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THE EFFECTS OF GEOMAGNETIC DISTURBANCES ON ELECTRICAL SYSTEMS AT THE EARTH'S SURFACE

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ABSTRACT

Geomagnetic disturbances have affected electrical systems on the ground for over 150 years. The first effects were noted on the early telegraph in the 1840s and in this century magnetic storms have caused power system blackouts and phone system outages. Affected systems include all those that use electrical conductors: whether for transmission of power or signals or where the conducting properties are incidental to their use such as with pipelines and railway tracks. In power systems geomagnetically induced currents cause partial saturation of power transformers producing transformer heating and distortion of the ac waveform leading to misoperation of relays and other equipment. On pipelines, induced currents may contribute to corrosion but also present a problem with the electrical surveys of the pipe performed to monitor the corrosion prevention systems. Severity of these effects depends on disturbance size, proximity to the auroral zone, and the conductivity structure of the Earth. Also significant are system parameters such as the use of higher resistance coatings on pipelines and the linking of power systems into larger networks. In this paper we have attempted to catalogue all the published reports of geomagnetic effects on electrical systems and show their occurrence in the context of the solar cycle and geomagnetic activity variations for the years 1844 to 1996.

INTRODUCTION

On 13 March 1989, one of the biggest magnetic storms this century sent electric currents surging through power systems in N. America and northern Europe. The result was saturation of transformers, overload of equipment, lines tripped out of service, burn-out of transformers, and the collapse of the Hydro-Québec power system, leaving the 6 million residents of Québec without power for over 9 hours (Allen et al, 1989). These effects and the near-collapse of other systems have prompted a renewed research effort to understand how the geomagnetically induced currents (GIC) affect electrical systems at the Earth's surface.

Research into geomagnetic effects on electrical systems dates back to the last century and the early days of the telegraph. Varley (1873) reports on the aurora he observed in 1847 in the south of England and commented that, at the same time, all telegraph lines in operation in Great Britain were stopped by earth currents. He thought it might be said that this was the first time attention was fully drawn to the subject, and it was taken up not only by the officers of the telegraph company, but also by the Astronomer Royal. During a major storm in 1859 telegraph operators in Boston and Portland were able to disconnect their batteries and "for more than one hour they held communication with the aid of celestial batteries alone" (Prescott, 1866).

Telluric currents produced by a major magnetic storm in 1921 started fires at several telegraph stations in Sweden (Karsberg et al, 1959) and fire was again a danger to telegraph equipment during a major storm on March 24, 1940 (Harang, 1941). The major storm of August 4, 1972, produced an outage of the L-4 phone cable system in the mid-western US (Anderson et al, 1974). Submarine cables have also been affected by magnetic disturbances, and transatlantic communication from Clarenville, Newfoundland, to Oban, Scotland, during the magnetic storm of February 10, 1958, proceeded as alternately loud squawks and faint whispers as the naturally induced voltage acted with or against the cable supply voltage (Anderson, 1978). Voltages of 700 V were detected on the TAT-8 cable during the March 13, 1989 magnetic storm (Medford et al, 1989).

Pipelines are also long electrical conductors, often stretching thousands of kilometres across the Earth's surface. Early work on a 1128-mile pipeline in Canada noted the existence of stray currents that could not be accounted for by any of the usual sources and considered a possible association with magnetic disturbances (Allison and Huddleston, 1952). Telluric currents have been an ongoing problem for engineers setting up cathodic protection systems and the variations in pipe-to-soil potential (PSP) produced by telluric currents often make pipeline surveys difficult (Proctor, 1974; Peabody, 1978). Construction of the Trans-Alaska Pipeline right under the auroral oval prompted considerable work on the currents that might be induced (Campbell, 1978) and has required special monitoring techniques to be developed (Degerstedt et al, 1995). More recently there has been renewed concern about telluric currents because the higher resistance coatings used on modern pipelines means that the telluric currents produce voltage fluctuations that are much larger than those on the older pipelines.

