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" Geomagnetic induction effects in ground-based systems "

presented by :

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GEOMAGNETIC INDUCTION EFFECTS IN GROUND-BASED SYSTEMS*

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Abstract. Plasma physics processes, whose ultimate origin is the Sun, exist in the Earth's magnetosphere and ionosphere and can produce effects which are detrimental to the operation of technological systems associated with long conductors deployed on the Earth's surface. Geomagnetic fluctuations produced by such plasma processes can cause disturbances and disruptions in cable communication systems, electrical power distribution systems, and long pipelines. This paper briefly addresses these three topics with illustrative examples of some measured effects from each topic area.

1. Introduction

Earth-based conductors are susceptible to induced currents produced by the fluctuating geomagnetic field. Indeed, the effects of geomagnetic induction on long telegraph cables were the earliest evidence (with the exception of lightning strikes on buildings) of the influences of the solar-terrestrial environment on man-made objects and systems (e.g., Barlow, 1849; Burbank, 1905). Soon after the installation of telegraph systems in England the effects of geomagnetic fluctuations on their operational characteristics were observed and reported (Barlow, 1849).

Essentially each time a technological advance has been made using a new, and longer, conductor such as a transatlantic telephone cable, a high voltage power line or the trans-Alaska pipeline, the effects of the solar-terrestrial environment has to be considered. The proper engineering must be done to prevent unwanted induction-produced disturbances and/or complete disruptions of service. Further, a deepening understanding of the solar-terrestrial environment in the last decade has meant that the influences of the environment on such systems can now be better assessed and the appropriate engineering carried out prior to installation. In addition, as the sophistication of the technology has increased, greater demands have been placed on the required level of knowledge of the environment in order to attempt the elimination of even the most subtle detrimental effects.

The geomagnetic fluctuations of most interest to the problems addressed here are those which occur in the frequency range from $\sim 10^{-4}$ to 10^{-1} Hz. In this range the normal geomagnetic spectrum varies with frequency f as $\sim f^{-2}$ (e.g., Lanzerotti, 1978), with the amplitude primarily dependent upon geomagnetic latitude and the level of geomagnetic activity. Statistical studies exist of the geomagnetic spectrum as a function of these variables (Campbell, 1976a, b; 1977; Surkan and Lanzerotti, 1974). There is not a clear relationship between the fluctuation spectrum and the geomagnetic activity index K_p (Lanzerotti and Surkan, 1974), even though the activity index continues to be used

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for practical purposes (e.g., Albertson and Thorson, 1974), largely for lack of any better measure of geomagnetic disturbance level. In addition to the fluctuation amplitude and spectra, the spatial scale sizes of the variations at various frequencies are important for determining induction effects. These scale sizes, and their temporal changes, remain largely unknown, particularly for the severe disturbances that can cause complete disruptions of systems.

The resultant effects of induction in a long conductor system depend upon the system itself. However, the basic physics of the phenomenon can be considered to be essentially independent of the system: a current is induced to flow in the conductor by virtue of a potential drop across the conductor, a drop produced by the fluctuating geomagnetic field incident on the conducting Earth (e.g., Root, 1979).

This paper contains several brief illustrations of the effects on long conductor systems of geomagnetic field fluctuations. Because of space limitations, the examples are not treated in depth; rather, they are intended to be only illustrations of several past and present areas of practical interest. Aspects of this subject have been addressed earlier (Lanzerotti, 1979a, b, c).

2. Cable Systems

Because telegraph history dates from the first half of the nineteenth century (as noted above), such systems provided the earliest awareness of geomagnetic induction phenomena (Barlow, 1849). Among the earliest widely reported induction effects were those which occurred in the northeastern United States and in Europe during the large solar disturbances of August–September 1859 (Silliman, 1860). A telegraph operator in Boston, Mr. George B. Prescott, reported that the lines running out from that city were rendered inoperative for long periods of time (Prescott, 1866). During other intervals, it was possible to operate the telegraph system without it being connected to its battery power supply; the potential drops generated by the (observed) aurora were sufficient. The geomagnetic storm was of such severity that even during local daytime (when the optical aurora was not visible), it was also possible at times to operate the telegraph without the battery supply. During nighttime conditions (when the aurora was visible), the telegraph operator commented that the increases and decreases in auroral surges (he termed them 'waves') appeared to coincide with increases and decreases in the induced currents on the telegraph line. The periodicity of these variations was estimated to range from 30 s to several minutes. (It is interesting to note that this is probably the first report of the association of auroral and magnetic variations in what we now call the ULF frequency range.)

