Study of the Disruption of Electric Power Systems by Magnetic Storms

Acres Consulting Services Limited
Niagara Falls, Ontario
1975

Energy, Mines and Resources Canada
Earth Physics Branch

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GEOMAGNETIC SERVICE OF CANADA

Study of the Disruption of Electric Power Systems (in Canada) by Magnetic Storms

Acres Consulting Service Ltd.

40 pp.
Price $8.00

Earth Physics Branch Open File No. 19
Ottawa, Canada
1977

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March 1975

Earth Physics Branch Open File 77-19

DEPARTMENT OF ENERGY,
MINES AND RESOURCES

Ottawa 3, Ontario

STUDY OF THE DISRUPTION OF ELECTRIC POWER SYSTEMS BY MAGNETIC STORMS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

TABLE OF CONTENTS – 2

LIST OF TABLES

Number | Title

LIST OF FIGURES

1 INTRODUCTION

Solar induced earth currents result when increased solar flare activity causes disturbances of the ionosphere in the form of geomagnetic storms. In a program designed to measure (over a 2-year period) the effects of the solar induced currents (SIC's) on transmission lines, primarily in the United States, Dr. Vernon Albertson* measured dc currents of up to more than 100 amp apparently attributable to SIC's and the cause of many relay trips. Interruptions of electricity supply have been reported by the Bowaters Paper Company on numerous occasions during the more intense of these storms. Since the zone of maximum auroral activity lies through Canada at midnorthern latitudes, the Department of Energy, Mines and Resources, Earth Physics Branch, became concerned over the possible effects on Canadian transmission lines, particularly in light of the steady increase in generation and transmission developments toward the north. Another trend of concern was the increase in intersystem ties so that disruption of one system can affect many.

In January 1975, the Department awarded a contract to Acres Consulting Services Limited with the following principal objectives:

(a) To determine, through a survey of principal Canadian electrical utilities, the economic cost because of failure to meet demand caused by SIC.

(b) To project the cost into the future based on known electric utility systems expansion plans.

This report documents and discusses the results of the survey.

Although the information contained in this report was obtained from a number of individual sources, the interpretation of these data has been made entirely by Acres Consulting Services Limited personnel. Thus, any errors or discrepancies remain the responsibility of the authors rather than the individual contributors. The assistance of the latter is nevertheless gratefully acknowledged.

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*Program was funded by the Edison Electric Institute. Dr. Albertson has acted as Specialist Consultant to Acres Consulting Services Limited on this project.

2 SUMMARY AND CONCLUSIONS

In the course of this study, Acres Consulting Services Limited made personal visits to the offices of:

- Newfoundland and Labrador Power Commission
- Hydro-Quebec
- Ontario Hydro
- Manitoba Hydro
- Saskatchewan Power Corporation

In addition, extensive telephone discussions were held with one or more representatives of Bowaters Paper Company and the power utilities of Nova Scotia, New Brunswick, Alberta and British Columbia. Also contacted were Calgary Power Company, Calgary Electric Company and the Northern Canada Power Commission, together with Memorial University in Newfoundland and the University of Saskatchewan.

On the basis of the data obtained and the discussions held, we conclude that, with the exception of Newfoundland, no other areas of Canada have suffered or are presently suffering any significant financial losses as a result of geomagnetic disturbances.

It is widely recognized that SIC's do indeed intrude into electric power systems many times each year, and often reach appreciable values of between 50 amp and 100 amp, or more. The duration of such currents varies from a very few minutes to as long as 15 minutes or more. Of the various utilities contacted, many (but not all) are making some form of measurements but, with the exception of Hydro-Quebec and Newfoundland, we conclude that the industry in general is not overly concerned about the situation.

Hydro-Quebec is concerned on two counts. Firstly, that their existing EHV system may have, in some way, already suffered some loss of life expectancy. They recognize that this is difficult to assess accurately but, apart from a relatively ambitious research program, they seem to be prepared to let matters take their natural course. Their second concern is that they may eventually suffer more severe problems in their projected east-west collector system in the Baie James project.

The problem in Newfoundland is more concrete. Equipment failures are minimal, but economic costs due to production losses in certain mines and paper mills together with energy interchange problems with the Power Commission do occur, and costs vary from as low as $10,000 in a "good" year to in excess of $100,000 in a "bad" year.

British Columbia Hydro is contemplating a long 500-kv line running east-west through the Rockies. Their position with regard to SIC's is, however, not yet formulated.

Elsewhere in Canada, SIC's frequently produce a variety of relatively minor system disturbances, but most systems are now so well integrated that no economic consequences have been identified.

3 UTILITIES SURVEYED

3.1 General Approach

Paragraph (c) of the Acres Consulting Services Limited contract document "Specific Work Items" requires Acres to contact five principal electrical utilities and enquire into the extent and cost of system disruptions caused by geomagnetic storms. These contacts were made by members of Acres staff making personal visits to the most appropriate representatives of the utilities selected. In geographic sequence, the utilities visited were:

- Newfoundland and Labrador Power Commission
- Hydro-Quebec
- Ontario Hydro
- Manitoba Hydro
- Sasketchewan Power Corporation

In general, the initial contact with each utility representative was made by a phone call, during which the general nature of the assignment was outlined. A tentative schedule for each visit was arranged during these calls. These calls were followed by a Telex to each contact (see Appendix A), listing the type of information being sought and a listing of the dates of the principal geomagnetic storms recorded for the years 1970 through 1974 inclusive. These dates had previously been obtained from the Earth Physics Branch of the Department of Energy, Mines and Resources.

A period of at least one full day was spent in the offices of each of the above-named utilities, examining past records and discussing the matter with interested persons. Such discussions frequently led to additional personal contacts being made. Whenever possible, these contacts were followed up in person, but in cases where such was not practicable, extensive telephone discussions were held.

As these visits progressed, and a general pattern began to emerge, additional telephone contacts were made in order to extend the coverage as widely as possible. Among the additional contacts made in this manner were:

- Bowaters Paper Company, Corner Brook
- Memorial University, St. John's

- Nova Scotia Power Commission
- New Brunswick Power Commission
- Calgary Power
- Alberta Power
- City of Calgary Electric System
- British Columbia Power Commission
- Northern Canada Power Commission
- University of Saskatchewan, Saskatoon

Thus, it may be said that by the end of the survey period at least one major electrical utility in each province (except Prince Edward Island) had been contacted in one manner or another.