The magnetic storm of March 24, 1940 produced the first reported effects on power systems (Davidson, 1940). Many utilities in the northern US reported problems ranging from voltage dips and reactive power swings to tripping of transformer banks. Problems again occurred during the next period of major storms, including September 22, 1957 and February 11, 1958 when there was a blackout in the Toronto area (Lanzerotti and Gregori, 1986). For the next peak in solar activity a study of geomagnetic effects was sponsored by the Edison Electric Institute and recordings of GIC were made on power systems across N. America (Albertson et al, 1974). During this time a number of system disturbances occurred on the Bowater Power Company's system in Newfoundland (Fisher, 1970), but it was not until solar activity was declining that the next major system effects happened with the occurrence of the August 4, 1972 magnetic storm. Manitoba Hydro, Hydro-Québec and the Newfoundland and Labrador Power Commission all reported voltage fluctuations and tripping of equipment; and quasi-dc currents of over 100 A were measured in transformer neutral-ground connections at Corner Brook, Newfoundland, and at La Verendrye and Grand Rapids, Manitoba (Albertson and Thorson, 1974), in addition to the L-4 cable outage mentioned earlier.

On March 13-14, 1989, the Earth experienced one of the worst geomagnetic storms recorded this century. The most serious effect of the storm occurred at 02.45 EST on March 13 when widespread geomagnetically induced currents caused the saturation of transformers on the Hydro-Québec power system. The resulting harmonics caused the tripping of several static VAR compensators, especially at Chibougamau and La Vérendrye substations. This led to voltage oscillations and power swings that caused a trip out of the lines from James Bay and the collapse of the system (Czech et al, 1992). In addition to Hydro-Québec, the Northeast Power Coordinating Council (NPCC) and the Mid-Atlantic Area Council (MAAC) power pools, which serve the entire northeastern United States from New England to Washington, D.C., were nearly involved in a cascading system collapse. Public Service Electric & Gas Co. did experience damage to two generator step-up transformers which necessitated their replacement (Balma, 1992).

The occurrence of geomagnetic effects on the operation of electrical systems are shown by black diamonds in Fig. 1, and the effects are described in an Appendix. Fig. 1 also shows the smoothed sunspot cycle and the occurrence of magnetic disturbances with aa*>60nT and with aa*>120nT. aa* is a 24-hour running mean of the 3-hourly aa magnetic index values. Allen (1994) has used this to create a list of the largest magnetic storms in the period for which aa values are available, ie since 1868. We have extended the record back to 1844 by using aa values derived from recordings of the Helsinki magnetic observatory (Nevanlinna and Kataja, 1993). The development of electro-technology started with Faraday's work in 1832 and Morse's and Wheatstone's patents for the telegraph in 1837. But it was only with the perfection of Daniell's and Grove's batteries in 1843 that allowed the telegraph to be operated to significant distances. Thus Fig. 1 shows the occurrence of magnetic disturbances during the whole period for which electrical systems have been in use.