The induction of 'earth currents' and their effects on both land and sea telegraph cables remained an important technical problem for communications engineers. For example, many papers and commentaries were devoted to the subject of Earth currents in the *Journal of the Society of Telegraphic Engineers* in the 1870's and 1880's.

Numerous examples can be cited from recent periods of geomagnetic activity of the effects on cable communications of geomagnetic storms. For example, during a 'great'

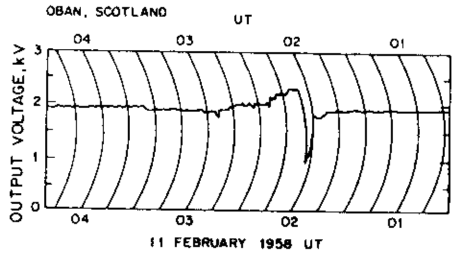

Fig. 1. Output voltage of the power feed equipment at the Oban, Scotland, end of the Oban–Clarenville, Newfoundland, cable. The voltage variation in North America was somewhat larger, leading to a total variation of about 2700 V across the cable (from Axe, 1968).

geomagnetic storm on 10 February, 1958, the Bell System transatlantic cable from Clarenville, Newfoundland, to Oban, Scotland, had total induced voltages estimated to be ~ 2.7 kV (Winckler *et al.*, 1959). The voltage excursion measured at Oban during the peak of the storm is shown in Figure 1 (Axe, 1968).

This first transatlantic cable system used two separate coaxes for the communications in the two directions (later designs, such as for the TAT-6 cable discussed below, used only one coax and separated the two directions using different frequency bands). Although the Clarenville–Oban cable system was never totally inoperative, the effect of time-varying Earth potentials was to have voices transmitted in the eastward direction as alternately loud squawks and faint whispers, while the westbound signal strengths remained near normal (Saunders, 1961; Anderson, 1979). A geomagnetic latitude effect was clearly evident in that no major voltage swings were observed on the San Francisco–Hawaii cable (Winkler *et al.*, 1959). The cause of a failure in a telecommunication cable system during such a geomagnetic disturbance is from the reaction of the power supply system to the induced potentials. The total potential across the cable can become so large that the voltage drop is greater than the protection circuit of the powering system and thus the system can shut down automatically in the most severe situations.

A detailed analysis of an outage of a transcontinental cable during the 4 August, 1972 magnetic storm showed that potentials as high as ~ 7 V km^{-1} were induced along a cable route from near Chicago to northern Iowa (Anderson *et al.*, 1974). A study of ground-based and satellite data indicated that an ordinary auroral current system was not the principal cause of the induced ground potentials in the United States. Rather, the large magnetopause currents associated with the significant compression of the magnetosphere at the time of the cable disruption (compression to an altitude of ~ 4 R_E over North America; Hoffman *et al.*, 1975) apparently provided the causative external source. The rate of change of the magnetic field intensity and direction over North America during the 1 min interval of probable largest magnetosphere compression is shown in Figure 2 (Anderson *et al.*, 1974). The location of the disturbance interruption