3.2 Newfoundland

3.2.1 Newfoundland and Laborador Power Commission

The St. John's office of the utility was visited on February 17, 1975. During the day the trouble report summary sheets for 1970 through 1974 were examined in detail with specific reference to those dates on which significant magnetic disturbances had occurred. Detailed discussions were also held with Power Commission personnel responsible for monitoring such events. Of all the provinces across Canada, Newfoundland is undoubtedly the one most affected by and conscious of geomagnetic disturbances.

In Newfoundland, the history of such events goes back at least as far as 1959, when the copper neutral ground connection of a large transformer was melted off, allegedly by either a SIC itself or the transformer harmonic currents created thereby. This event was, of course, outside the period of our study, and in any case resulted in only a negligible amount of financial damage.

More recently, however, the Power Commission did in fact suffer a major transformer failure. The unit affected was a 230-66-kv, 83-Mva transformer located at Long Harbour (near St. John's). At the time, the transformer was 2 years old. The failure occurred on October 31, 1969, at 2206 hours local time. However, since the location of the failure was subsequently found to be in the 230-kv winding, i.e. toward the outer sections of the winding rather than in the core, it is concluded that the failure was not related to SIC.

Nevertheless, SIC's are very much in evidence in Newfoundland. The Power Commission has for some years maintained two recording instruments which, from time to time, are rotated around the various substations. These instruments record the magnitude and polarity of any dc currents which flow in the neutrals of the main transformers. On occasion, these currents have been known to go off-scale on a 100-amp instrument.

To date, while there has been no evidence of any equipment failure resulting from these currents, they do in fact cause a significant loss of revenue to the province as a whole. This loss of revenue is brought about by the fact that solar induced dc currents flowing through a "wye-grounded" transformer winding increases the magnetizing current in that winding only, thereby activating the differential relays. The "nuisance trips" thus caused have given rise in the past, and no doubt will continue to give rise in the future, to significant losses of revenue to both the Commission and to the customers affected.

The most recent example of this is at the small mining town of Buchans, where the present load is about 5 Mw. A new 230-kv line and a 10-Mva transformer was installed a little over a year ago, and has already tripped out twice due to SIC effects. Each time the shut-down has lasted several hours. The loss of revenue to the Power Commission is probably not more than $200 to $300 for each event. The loss to the mine has not been investigated, but is almost sure to be considerably more.

3.2.2 Bowaters Paper Company

While the example quoted above does not appear notably costly, the similar effects on the Bowaters Paper Company's installations at Deer Lake and Corner Brook are most certainly in a different category. In addition to its paper mill at Corner Brook, this company operates a significant amount of its own generation (in excess of 100 Mw), some of it at Deer Lake and some at Corner Brook. These two plants are connected by four 69-kv circuits about 50 miles long. Most of the older equipment runs at 50 hertz, so that three of these lines operate at 50 hertz and the fourth line at 60 hertz. The connection to the Power Commission at Corner Brook includes a 25-Mva frequency converter. Here again the primary cause of outages is faulty tripping of transformer differential relays but, at this location, unless proper precautions are taken considerable loss of production results. While in St. John's, the Acres representative had several long telephone discussions with two members of the Bowatersstaff at Deer Lake. It would appear that handling SIC's is now relatively routine. Upon receipt of a warning from Boulder, Colorado, Bowaters and the Power Commission so arrange their generation schedules that the net flow of power across the Corner Brook frequency converter is effectively zero, i.e., the machine is running as "spinning reserve" only, for use in case of emergency. Thus, if it is tripped off by a SIC, it does not affect the production of paper. There are, however, occasions when even these precautions are insufficient. The resulting effects are described in Subsection 5.2.

3.2.3 Visit to Memorial University

While in St. John's, the Acres representative took the opportunity to meet with Professor J. Wright of the Geophysics Department. Geological maps of the Deer Lake/Corner Brook/Buchans area were examined. From these and other data made available by Professor Wright, it was concluded that the troubles outlined above were almost certainly caused by SIC's seeking to bridge areas of high ground resistivity. Deer Lake lies in an area of relatively low ground resistivity. Corner Brook is close to the sea and lies on the opposite side of a major fault in the bedrock. The last 8 to 10 miles are also of a higher resistivity rock. Similarly, the line from Deer Lake to Buchans crosses over a second major rock fault.

Unfortunately, at the present time, no definitive studies have yet been made to establish the direction of potential gradients in the Deer Lake area, but Professor Wright is of the opinion that, particularly at times of geomagnetic disturbance, they are such as to tend to produce a flow of current from Deer Lake to both Corner Brook and Buchans. The fact that the lines which cross these areas have a wye-grounded transformer at each end leads to the conclusion that the lines are acting as bridges across the high-resistance areas. The fact that one line runs approximately northeast-southwest and the other runs essentially east-west remains an unexplained factor at this time.

3.3 Hydro-Quebec

The Montreal offices of Hydro-Quebec were visited on February 11, 1975. The greater part of the visit was spent in the office of the Equipment Maintenance Department where, in addition to obtaining full access to all necessary data on equipment failures over the last 5 years, a complete set of daily trouble reports for the same period was examined.

From a preliminary discussion of the situation, it was concluded that Hydro-Quebec is very much conscious of the presence of SIC's and also of their potentially harmful effects. To date, however, it has not experienced any major problems which can be specifically attributed to such events. Since commissioning the 735-kv system 9 years ago, it has had what may be considered an enviable record of reliability. Similarly, the remainder of the system at 300 kv, 230 kv and lower voltages appears to have a sufficiently low equipment failure rate.

Furthermore, the present-day Hydro-Quebec system is now very closely integrated. Thus, its overall system reliability is of a high order. This means that, although there are a considerable number of line trip outs over the year (from a variety of causes), little, if any, load is ever lost. Most transmission and distribution lines have automatic reclosing features, which restore power within a matter of cycles. In addition, most major circuits are duplicated in one way or another so that the overall flow of power is not usually interrupted by the loss of a single section of line.