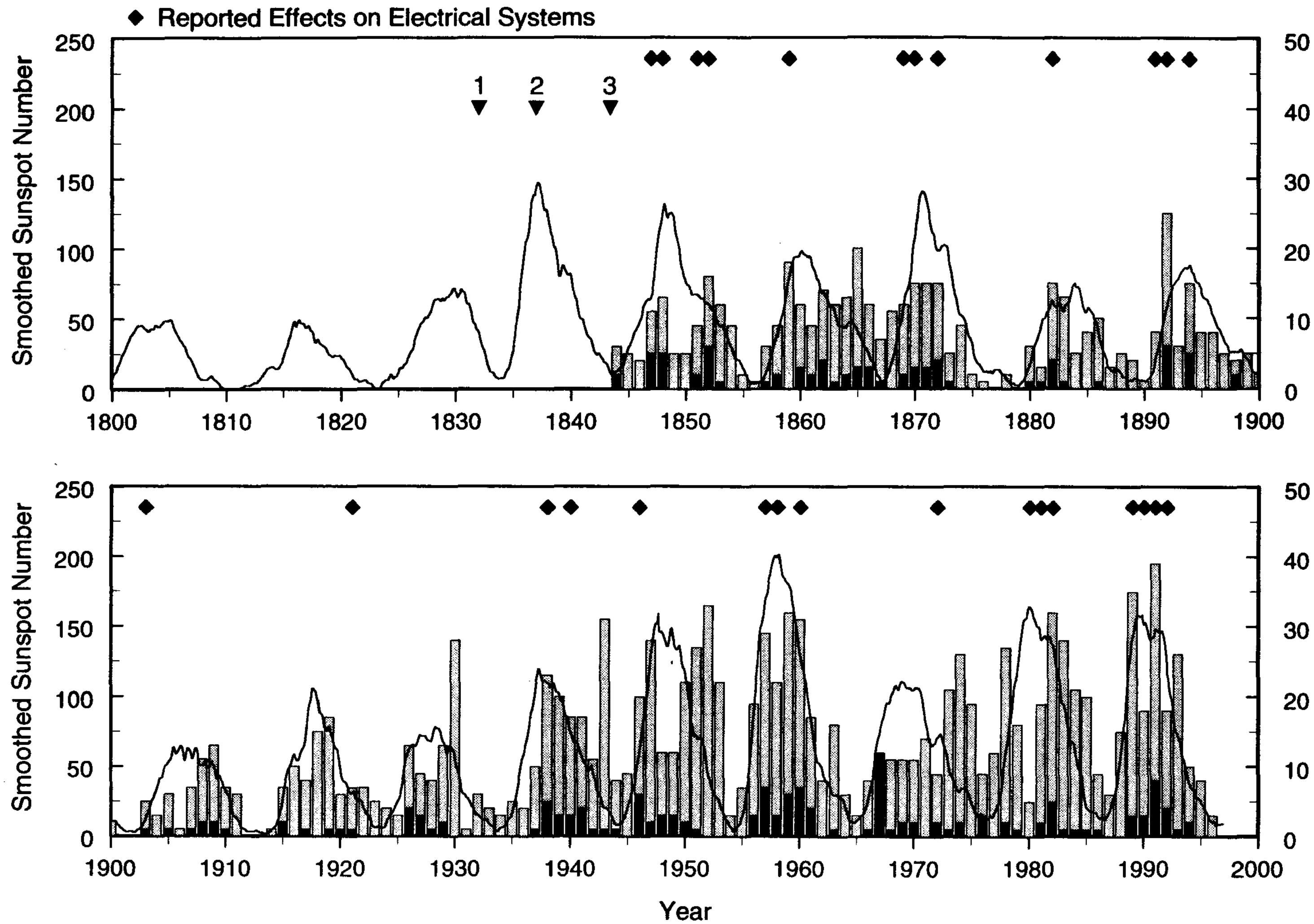

Fig. 1. Solar and geomagnetic activity and the occasions when this has disrupted the operation of long electrical systems on the Earth. Number of magnetic disturbances with aa*>60 nT is shown by the grey bars, and with aa*>120 nT is shown by black bars. Smoothed sunspot number is shown by the solid line. The development of long electrical systems is marked by:
1, Faraday's discovery of electromagnetic induction in 1832, **2**, Morse's and Wheatstone's patents for the telegraph in 1837, **3**, the perfection of Daniell's and Grove's batteries in 1843, that allowed the telegraph to be operated to significant distances.

OCCURRENCE OF DISTURBANCES

It is obvious from Fig. 1 that the occurrences of disturbances on electrical systems are clustered in the years around the peak of each solar cycle. Burbank (1905) mentions that the years 1848, 1859-60, 1872, 1883, and 1903 were characterised by particularly severe disturbances to telegraph operation, and commented that the major disturbance on October 30-31, 1903 occurred almost exactly 55 years after the heavy disturbances of October 27-28, 1848. However, every disturbance on the Sun is not followed by a corresponding event at the Earth's surface. Quenisset (1903) pointed out that, whilst the passage of a large group of sun-spots across the Sun's central meridian on October 31, 1903, coincided with a terrestrial magnetic storm of exceptional activity, the passage of a much larger group on October 11 was marked by a very faint perturbation of the magnets.