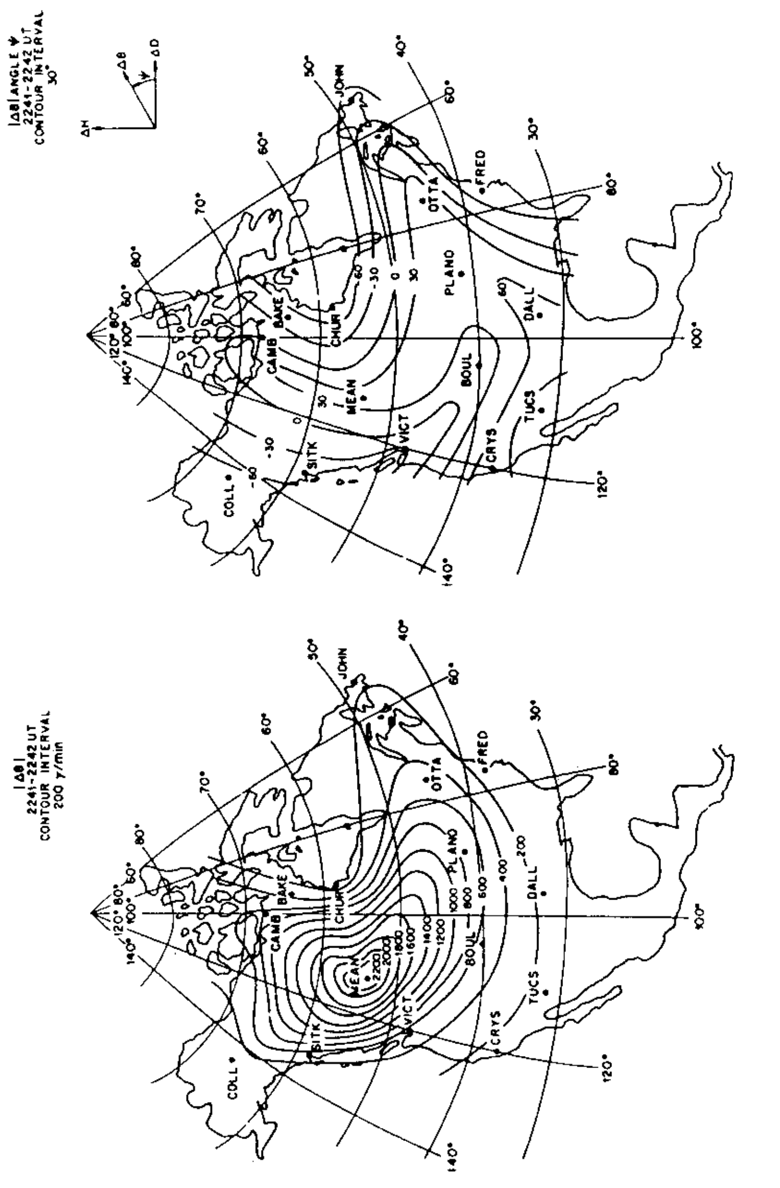

Fig. 2. Distribution across North America of the rate of change (per minute at the time specified) of the geomagnetic disturbance of 4 August, 1972, during the time of disruption of a telecommunications cable system at Plano, Illinois (from Anderson *et al.*, 1974).

(Plano) is shown. This diagram illustrates the nature of the scale size of the disturbance during the storm.

Recently, the diurnal and higher frequency variations in an operational transatlantic cable (TAT-6) have been studied more closely in order to possibly use the induced current measurements to draw conclusions about the nature of the Earth's conductivity structure under the Atlantic Ocean, including the mid-Atlantic ridge region (Medford *et al.*, 1981). Using a simple induction model, Medford *et al.* (1981) showed that the daily geomagnetic variation Sq can produce a voltage in the cable that has a diurnal dependence very similar to that measured. These authors found that an equality between the relative calculated voltage amplitudes (from a model Sq pattern) and the observed diurnal voltage (~ 5 V) implied an area of $\sim 10^{12}$ m^2 influenced by the induction process (where the cable length across the Atlantic was used as one dimension).

The data in Figure 3, from Lanzerotti *et al.* (1982), shows the induced voltage variations (top panels) on two days of moderate geomagnetic activity (7 May, 1980, $K_p = 1S$; 11 May, $K_p = 32$). Also shown are the magnetic field fluctuations in the north–south (H), east–west (D), and vertical (Z) components as measured at the western terminus of the cable. The dashed lines in all of the panels show the daily variations averaged over five geomagnetically quiet days in May. The voltage variations show higher frequency variations superimposed on variations which roughly follow the average daily patterns. The data from 7 May show the onset at $\sim$ 08 : 20 UT of a sudden magnetospheric impulse. This impulse in the magnetosphere, evidenced by sharp changes in the three magnetic field components, is reflected as a change of ~ 1 V in the cable powering voltage. Spectral analysis of the voltage and magnetic field variations show similar spectra, with power law slopes (varying with frequency as $\sim f^{-2.5}$) that are rather similar in each of the variables.

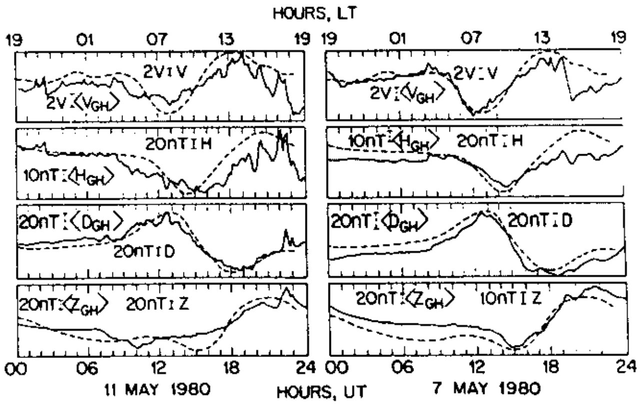

Fig. 3. Solid line: geomagnetic and induced voltage variations in the TAT-6 cable on two days with moderate geomagnetic activity. Dashed line: average quantities for five geomagnetically quiet days in May 1980 (from Lanzerotti *et al.*, 1982).