In general, therefore, it was concluded that, although there has been a variety of incidents during the various geomagnetic storms considered (see Table 1), none of them appear to have caused any major equipment failures, and none of them have caused any recorded power outages or blackouts to which an appreciable financial cost can be attributed.

Nevertheless, certain departments within Hydro-Quebec are definitely concerned with the possible long-term effects of SIC's. An active metering program has been in progress since 1969, and currents in the 50-amp to 60-amp range have been recorded, i.e. somewhat less than the values recorded in Newfoundland. Hydro-Quebec is also concerned that many of its EHV transformers may already have suffered some form of insulation degradation as a result of the high magnetizing currents caused by SIC's. It is appreciated that this is a very intangible consideration, but Hydro-Quebec is presently carrying out some quite extensive laboratory tests in an attempt to evaluate the problem. At present, the transformers under test are relatively small, but it is understood that they may eventually test a 200-Mva unit.

With regard to the actual events noted and summarized in Table 1, some comments are offered here:

- A number of gas alarms were recorded on various 735-kv shunt reactors. However, it is understood that this is by no means uncommon with this equipment and has been known to occur at other times not coincident with geomagnetic storms.

- Numerous line trips were recorded as noted in the table. However, much lightning activity was noted at the same time, particularly during the summer months, so that these trips were quite probably caused by the latter rather than by SIC's.

- On occasion, fading of the microwave and power line carrier communicating signals was noted. Although this does not seem to have caused any direct financial loss so far, the potential for this to initiate a major system blackout should not be overlooked.

- A search of the trouble reports indicated a relatively large number of capacitor banks tripping off due to unbalanced voltage. This, however, seems to be a random effect which occurs with equal frequency at all times of the year. Such failures were therefore not listed in Table 1.

3.4 Ontario Hydro

The Toronto offices of Ontario Hydro were visited on February 27, 1975. Contact was made with a number of Ontario Hydro personnel in different divisions, including the System Control Centre, System Operations and the System Studies Department. Documents studied during the discussions included a report on the system disturbances during the August 4, 1972 geomagnetic storm, and a file containing data as far back as a storm which occurred on March 28, 1946.

The disturbance on the Ontario Hydro system due to the geomagnetic storm of August 4, 1972 is summarized in Appendix B. In addition to variations in frequency and line loadings, voltage variation of up to 8 per cent was reported.

From these various discussions and a study of the documentary evidence, it would appear that Ontario Hydro is no longer monitoring records of SIC's on an active basis. The effects of the disturbance of August 4, 1972 is perhaps a special case, detailed in Appendix B, and is also summarized in Table 1.

The remaining data available from 1946 to 1970 of general interest, and some salient features are listed below:

- Charts of transformer neutral current at Port Arthur for several dates between 1946 and 1970 were obtained. On September 22, 1946 a maximum current of 93 amp was measured. (The chart for this date is not available.) The chart of March 8, 1970 (see Figure 1) shows a maximum current of 30 amp as compared with charts of other storms which reported only about 10 amp.

- On March 28, 1946 between 0646 and 0717 hours EST, the Port Arthur transformer tripped six times and the Crow River transformer twice; it was reported that the telephone relays chattered quite vigorously just preceding each operation of the transformer differential relay.

- On September 22, 1946, the Port Arthur transformer differential relay protection operated eight times between 0515 and 0946 hours EST.

- On February 10, 1958 at exactly 2104 EST, a transformer at Rayner Generating Station and the Port Arthur transformers T1 and T2 were simultaneously tripped by differential relay operation. Since both transformers tripped at Port Arthur, loss of load occurred for about 4 minutes. However, Ontario Hydro does not know of any significant loss of revenue or any problems to the customers served by this station.

Since no damage to equipment as a result of these magnetic storms has been reported, it is concluded that, although SIC's are indeed present from time to time in Ontario, these effects are no longer considered to be of any financial consequence.

3.5 Manitoba Hydro

In Manitoba Hydro, a series of meetings was held with the representatives from System Operating, Construction, System Planning, and System Control groups to discuss any power system problems which may have been encountered during the magnetic storm studied. They kindly provided reports on a variety of events including the system disturbances of August 4, 1972 and transmission line trippings between 1970 and 1974 coincident with magnetic storm dates from system log sheets. Also studied were ground potential graphs for the June 17 to 19, 1972 storm for two Stonewall sites which Manitoba Hydro had set up to check the effect of magnetic storms in that province.

It was indicated that recordings on the SIC currents through transformer neutrals have been obtained for a number of locations, but have not been correlated as of this time. Except for the August 4, 1972 storm, no other storm events have been documented, since their effects on system operation have been minor.

A review of the August 4, 1972 disturbance has, however, revealed several interesting facts. The power flow being supplied by Manitoba Hydro to Minnesota at that time dropped from 164 Mw to 44 Mw for about a minute, and later on from 105 Mw to an average value of 60 Mw for about 10 or 15 minutes. However, we calculate that the loss of revenue to Manitoba Hydro due to this reduction in Mw sales is essentially negligible, being only a matter of about $300. These variations in flow have also been cross-checked from the Minnesota end and, while the actual figures do not correspond exactly, the net reduction in flow appears to be approximately correct.

During this same storm, the SIC currents through the neutral of the La Verendrye and Grand Rapids transformers reached values of 100 amp or more (see Figure 2). Concurrently, the system voltage dropped from 111 kv to 90 kv resulting in a number of system component trippings and a fluctuation in Mw and Mvar flows. In addition, a current of 90 amp was observed flowing through a by-pass switch which was closed at the time to by-pass a 450-kv dc valve at the Nelson River site. (The circuitry of the dc equipment is such that when the by-pass switch is closed, no current should flow.) These and other system disturbances are outlined in Appendix B.

A total of tweive line tripping cases have been reported between 1970 and 1974 to coincide with the geomagnetic storm dates currently being studied. The number of line trippings due to ground current, phase current and both ground and phase current relays were found to be 6, 4 and 5, respectively. However, it should be pointed out that some of these line trippings could have been caused by lightning storms, since the system was not being specifically monitored for SIC effects at the time.