As well as following the solar cycle, geomagnetic activity has a seasonal variation due to changes in the coupling between the Earth's magnetic field and the interplanetary magnetic field (Russell and McPherron, 1973). A similar variation is to be expected in the occurrence of system effects. This was first tested by Tromholt (1885) who recorded the number of disturbances each month on four telegraph lines in Norway. The sum of the disturbances on all four lines is shown in Fig. 2 and clearly shows the same peaks near the equinoxes as observed in the occurrence of geomagnetic disturbances.

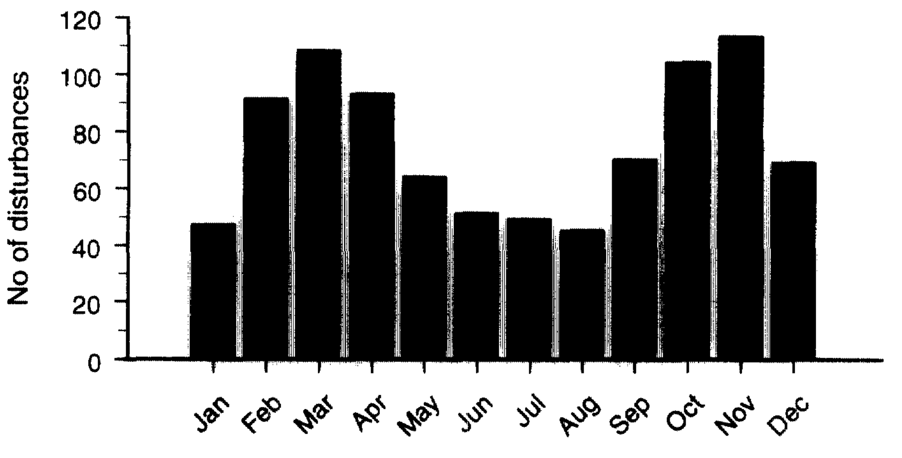

Fig. 2. Sum of telegraph disturbances in each month recorded on four lines in Norway during the years 1881 to 1884 (drawn from data given in Tromholt (1885)).

Tromholt (1885) also tried to examine the diurnal variation of telegraphic disturbances but the telegraph was only operated during the day so his results are limited. On modern systems the disturbances are too sporadic to use to investigate the diurnal variation. However, the occurrence of magnetic variations that are critical to power systems has been examined in a study of geomagnetic hazard conducted in partnership with the Canadian power industry (Boteler et al, 1997). Statistics on peak dB/dt values and hourly range values were compiled using 16 years of data from the Canadian magnetic observatory network which extends from mid latitudes to near the magnetic pole. The occurrence of X component hourly range values > 240 nT and X component hourly maximum dB/dt > 60 nT/min are shown in Fig. 3. Both plots show a peak occurrence near midnight at lower latitude stations. Moving polewards the occurrence pattern shifts to a later time and at the high latitude stations the magnetic activity is principally in the day time. Similar results were obtained for the Y component.