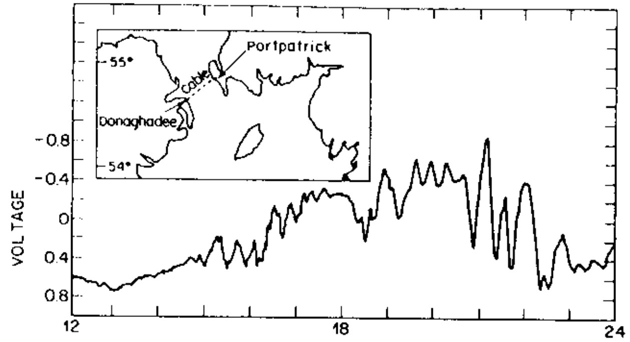

Fig. 4. Cable voltage on the Donaghadee–Port Patrick cable on a geomagnetically disturbed day (from Prandle and Harrison, 1975).

Shorter undersea cables (such as those across the Dover Strait) can be used for studies of tidal oscillations and water flow. Cables across the Irish Sea have been used for such studies in that region (for example, Prandle and Harrison, 1975; Prandle, 1979). Geomagnetic disturbances can affect the measurement capabilities and, hence, results of such a cable monitoring system. The data in Figure 4 are from chart recordings of the cable voltage on the Donaghadee–Port Patrick cable on a day of geomagnetic disturbances (Prandle and Harrison, 1975). The low frequency variation in the voltage, spanning the record, is produced by the tidal flow. The higher frequency variations, produced by geomagnetic storm-induction of currents in the cable, obscure the variations in such a manner that the data cannot be reliably used on such a day.

Wertheim (1954), in studying water flow across the Florida straits using the Key West-Havana cable, found occasional rapid variations in the cable voltage. He attributed these to geomagnetic effects and tried to model them using magnetometer data from the San Juan Observatory. Additional discussions of tidal and water flow effects on cables are contained in a recent review by Meloni *et al.* (1983).

Thus, geomagnetic induction can affect cable communication systems, both continental and oceanic, and can produce disturbances and/or disruptions in the systems. The measured induced currents can also be used for scientific purposes, for example in studying the nature of the crust in continental and ocean regions. Finally, geomagnetic induction effects can also disrupt scientific measurements which use voltage measurements to study waterflow in narrow straits.

3. Electric Power Systems

Disruptions of power systems by geomagnetic disturbances have also been well-documented in the past (e.g., Albertson *et al.*, 1973; Davidson, 1940; Slothower and Albertson, 1967; Gorely and Uvarov, 1981). For example, during a magnetic storm in

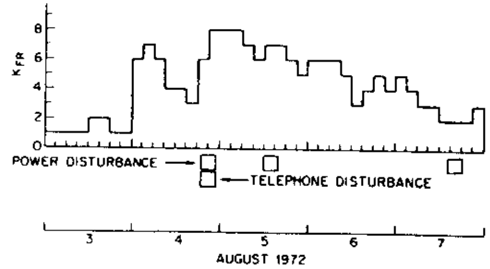

Fig. 5. Geomagnetic activity index from the Fredericksburg Geomagnetic Observatory during the period of intense geomagnetic activity in August, 1972. Times of disruptions of power and communications systems are indicated (from Albertson and Thorson, 1974).

1958, Toronto, Canada, was plunged into a temporary blackout because of the tripping of circuit breakers in an Ontario transformer station (Brooks, 1959). The possible problems of geomagnetically-induced effects on systems continues to be of considerable interest in the electricity transmission and distribution community (e.g., Albertson *et al.*, 1973, 1974; Sebesta, 1979; Wolff, 1979).

The relationship of power system disruptions to the geomagnetic activity (as measured by the Fredericksburg geomagnetic index) during the August 1972 magnetic disturbance (see also Figure 2) is shown in Figure 5 (Albertson and Thorson, 1974). Three major intervals of disturbances in the U.S. (primarily in the northern part of the country) were noted over the several days of the magnetic activity. However, as noted in the previous section, there is not a good one-to-one relationship between the magnetic activity index and the spectrum of the geomagnetic fluctuations of most interest in determining possible disturbances.