Ground potential graphs for June 17 to 19, 1972 at Stonewall confirm the occurrence of a magnetic storm in Manitoba at that time. A maximum ground potential of 1.0 volt per mile was recorded around 1915 hours on June 17,1972.

Once again, therefore, we note that no evidence of equipment damage has been uncovered. However, in the case of Manitoba the potential consequences of the major swings in power flow over the United States interconnection during the August 4, 1972 disturbance should not be overlooked. In point of fact, although the two systems did indeed remain in synchronism, it would appear that if the disturbance had been slightly more severe, a complete system separation could have occurred. In such an event, it is possible to visualize a major system blackout taking place. Nonetheless, since the August 1972 geomagnetic disturbance was one of the most severe on record, the possibility of a serious future blackout being caused for similar reasons remains strictly hypothetical.

3.6 Saskatchewan

3.6.1 Saskatchewan Power Corporation

In Saskatchewan Power, meetings were held with representatives of the Dispatch, Transmission Planning, Systems Engineering and Transmission and Maintenance Engineering departments. These various departments kindly provided information on the system disturbances of August 4, 1972, as well as data on transmission line and transformer trippings between 1970 and 1974 coincident with magnetic storm dates under study.

Other than the August 4, 1972 storm, no other storm events have been documented, since their effects on the system have been minor. Saskatchewan Power does not have meters to record SIC currents through transformer neutrals.

The effects of the August 4, 1972 disturbance is summarized in Appendix B. It indicates that frequency, Mw and Mvar variations were experienced at a number of locations.

A review of line trippings between 1970 and 1974 which coincide with the geomagnetic storm activity has revealed 37 instances of line trippings; 11 of the trippings are by ground current relays, 4 by phase current relays, 13 by both ground and phase current relays, and 2 unknown. One case of differential relay tripping a three-legged core transformer (connected "Delta-wye") was reported. Once again, it is difficult to distinguish between the number of trippings caused by lightning storms and those caused by geomagnetic storms. Indeed there seems to be some indication that lightning and geomagnetic storms often seem to be coincident, despite theoretical evidence to the contrary. Once again, however, no evidence of measurable financial consequences has been uncovered.

3.6.2 Visit to University of Saskatchewan at Saskatoon

While in Saskatchewan, a meeting with Professors B. Currie, D. McEwen and K. Paulson of the Physics Department was arranged to discuss their work as it relates to the present study. They outlined their study pertaining to earthquakes in Saskatchewan and earth current measurements at Lucky Lake. Their magnetometer records at Lucky Lake confirm the existence of a severe geomagnetic storm on August 4, 1972. They will be participating in the

International Magnetospheric Study (IMS) to be conducted in the 3-year period from 1976 to 1978. The prime objective of this study is to obtain a comprehensive quantitative understanding of the dynamic processes operating on plasmas in the geomagnetic field.

They have not conducted any magnetic storm studies as they relate to the performance of power systems.

3.7 Other Utilities

In addition to those utilities visited, as outlined above, a number of other utilities were contacted by telephone. In general, the findings from these contacts were essentially negative, but for the sake of completeness, each individual situation is briefly summarized as follows:

- In Nova Scotia, the authorities are aware of the incidents of SIC's in other provinces — notably Newfoundland, but have not noted any effects on their own system. No analyses have been reported and noted measurements are being made.
- In New Brunswick, measurements of neutral currents are being recorded on two instruments which are circulated between their various substations. However, the only outage attributable to SIC's took place in 1966 when a 50-Mva unit tripped falsely. No damage was sustained, and little or no revenue was lost.
- In Alberta, telephone discussions were held with personnel in Alberta Power, Calgary Power and City of Calgary Electric System to determine the extent of data available on the present study. Since the effects from the magnetic storms were not documented, personal visits were not made to these utilities.
- The System Operations Department of the City of Calgary Electric System reviewed its records against the dates of magnetic storm occurrences between 1970 and 1974 to determine problems on its systems. This report indicated the following:

    (a) On August 9, 1972, a 50-Mva, 138/69-kv autotransformer with a buried tertiary failed while in operation. The failure was not coincident with lightning strikes. Inspection of the transformer showed two badly damaged tertiary windings.

(b) Two 4-kv underground distribution cable failures on June 10, 1973 and April 20, 1974.

(c) A transformer differential trip without any cause on April 13, 1973 at 0701 hours.

(d) A fuse blew in the largest residential underground area on November 21, 1970 at 2126 hours.

– Calgary Power also indicated the reporting of unspecified problems on two generators and a synchronous condenser.

– Both Alberta Power and Calgary Power reported that they have experienced a number of problems on their system during magnetic storm activity, but they have not been documented.

– A representative of the Ottawa office of the Northern Canada Power Commission was also contacted by telephone. It would appear that while this undertaking is generally aware of the effects of SIC's in other systems, no effects have been noted on its own system. We understand also that no measurements of such currents are being taken at this time.

– In British Columbia, at the present time, no effects have been noted and no measurements are being made. In one respect, however, this province is notably different from most others. This difference lies in the fact that we understand a major EHV intertie running east-west through the Rockies is being contemplated. If such a line is eventually built, it is possible that some effects could be noted. At this time we are not aware of any consideration being given to this matter.

4 GEOLOGICAL CONSIDERATIONS

4.1 Geological Materials at the Earth's Surface

Changes in the earth's magnetic field act on soils and rocks to produce dc currents whose characteristics depend on the rate of change of the field and on the resistivity of the geological materials at the surface.

The resistivity of rocks and soils depends on many factors. At the relatively low temperatures of the earth's surface and uppermost crust, the most important factors are the amount and composition of the pore fluids in the soil or rock. The mineral constituents are of lesser importance because most minerals, and all of the most abundant ones, are insulators, being composed primarily of silicates, oxides, and carbonates.

The minerals which are semiconductors or conductors are relatively much less abundant, although they do occur in local concentrations, extreme examples of which are ore bodies. Table 4.1.1 gives the resistivities of some selected mineral semiconductors and conductors as reported in the literature. It will be noted that some mineral species can display resistivities varying by several orders of magnitude. In the case of the most extreme examples quoted (sphalerite, hematite, and magnetite), these variations probably relate primarily to the iron content and its state of oxidation.