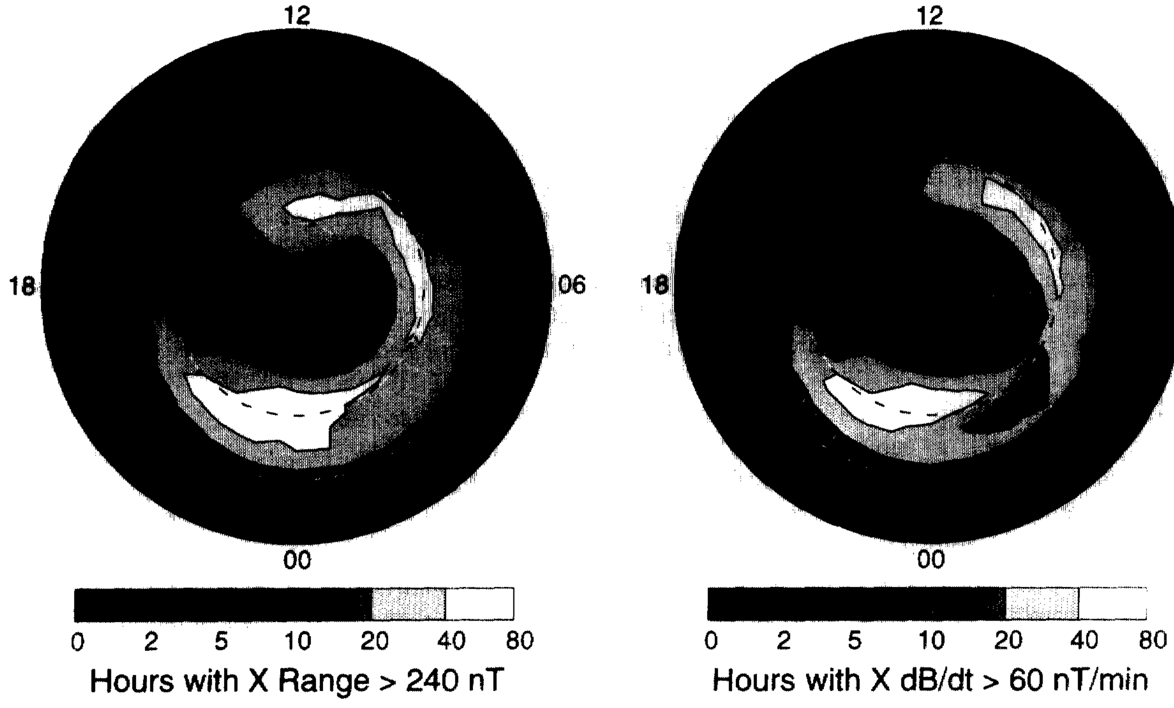

Fig. 3. Occurrence of magnetic hourly range values > 240 nT and hourly max dB/dt > 60nT/min. The numbers represent average yearly values derived from an analysis of 16 years of data, 1976 to 1991, from 9 Canadian magnetic observatories. The edge of the plot is at geomagnetic latitude 50°. Inner circles show geomagnetic latitudes 60°, 70°, 80°.

SUSCEPTIBILITY TO GEOMAGNETIC DISTURBANCES

Whether a system is affected by a geomagnetic disturbance depends on two sets of factors: the geophysical parameters that determine the size of the electric fields in the system, and the engineering characteristics that determine the response of the system to that electric field. The occurrence of geomagnetic disturbances likely to affect electrical systems has been outlined in the previous section. The electric fields that these disturbances create are dependent on the conductivity structure of the Earth and high resistivity regions are more affected than others. Conductivity contrasts, such as occur at a coastline, can also produce larger electric fields that increase the hazard for systems in the area. The system configuration can have a significant effect on where induced currents flow to ground and which parts of the system are most affected (Boteler et al, 1997).

A general characteristic affecting all systems, shown by Fig. 3, is their proximity to the auroral zone and the auroral electrojet currents flowing there in the ionosphere. However, because the auroral zone is expanded during large events, the worst effects can occur at lower latitudes than indicated by Fig. 3. For example, during the March 13, 1989 magnetic disturbance the auroral oval had expanded considerably, and it was the rapid westward expansion of the westward electrojet that was responsible for the blackout of Québec (Boteler and Jansen van Beek, 1993). These authors also show that, later, an eastward electrojet extended down across Canada and the US and produced disturbances on power systems from coast to coast. It is this disturbance that was most likely responsible for the burn-out of the transformer at the Salem generating station on the US east coast. Medford et al (1989) comment that "Such an intense, long-lasting, eastward current, and at such low magnetic latitudes, has, to the best of our knowledge, not been reported previously".

The comment by Medford et al (1989) is probably correct, but we believe that an equally significant eastward electrojet has occurred before, and that it was the cause of the L-4 cable outage in 1972. This event was investigated by Anderson et al (1974) who found that a rapid change of the magnetic field coincided with the system outage. Their contour map of the disturbance shows that the disturbance was centred over Meanook, Canada, and extended down over the mid-western US where the outage of the L-4 system occurred. Anderson et al (1974) concluded that the disturbance responsible for the L-4 outage was produced by a compression of the magnetopause that occurred at the same time. However, the magnetic disturbance on the ground was too localised to have been produced by currents at a height of 32500 km, the position of the magnetopause at the time of the L-4 outage. Instead, the spatial extent of the magnetic disturbance is more consistent with that produced by currents at a height of 100 km, ie in the ionosphere. A re-examination of the magnetic records from 1972 is underway to determine the current systems involved.