The geomagnetic currents induced in a power system can produce problems of several different types (Albertson *et al.*, 1973, 1974). First, the arbitrary differential relay operation in power distribution systems during geomagnetic storms can produce a judgmental problem; system operators are unsure of whether or not the malfunctioning relay indication is an induced current effect in a transformer or a real transformer malfunction. Second, the currents actually induced in the winding of a power transformer can result in half cycle saturation of the transformer core. This saturation can produce fluctuations in the transformer operation itself. This local heating can greatly shorten the lifetime of a transformer.

Examples of magnetic disturbance and the resulting geomagnetically-induced currents in the transformer windings at different utilities were given by Williams (1979). Auroral current-produced surges in a protective relay system and the auto transformer neutral current of a power substation near Fairbanks, Alaska, is shown in Figure 6 (Akasofu and Aspnes, 1982; Aspnes and Akasofu, 1982). As human activity becomes more intense in geographical regions that include the auroral regions, such induction effects will play a more significant role in defining the limits and directions of some technologies that will be employed (see following section).

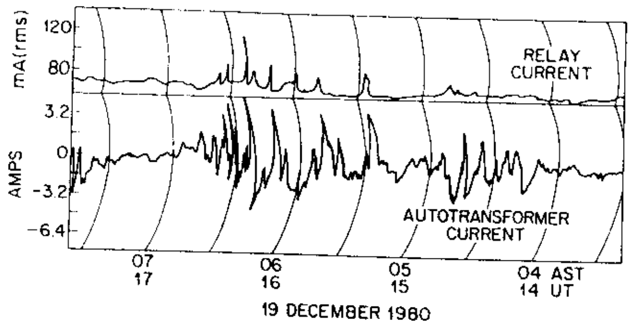

Fig. 6. Simultaneous recordings of geomagnetic induction effects observed as current surges in a protective relay system and an auto transformer in a power substation near Fairbanks, Alaska, on 19 December, 1980 (from Akasofu and Aspnes, 1982).

4. Pipelines

A pipeline represents another form of long conductor that can be affected by induced currents from natural geomagnetic activity. There does not seem to be a severe corrosion problem on present-day pipelines from induced currents (Peabody, 1979; Campbell, 1978, 1979), as long as cathodic protection circuits are in place. Rather, the induced currents are more of a nuisance in that they can interfere with engineering work associated with normal pipeline corrosion surveys.

The effects of auroral currents on the Alaskan pipeline, which extends for $\sim 1.3 \times 10^3$ km in an essentially geomagnetic north–south direction, across the auroral zone, is under active study (Campbell, 1980). Probably the most important effects that

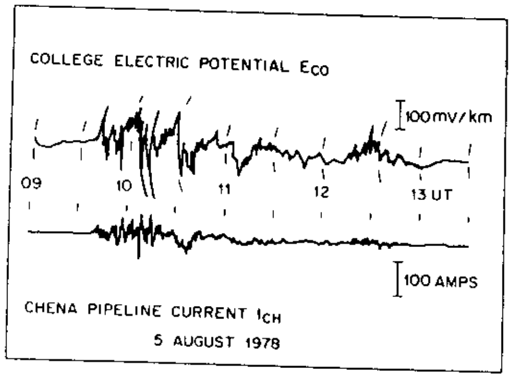

Fig. 7. Comparison of the Earth currents measured near Fairbanks and the induced currents measured in the Alaskan pipeline at the Chena test site (near Fairbanks) on 5 August, 1978 (from Campbell and Zimmerman, 1980).

can arise from the currents are their impacts on the pipeline monitoring and control electronics. Further, large induced currents of a transient nature can greatly disrupt, or even prevent, corrosion survey engineering studies on the pipeline.

A comparison of the current induced in the pipeline as measured near Fairbanks (Chena) and the Earth currents measured at Fairbanks (College) is shown in Figure 7 (Campbell and Zimmerman, 1981). Campbell (1980) has analyzed geomagnetic fluctuations as observed at Fairbanks and has been able to provide empirical predictions as to the time intervals expected between induced currents of a given magnitude. Such studies are of considerable importance for engineering design considerations of future long conducting systems that will be expected to operate in auroral regions.

Summary

The examples cited in the previous sections illustrate some contemporary engineering concerns involving the effects of geomagnetic induction in long, man-made conductors. As new technologies are implemented for operation in association with such conductors, the geographical and geomagnetic locations of the systems will have to be evaluated in order to ascertain the appropriate engineering design criteria for avoiding geophysically-produced impairments. Further, the use of such long conductors for scientific investigations must take into account the possibility of disturbances of geomagnetic origin which can at times affect significantly the primary measurements.

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