Many of the common silicate minerals may also contain iron, either as an essential constituent or as an impurity. The resistivities of such insulating minerals may therefore also be extremely variable, although the absolute values are in higher ranges than those of the semiconductors and conductors shown in Table 4.1.1. Probably all the common rock-forming minerals would display resistivities in the range between say 10^5 and 10^{10} ohm-metres, depending on their purity, etc., but the values do not appear to be reported in the literature. However, the values for two monomineralic rocks are known. Table 4.1.3 shows resistivities for dry samples (at 200 degrees C) of three rock types. Two of these are essentially monomineralic. Anorthosite is composed of the mineral labradorite, a type of plagioclase feldspar. Amphibolite is, in this case, composed primarily of the mineral actinolite, a type of amphibole. The respective resistivities therefore show the values to be expected of aggregates of these minerals under the experimental conditions.

However, when water can penetrate the pores of the rock or soil, resistivities are much affected. Table 4.1.2 gives resistivities of naturally occurring pore waters from different types of rocks of various geological ages and geographical regions. As would be expected, the oil field brines have the lowest values. Igneous rocks, with their small proportion of easily soluble constituents contain waters with somewhat higher resistivities. These values are the means from large numbers of samples, and the range is not given. Great variations would be expected from place to place.

The influence of pore fluids on resistivity of the whole rock can be seen by comparing Tables 4.1.3, 4.1.4 and 4.1.6. Although quoted for ac conditions and 200 degrees C, the resistivities of the three rocks in Table 4.1.3 are probably within an order of magnitude of their dc resistivities at standard temperature. However, their resistivities are several orders of magnitude higher than those quoted in 4.1.4 and 4.1.6, presumably because they are dry. This effect can also be seen in Table 4.1.5, where the resistivity of sandstone samples varies by three orders of magnitude when the degree of saturation varies between 10 per cent and 50 per cent.

Table 4.1.6 also illustrates the effect of absolute quantity of pore fluid, as shown by the variations in conductivity of rocks of different ages and hence of different degrees of compaction. The older rocks (at the right in the table) are, on the average, more consolidated, less porous, and less conductive than the more recent ones. This effect overshadows the influence of differences in rock types and origins. Thus a Precambrian sandstone or limestone may have higher resistivity than a younger granite, etc. In fact, limestones and dolomites (sedimentary rocks) may very well have lower conductivities than granites and basalts (igneous rocks). The actual values can be determined only by measurement in each case and depend on previous geological history (degree of porosity, etc.) and especially on the nature of the pore fluids.

This dependence of resistivity on abundance and composition of pore fluids is well known and is commonly encountered in mineral prospecting by geophysical methods and in civil engineering work. The depth to water table can often be calculated from electrical measurements made at the ground surface. In special cases, the salinity of the groundwater can be estimated as well.

It should be noted that there are many other conductors at or near the ground surface, such as railway tracks and pipelines, which show much lower resistivities than any common geological material. Because of their relatively small cross section, such features may carry only small currents as compared to geological conductors of large cross-sectional areas.

4.2 Geological Materials at Depth

A varying electromagnetic field will penetrate below the surface of the earth to a degree which depends on the resistivity of the rocks as well as on the rate of change of the field. Table 4.2 shows the depth of penetration, defined as the "skin depth", the "distance an electromagnetic field will penetrate a conductor before being attenuated to 1/e of its amplitude at the surface". (The numerical value of 1/e is about 0.368) .

It will be noted that, for the period (minutes to hours) of major variation of the magnetic field during geomagnetic storms, depths of penetration are of the order of hundreds to thousands of kilometers in materials of the resistivities which might be expected at shallow depth in thick piles of limestones and sandstones saturated by water of moderately high salinity (for example, the Canadian prairies). In practice, the depth of penetration is probably limited primarily by the geothermal gradient which results in increased temperatures and consequent decreased resistivities with depth.

The currents induced in deep conductors may themselves affect surface conditions because of the magnetic fields they produce. The mathematical theory is summarized by Madden and Swift in the reference cited at the top of Table 4.2.

In general, moderate depth of burial should be expected to increase the resistivity of most rocks under drained conditions since the void ratio, and hence the proportion of conductive pore fluid, decreases with increasing pressure. At greater depth, however, the effect of temperature would be expected to be more important (below depths of a few thousand feet to a few miles) because the resistivity of rocks is strongly influenced by temperature. In general, therefore, the mathematical treatment which assumes a conductively layered earth is applicable.

However, there are several areas in Canada where anomalously low resistivities appear to occur at depth. The Institute of Earth and Planetary Physics of the University of Alberta, with support from the Earth Physics Branch, Department of Energy, Mines and Resources, has been conducting investigations, reports (Annual Report, December 31, 1974, pages 33 to 36) that the North American Central Plains conductivity anomaly, long known to exist at depth in South Dakota, has been traced to the Canadian border, through southern Saskatchewan in a northerly direction, and almost as far as the edge of the Canadian Shield in northern Saskatchewan. This anomaly may correlate with geological structures exposed in the Precambrian rocks of the Shield, and the suggestion is made that the continuation of these structures in the Precambrian rock at depth toward the south may account for the presence of this conductivity anomaly all the way south to about latitude 42 degrees. It is interesting to note that at the point where this anomaly crosses the Canadian–United States border, the top of Precambrian rock is believed to be covered by a thickness of the order of 10,000 feet of younger sedimentary rocks [Geological Survey of Canada, Tectonic Map of Canada, Map No. 1251A, (1969)].

4.3 Areas Studied

Some data from Saskatchewan, Manitoba and Newfoundland were available for study. They suggest that certain transmission lines are more liable than others to malfunction during periods of magnetic storms. Geological maps of the areas traversed by these lines were studied to determine whether there is any correlation between gross geological conditions and transmission line malfunction. The time scale of the study restricted the amount of detail which could be obtained with respect to both the locations of the lines and the geological conditions in the vicinity. There is no obvious correlation with geological conditions.