The engineering dimension involves design questions such as the reserve capacity of the power feed equipment on a submarine cable (Root, 1979) or the type of cathodic protection used on a pipeline (Smart, 1982; Shapka, 1993). Power systems are affected by geomagnetic disturbances because the geomagnetically induced currents flowing through transformer windings cause extra magnetisation that can saturate the transformer core. This causes distortion of the ac waveform with high harmonic currents that cause misoperation of system relays. Additionally, magnetic flux spilled out of the core can cause eddy currents in structural members of the transformer resulting in hot-spots that may damage winding insulation. The full extent of these effects are described by Albertson et al (1993) and Bozoki et al (1996). Whether particular systems are affected by geomagnetic disturbances can depend significantly on system characteristics and the design of particular pieces of equipment, particularly the transformers. For example, the choice of transformers in Finland has meant that they seldom operate at their highest capacity and, although Finland experiences large geomagnetic disturbances, no significant GIC inconveniences have occurred there.

Measures can be taken to make systems less vulnerable to geomagnetic disturbances. For example, power feed equipment on modern cable systems has been designed to cope with larger voltage swings than was the case in the past. On power systems the response has been to block the flow of geomagnetically induced currents and systems have been developed for insertion in the neutral-ground connection of transformers (Kappenman et al, 1991). On the Hydro-Québec system capacitors have been inserted in many of the transmission lines to block GIC flow (Blais and Metsa, 1993). Blocking current flow has also been suggested as a remedy for geomagnetic effects on pipelines (Peabody, 1979). However, in some situations this does not limit the size of the induced currents and just creates another site where the currents are forced to flow to ground and so may actually increase the problem (Boteler and Seager, 1997). This shows that a full understanding of the interaction of geomagnetic disturbances with each system is needed before planning a mitigation strategy.

DISCUSSION

Many different man-made systems are affected during geomagnetic disturbances (see Lanzerotti, 1979a,b). Here we have only attempted to document the effects of geomagnetic disturbances on electrical systems at the Earth's surface. Our list only shows incidents that can be related to a specific magnetic disturbance, and it is likely that some failures, due to cumulative effects, have never been related to geomagnetic influence. Such cumulative action has usually been associated with pipeline corrosion, but there is now evidence that GIC may also be producing cumulative stresses on generator step-up transformers (Kappenman, 1996). The events listed in the Appendix are only those for which we could find a published source. There are a few events for which we only have anecdotal evidence, and these have not been included. There are other events where we have hints that something happened but have been unable to find the original sources. For example, Stetson (1947) in his book on sunspots recalls headlines from the previous two or three years such as: "Sunspots Blot Out U.S.-Europe Radio"; "Record Sunspot Upsets World Communication"; "Sunspots Jam Radio - Delay Ocean Planes"; "Sunspots Cause Phone Failures Across the Atlantic". However we have not found the newspaper articles or any other reports describing these events. The list of magnetic storms compiled by Allen (1994) provides a useful guide as to when effects could be expected to have occurred on technological systems. In 1946 there were two notable magnetic disturbances: March 28-29 which had an aa*=329 and is 9th in Allen's list of largest storms, and September 22-23 which had an aa*=295 and is the 17th largest storm recorded. Another notable event occurred on September 18-19, 1941 but we know of no reports of technological effects for this time. This is surprising because the magnetic storm had an aa*=429 and is 2nd only to the March 13, 1989 storm in the list of largest disturbances. Thus more reports of system effects may be uncovered as further research is done on this topic.

ACKNOWLEDGEMENTS

The starting point for the catalogue of geomagnetic effects given in Appendix A was the paper by Lanzerotti and Gregori (1986) and the references therein. George Siscoe referred us to Stetson's (1947) book.

