjola and Viljanen, 1998; Viljanen et al., 2004; and references therein).

The electric field provided by Part 1 and the network configuration and resistances constitute the input for Part 2. Since geoelectromagnetic phenomena are slow as compared, e.g., to the 50- or 60-Hz frequency used in electric power transmission, Part 2 involves a dc treatment. For a power system, Part 2 can be performed by appropriate matrix formulas discussed in greater detail in Section 2. Besides equations presented several times before, alternative formulas, which explicitly include the geovoltages produced by the geoelectric field, are also given. In the case of a buried pipeline, GIC and pipe-to-soil voltages can be solved by the distributed-source transmission line (DSTL) theory (Boteler and Cookson, 1986; Boteler, 1997; Pulkkinen et al., 2001).

In the calculation of GIC in a power grid, the three phases are usually treated as one circuit element, whose resistance is one-third of that of a single phase and which carries a GIC three times larger than that flowing in a single conductor (Mäkinen, 1993; Pirjola, 2005a). This is acceptable due to symmetry. Similarly, parallel transmission lines between two substations are also convenient to regard as one line, and an analogous description holds true for parallel transformers at a station. Special modelling techniques are needed for investigations of GIC in systems of two different voltage levels, in which cases stations with full-wound transformers and with autotransformers naturally require different treatments (Mäkinen, 1993; Pirjola, 2005a).

Power grids are protected by overhead shield wires earthed at the towers (Pesonen, 1980). They are usually ignored in connection with GIC studies. But at least in principle, shield wires can affect both parts of a GIC calculation. (1) Shield wires are conductors parallel to the transmission lines, and so similar to any ground conductivity anomaly, they may have an influence on the geoelectric field that drives GIC. Thus, shield wires should in principle be taken into account in the “geophysical part”. (2) GIC from (to) a transformer neutral to (from) the ground partly also flows in the shield wire system. Consequently, due to this parallel path, the resistance met by GIC is somewhat smaller than the actual substation earthing resistance. However, measured earthing resistance values implicitly include the influence of the shield wire system, so it need not be considered separately in the “engineering part”. In this connection, resistances refer to the real parts of 50- or 60-Hz impedances but, based on Albertson et al. (1981), the error caused by the application of ac values to GIC purposes is insignificant. Since GIC values are not very sensitive to small changes of earthing resistances, the overall effect of shield wires on the “engineering part” is obviously of minor importance anyway, and it is not discussed in this paper. In practice, the resistance met by GIC flowing into (or from) the ground is dominated by the resistance of a neutral point reactor whenever such a device is installed in the earthing lead of a transformer neutral (Pirjola, 2005b).

We show in Section 3 that the effect of shield wires on the geoelectric field, which can be investigated with the same formalism as used in the “engineering part” of an actual GIC calculation and presented in Section 2, is also negligible.

2. Calculation of GIC in a power grid

Load-flow calculation techniques used by electric power industry can be utilised for developing modelling methods of GIC in power grids. In this connection, however, it is very important to note that the geoelectric field is generally rotational, i.e., there exists no (geo)potential but the (geo)voltages driving GIC have to be calculated by integrating the geoelectric field along the transmission lines (e.g., Pirjola, 2000; Boteler and Pirjola, 1998b). As