The southern Manitoba and Saskatchewan cases are in areas underlain by sedimentary rocks which are almost horizontal. The beds are primarily limestones, dolomites, shales and sandstones. Soil conditions are complex and vary from uniform thick deposits of clay to heterogeneous boulder-soil mixtures. The one factor which all the areas in Manitoba and Saskatchewan may possibly have in common is that the groundwater in the pores of shallow rock layers may be quite saline, resulting in low bulk resistivity of the rock.

In the Newfoundland case (the line between Corner Brook and Deer Lake), the geological conditions are far more complex. This relatively short line crosses steeply dipping folded and faulted metamorphic and sedimentary rocks, including gneisses, schists, marble, shale, sandstone, limestone, dolomite, conglomerate, etc. Its northern terminal is on rocks which are probably simpler, and of sedimentary origin. These are conglomerates, sandstones, siltstones, etc. of Carboniferous age.

It is notable that gypsum and anhydrite are listed as being present in the succession and it is therefore possible that at least some of the groundwater in these rocks near the Deer Lake terminal may be saturated with sulphates, and therefore conductive.

Another point which appears to be common to all, or almost all, of the lines in question, in the two Prairie provinces as well as in Newfoundland, is the presence of railway lines. So far as can be ascertained from the available maps, all the line segments which are prone to tripping during magnetic storms have some relation to railway right of way. In some cases they ran parallel for long distances. In others the transmission line crosses two or more tracks. It is not known whether this observation is significant. There are so many railway rights of way in Saskatchewan and Manitoba that it may very well be possible to relate any arbitrarily chosen length of transmission line to one or more of them. A statistical study would be needed before any firm conclusions could be drawn from this observation.

TABLE 4.1

TYPICAL RESISTIVITIES

Adapted from G. V. Keller: Electrical Properties of Rocks and Minerals, in Handbook of Physical Constants, Revised Edition. S. P. Clark, Jr. (ed.), Geological Society of America Memoir 97 (1966). Data are from various sources (page 577). Page references in Table 4.1 refer to this publication.

4.1.1 Selected Mineral Conductors and Semiconductors (pages 557 to 561)

Mineral	Composition	Resistivity (Averages Reported) (ohm-metres)
Native Copper	Cu	1.2×10^{-8}, 3.0×10^{-7}
Graphite	C	Parallel basal plane 6.4×10^{-5}, 9.9×10^{-3} Across basal plane 4.6×10^{-7}, 1.0×10^{-6}
Galena	PbS	1.87×10^{-2}
Pyrite	FeS_2	10^{-3} to 10^{-1} range
Sphalerite	ZnS	2.7×10^{-2}, 1.2×10^{4}
Arsenopyrite	$FeAsS$	3.0×10^{-4}, 1.93×10^{-2}
Hematite	Fe_2O_3	4.0×10^{-3} to 4.7×10^{5} range
Magnetite	Fe_3O_4	5.2×10^{-5} to 7.1×10^{2} range

4.1.2 Natural Waters
(page 563)

Source of Sample of Water	No. of Samples	Resistivity at 20 degrees C (Median value) (ohm-metres)
Igneous rocks, Europe	314	7.6
Igneous rocks, South Africa	175	11.0
Metamorphic rocks, South Africa	88	7.6
Metamorphic rocks, Precambrian, Australia	31	3.6
Recent and Pleistocene continental sediments, Europe	610	3.9
Recent and Pleistocene sediments, Australia	323	3.2
Tertiary sediments, Europe	993	1.4
Tertiary sedimentary rocks, Australia	240	3.2
Mesozoic sedimentary rocks, Europe	105	2.5
Paleozoic sedimentary rocks, Europe	161	0.93
Chloride waters from oil fields	967	0.16
Sulphate waters from oil fields	256	1.2
Bicarbonate waters from oil fields	630	0.98

4.1.3 Dry Rocks at 200 Degrees C, Low Frequencies (pages 573 to 575)

Rock Type	Frequency (hertz)	Resistivity (ohm-metres)
Granodiorite	1,000	6.3×10^7
Anorthosite	1,000	1.8×10^7
Amphibolite	100	3.2×10^7

4.1.4 Ordinary Rocks, Sources and Conditions of Testing Unknown (page 571)

Rock Origin	Type	Resistivity (ohm-metres)
Sedimentary	Graywacke sandstone	910
	Quartzitic sandstone	388
	Shale	163 – 192
	Limestone	292 – 29,000
	Dolomite	1,435 – 9,350
Igneous	Granite	19,800 – 23,400
	Quartz porphyry	48,000 – 143,000
	Monzonite	740 – 5,500
	Diorite	2,370 – 77,000
	Feldspar porphyry	7,400
	Hornblendite	2,420 – 8,500
	Felsite	7,400 – 7,900
	Basalt	81 – 1,120
Metamorphic	Gneiss	660 – 27,000
	Granulite	3,600 – 195,000
	Greenstone	9,900 – 11,800

4.1.5 Water-bearing Sandstone, as a Function of Saturation at Frequency of 100 Hertz (page 572)

Degree of Saturation (per cent)	No. of Samples	Resistivity (ohm-metres)
10	7	1×10^6
30	6	4×10^4
50	5	1.1×10^3

4.1.6 Water-bearing Rocks of Various Types and Ages (page 562)

Rock Type	Quaternary, Tertiary (ohm-metres)	Mesozoic (ohm-metres)	Carboniferous (ohm-metres)	Pre-Carb. Paleozoic (ohm-metres)	Precambrian (ohm-metres)
Marine sand, shale, graywacke	1 – 10	5 – 20	10 – 40	40 – 200	100 – 2,000
Terrestrial sands, claystone, arkose	15 – 50	25 – 100	50 – 300	100 – 500	300 – 5,000
Limestone, dolomite, anhydrite, salt	50 – 5,000	100 – 10,000	200 – 10^5	10^4 – 10^5	10^4 – 10^5
Granite, gabbro, etc.	500 – 2,000	500 – 2,000	1,000 – 5,000	1,000 – 5,000	5,000 – 20,000

TABLE 4.2

SKIN DEPTHS IN KILOMETRES

Adapted from T. R. Madden and C. M. Swift, Jr.: Magnetotelluric Studies of the Electrical Conductivity Structure of the Crust and Upper Mantle, in The Earth's Crust and Upper Mantle. P. J. Hart (ed.). AGU Geophysical Monograph 13 (1969).