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APPENDIX: MAGNETIC DISTURBANCES THAT HAVE AFFECTED ELECTRICAL SYSTEMS AT THE EARTH'S SURFACE

1847, Mar. 19 Sept.24-25 Oct. 23-25	Spontaneous deflections observed in the needles of the electric telegraph in England. It was noticed that the largest deflections occurred whenever aurora were visible. (Barlow, 1849; also see Varley, 1873).
1848, Oct 27-28	Occasion of heavy disturbances on the telegraph (Burbank, 1905). Matteucci remarked the coincidence of aurora with interruptions in telegraphic communications, produced by telluric currents (Angot, 1897, p 138).
Nov. 17	Appearance of the aurora coincided with effects on the electric telegraph between Florence and Pisa (Prescott, 1866, p 317).
1851, Sept.	Prescott (1866) reports, " a remarkable aurora, which took complete possession of all the telegraph lines in New England, and prevented any business from being transacted during its continuance".
1852, Feb. 19	Brilliant auroral display observed. Associated with it were currents that burnt through the chemical paper used with the Bain's chemical telegraph in the northeastern US (Prescott, 1866, p 318).
1859, Aug. 28 - Sept. 2	Mr O. S. Wood, Superintendent of the Canadian telegraph lines, says: "... so completely were the lines under the influence of the aurora borealis, that it was found utterly impossible to communicate between the telegraph stations, and the line was closed for the night". Problems also reported by telegraph operators in New York, Washington, Philadelphia, Vermont and Massachussetts (Prescott, 1860, 1866; also see Clement, 1860) and Gothenburg, Sweden (Rubenson, 1882). At all telegraphic stations in France service was impeded during the whole of September 2 (Blavier, 1859; see also Angot, 1897).
1869, May 30	Out of the sixteen lines which terminated in the telegraphic office at Basle, six were almost useless during the two hours that the phenomena lasted (Angot, 1897, p 141).
1870, April 5 & Oct 24	Coincidences between aurora borealis and telluric currents in telegraphic service noted by Angot (1897), p 142.
1872, Feb 4	The telluric currents attained an extraordinary development during the aurora which was one of the most extensive known. The disturbances in telegraphic communication were not less extensive. In Germany all the lines were affected, and communication was for a long time impossible between Cologne and London. Telluric currents were also observed in England, France, Austria, Switzerland, Italy and Turkey. Transmission of messages was also prevented on submarine cables, especially on the line from Lisbon to Gibraltar, on the line from Suez to Aden, and from Aden to Bombay, and on the transatlantic cable from Brest to Duxbury (Angot, 1897; see also Arrhenius, 1903).
1872 - 1873	Earth current effects on Atlantic cables (Graves, 1873), wrongly attributed to earthquakes.
1882, Nov 17	Telluric currents observed in England were, according to Preece [Superintendent of the Telegraph] five times as strong as the current usually employed in telegraphy. Communication was interrupted as long as the disturbance lasted (Angot, 1897, p 143).
1891	Electromotive force of 768 volts was recorded on the Western Union lines between New York and Buffalo, the circuits varying from 450 to 480 miles in length. On several occasions the strength of the earth current reached nearly 300 mA, compared to normal working currents that did not excced 35 mA (Finn, 1903).
1892, July 16	Serious interruption of wire service in US (Sanders, 1961). Burbank (1905) gives details of voltages observed on various lines, including 210 volts, about 9 V/km, on line from New York to Elizabeth, N.J.
1894, Mar 30-31	Telegraph operators had been supplied with telephones and heard a variety of sounds produced by earth currents in the lines (Preece, 1894).

1903, Oct 31	Practically the world's whole telegraph system was upset, and information from England, France, the United States and other lands shows that for several hours communication was almost completely interrupted (Lockyer, 1903; see also Finn, 1903).
1921, May	Karsberg et al (1959) report that induced currents caused fires in telegraph equipment in Sweden. Exact date is not given, but Chapman and Bartels (1940) show that a great magnetic storm occurred on May 13 - 15, 1921.
1938, Apr. 16	Several hundred volts on wires in Norway (Chapman and Bartels, 1940). Problems on telegraph system in Norway same as occurred in 1940 (Harang, 1941).
1940, Mar. 24	First reported effects on power systems, with voltage dips, large swings in reactive power, and tripping of transformer banks, reported from power companies in the US and Canada (Davidson, 1940). Effects also observed on the telephone and telegraph systems in US (Germaine, 1940; Stetson, 1947) and Norway (Harang, 1941; repeated in Ramleth, 1982).
1946, Mar 28	Transformers tripped at Port Arthur and Crow River, Ontario (Acres, 1975).
Sept. 22	Transformer tripped out of operation at Port Arthur, Ontario (Acres, 1975)
1957, Jan. 21	Disturbances on power feeding circuits on transatlantic submarine cables (Axe, 1968).
1957, Sept. 22	Power system effects: trip of 230kV breaker due to saturation of transformer cores and excessive 3rd harmonic currents in ground relays (Slothower and Albertson, 1967).
1958, Feb. 10	Toronto area suffered from a blackout (Lanzerotti and Gregori, 1986). Abnormal power flows in Minnesota (Slothower and Albertson, 1967). TAT-1 transatlantic cable suffered a disruption of service (Winckler et al, 1959).
1960, Nov. 13	Disturbances on power feeding circuits on Transatlantic cables (Axe, 1968). Tripping of 30 line circuit breakers in Sweden (Tillberg and Andersson, 1977; Elovaara et al, 1992).
1972, Aug. 4	Outage of the L-4 cable system in the continental US (Anderson et al, 1974). Problems also experienced on power systems (Albertson and Thorson, 1974).
1980, Oct.	Trip of 500 kV line from Manitoba to Minnesota (Aspnes et al, 1981).
1981, Apr.	Trip of 500 kV line (again) from Manitoba to Minnesota. (Aspnes et al, 1981).
1982, July 13	Four transformers and 15 lines tripped in Sweden (Elovaara et al, 1992).
- July 14	Railway traffic signals were turned to red by the induced voltage (Wallerius, 1982)
1989, Mar. 13 - Mar. 14	Blackout of Québec for 9 hours, and effects on other power systems across North America including burnout of power transformers (Allen et al, 1989; Cucchi and Ponder, 1991). Five 130 kV lines were tripped in Sweden (Elovaara et al, 1992).
1989, Sept 19	Transformer damage on Public Service Electric & Gas system (Bozoki et al, 1996).
1989, Oct 20	SC tripped by neutral unbalance protection (Bozoki et al, 1996).
Nov 17-18	SC tripped by neutral unbalance protection (Bozoki et al, 1996).
1990, Mar 30	SC tripped by neutral unbalance protection (Bozoki et al, 1996).
1991, Mar. 24	Nine 220 kV lines and one transformer were tripped in Sweden (Elovaara et al, 1992). Low voltage, zero-sequence capacitor neutral and transformer harmonic alarms and tripping of capacitor bank and SVC in US (Bozoki et al, 1996).
1991, Apr 28	SC removed from service on Allegheny Power System in US (Bozoki et al, 1996).
May 16	Capacitor neutral harmonic alarm on Allegheny Power system (Bozoki et al, 1996).
May 28	Filter arrester failed on Québec - New England DC link (Dickmander et al, 1994).
June 4-5	BC Hydro 138 kV line tripped on ground overcurrent (Bozoki et al, 1996).
June 10	Transformer removed from service and several SC trips in US (Bozoki et al, 1996).
Nov 8	minor effects on US power systems (Bozoki et al, 1996).
1991, Oct. 28	The Québec - New England DC line tripped out of service (Blais and Metsa, 1993). In the US, capacitor banks and transformers tripped out, voltage dips occurred and the New Mexico HVDC terminal tripped (Allen and Wilkinson, 1993, Bozoki et al, 1996).
1992, Sept 10	115 kV SC tripped on Central Hudson Gas & Electric in US (Bozoki et al, 1996).
Nov 11	115 kV SC tripped on Central Hudson Gas & Electric in US (Bozoki et al, 1996).