Period Sec.	Resistivity 10^3 (ohm-metres)	10^2 (ohm-metres)	10 (ohm-metres)	1 (ohm-metres)	10^{-1} (ohm-metres)
1	16	5	1.6	0.5	0.16
10	50	16	5	1.6	0.5
10^2	159	50	16	5	1.6
10^3	503	159	50	16	5
10^4	1,590	503	159	50	16
10^5	–	1,590	503	159	50
10^6	–	–	1,590	503	159

5 DISCUSSION OF FINDINGS

5.1 General

Following a review of the various provincial undertakings outlined in Section 3, it is concluded that, considering Canada as a whole, there do not appear to be any very serious consequences which can at this time be definitively attributed to the effects of SIC's. Such effects as have been encountered over the last 5 years (1970 to 1974) are summarized in Table 1. From this table, we conclude that, with the exception of the major storm of August 4, 1972, there does not appear to be any particular correlation between system disturbances for any of the storms studied.

5.2 Newfoundland Costs

A notable exception to the foregoing, however, is the Province of Newfoundland where not only do the SIC's appear to reach greater magnitude, but finite economic costs can be identified. Although they vary from year to year, such costs are always present to a greater or lesser extent, not only to the Power Commission but in the form of lost production in the paper mills and mixing industry. If the precautions discussed in Subsection 3.2.2 are successful, the costs can apparently be confined to about $2,500 per incident, or say $10,000 per year. However, during the August 1972 disturbance, extensive "paper breaks" were experienced, resulting in over an hour's complete loss of production in the Bowaters Paper Mill. At $250 per ton for the 240 tons lost, the cost of this one event is estimated at $60,000 or more. (There does not appear to be any accurate record of the exact duration of the shut-down.)

Cost of lost mining production is also occurring, although the time schedule of this report has not permitted it to be quantified. In addition to this, there is hidden cost in the need to "float" the frequency converter power interchange at Corner Brook, sometimes for several days at a time. While the actual difference in the power bill is settled by mutual agreement between the two parties concerned, there is undoubtedly a cost to the economy of Newfoundland as a whole. In order to make up the lost energy sales during normal periods, the Power Commission must start up additional generation. Purely as a sensitivity test, and using an incremental power cost of 15 mills, the cost of a single 24-hour period supplying, say, 20 Mw comes to about $7,500. Thus, if such an event occurs ten times in a "bad" year, the hidden cost might be of the order of $75,000.

It is therefore concluded that for Newfoundland as a whole, the approximate overall cost of the effects of SIC's may vary from a low of $10,000 in a "good" year to a high of $100,000 or more in a "bad" year. In the 5-year period studied, it has not been possible to determine accurately the long-term proportion of "good" and "bad" years except that 1972 was a "bad" year and the others were relatively "good".

5.3 Potential for System Disruptions

As discussed in Subsection 3.5, the disturbance of August 4, 1972 was seen to cause a considerable temporary fluctuation of power transfer between Manitoba and Minnesota. This was the only disturbance of this kind noted during the period of the study. This storm was one of the most severe on record and, although the two systems did retain their connections intact, we understand that it was a very close situation. Nevertheless since the tie was, in fact, maintained, the potential cost of a blackout remains purely speculative.

As a rider to the above remarks, Acres also submits the following observation:

- Power system log sheets have, on numerous occasions shown marked fluctuations in both power (Mw) and reactive (Mvar) at times of SIC disturbance. To date, most of these effects have been attributed to the effects of SIC's on such major items as transformers and voltage sensitive loads. In the case of reactive flows this may reasonably be attributed to the effect of saturating magnetic structures. However, a SIC causing a major fluctuation in real power flow presents a somewhat more complex situation. Therefore, an additional possibility comes to mind which apparently has not yet been considered in detail; namely, the effect of SIC's on metering transformers. Most high voltage system metering is supplied by potential transformers connected line to ground. It is therefore possible to visualize a condition whereby these transformers are also affected in the same way as power transformers. If this were the case, it is quite possible to theorize that in actual fact the true power flow remains essentially steady, and it is only the instrumentation which is recording incorrectly.

5.4 Geomagnetic Storm Experience in Other Countries

5.4.1 Sweden

Due to proximity to the auroral zone and general geology, geomagnetic storm effects have also been observed in the Swedish power system. Mr. P. O. Persson of the Swedish State Power Board examines some of the causes and effects of these disturbances in a 1962 paper titled: "Disturbances in Directly Earthed Transmission Systems caused by Magnetic Storms". The paper summary is quoted below:

> "Without apparent reason, relay trippings in the directly earthed Swedish primary-transmission system have occurred twice during recent years, disconnecting sections of transmission lines and transformers. The cause has been traced to geomagnetic storms which occurred concurrently. This report describes briefly the origin of these storms and how they affect the operation of the high-tension transmission system in Sweden.
>
> "Effects of magnetic storms on apparatus included in the directly-earthed transmission system are analyzed. Magnetic saturation of power transformers by direct currents occurring in connection with geomagnetic storms is found to be a determining factor in the origin of currents which cause tripping of the protective relays."

Some general observations and conclusions from this paper are noted for convenience:

- Geomagnetic storm effects were not observed in Swedish Power Systems prior to the direct earthing of the power system.
- Cases of undesired relay tripping have been traced to harmonic currents (primarily third harmonics) due to "dc" saturation of power transformer cores.
- Undesired relay tripping has been most frequently encountered where single-phase, five-limb shell transformers are used.
- The flow of dc in current transformer primaries does not lead to harmonic current production to the same extent as in power transformers, hence this is not regarded as a significant factor in unwanted relay tripping.

5.4.2 Other Countries

Work is being done in Japan, Australia, New Zealand and the U.S.S.R., but no significant references or publications have been located.

6 POSSIBLE FUTURE PROBLEMS AND SOLUTIONS

6.1 General

As previously stated, it is our general conclusion that the effects of SIC's on power systems in Canada are not particularly serious–Newfoundland excepted. Certain items do, however, seem to warrant some further consideration:

- In the case of Newfoundland, the trouble is mostly concentrated in the Deer Lake/Buchans/Corner Brook area. Since the common factor here seems to be the fact that the lines cross from areas of high resistivity to low resistivity, the possibility of significantly increasing the size of the buried counterpoise wire might be worth examining. This suggestion has already been made verbally to the parties concerned.

- Hydro-Quebec is, itself, already aware of and concerned about possible harmful effects on its proposed 300-kv collector circuits which will run east-west between the various plants in the Baie James Hydro complex. Consideration is being given to including a clause in the purchase specification for transformers to the effect that they be capable of carrying a certain amount of dc current in addition to normal magnetizing current. However, at this time no final conclusion has been reached on this point, probably because of the difficulty of proving it under test. Such a clause would also be difficult to evaluate commercially.

- Hydro-Quebec is also known to be concerned that some loss of life expectancy may have already been suffered in the EHV system. As mentioned previously in Subsection 3.3, it is believed to be considering testing a 200-Mva transformer. As far as existing equipment is concerned, however, there seems to be no alternative but to "wait and see".

- During the planning stage of the proposed EHV east-west intertie in British Columbia, an examination of the geology of the route might be worthwhile. Such an examination, which need not be costly, would indicate whether or not rock conditions similar to those in Newfoundland might be encountered or perhaps avoided.

- In the event that SIC's became a serious nuisance in other areas, the most promising solution would seem to be the development of a thyrite type of diverter mechanism which could be easily connected in the neutrals of the transformers concerned. No costs for such a device are known, but in the cost of large power transformers it could probably be produced for an economic price.

TABLE 1

SUMMARY OF EFFECTS OF GEOMAGNETIC STORMS

	Newfoundland	Quebec	Ontario	Manitoba	Saskatchewan	Alberta
1970						
March 8	–	–	I(30)	–	L(1)	–
August 17	L(10)	L(10±)	–	–	–	–
November 7	–	–	–	–	–	–
November 21	–	–	–	–	–	FB
December 14	–	–	–	–	–	–
1971						
January 27	L(1)	–	–	–	–	–
April 9	–	–	–	L(1)	–	–
April 14	L(1)	–	–	–	–	–
May 6	–	–	–	–	–	GP(1)
June 1	–	–	–	L(3)	L(9)	–
June 25	–	L(1)?	–	–	–	CB_{Fr}(1)
October 1	–	–	–	–	L(3)	–
1972						
June 18	FC(3)	L(2)?	–	P	L(1)	GP(1)
August 4–6	L(1)	L(5)?	X AT(1)	X – 20% V G(2) L(1) I(100)? AG(2)	L(2) X	SC
August 9	–	L(5)?	–	–	L(3)	TF
September 14	–	–	–	–	–	–
November 1	L(1)	–	–	L(1)	–	–
1973						
January 3	–	–	–	–	–	–
February 21–25	–	–	–	–	–	–
March 19–25	–	–	–	L(1)	–	–
April 1–2	–	M, L(1)	–	L(1)	–	–
April 4	L(3)	–	–	–	–	–
April 13–14	–	–	–	–	–	D(1)
April 16–19	–	CT(1)	–	L(1)	–	–
May 13–15	–	–	–	–	–	X–?
May 21–22	–	LA(1)	–	–	–	–
June 10–11	L(1)	GA(1)	–	–	–	CB_{Fr}(1)
September 23–24	–	–	–	–	L(2)	–
October 28–30	L(3)?	–	–	–	–	–

TABLE 1

SUMMARY OF EFFECTS OF GEOMAGNETIC STORMS (Cont'd)

	Newfoundland	Quebec	Ontario	Manitoba	Saskatchewan	Alberta
1974						
January 27	–	D(1)?	–	–	–	GT(1)
March 27	–	–	–	–	–	–
April 4	–	–	–	–	–	–
April 21	–	D+CB_{ft}	–	–	–	CB_{fr}(1)
May 5	–	–	–	–	–	–
June 26–27	–	–	–	–	L(6) D(1)	–
July 5–6	D(1)	L(5)? CP	–	–	L(1)	–
July 23	–	L(1)	–	L(1) I	L(5)	–
August 19	–	–	–	–	–	–
August 21–23	–	LA(3) GA(1) M	–	–	L(3)	–
August 29	–	R(1)	–	–	–	–
September 15–16	–	M	L(1)	– I	–	
September 21	–	–	–	–	–	–
September 26–27	–	–	–	L(2) I	–	–
October 13	–	–	–	–	–	–
October 15-6	–	–	–	–	–	–
November 9	–	GA(1)	–	–	–	–
November 12	–	D(1) GA(1)	–	–	–	–

AG	Generator Plan Unbalance Annunciation
AT	Tertiary Winding Ground Annunciation
CB_{fr}	Cable Failure
CB_{ft}( )	Cable Fault
CT( )	CT Failure
CP( )	Capacitor Tripping
D( )	Transfer Differential Relay Operation
FB	Fuse Blowing
Ft( )	Frequency Converter Trip (Bowaters Power Company)
GA( )	Reactor Gas Alarm
GP( )	Generator Problems
GT( )	Generators Tripping
I( )	Transformer Neutral Current in Amp as Indicated
L( )	Line Tripping
LA( )	L/A Failure
M	Microwave System Problem
P	Ground Potential Graphs Indicated Considerable Storm
R( )	Reactor Tripping
Sc	Synchronous Condenser Problems
TF	Transformer Failure
X	Variation in Watts, Vars, Frequency Recorded

BIBLIOGRAPHY

Albertson, V. D., J. M. Thorson, Jr., R. E. Clayton and S. C. Tripathy. "Solar-Induced Currents in Power Systems: Cause and Effects". PAS-92, pp. 471 – 477. March/April 1973.

Albertson, V. D. and J. M. Thorson, Jr. "Power System Disturbances During A K-8 Geomagnetic Storm: August 4, 1972". PAS-93, pp. 1025 – 1030. July/August 1974.

Albertson, V. D., J. M. Thorson, Jr. and S. A. Miske, Jr. "The Effects of Geomagnetic Storms on Electrical Power Systems". PAS-93, pp. 1031 – 1044. July/August 1974.

Albertson, V. D., S. C. Tripathy and R. E. Clayton. "Electric Power Systems and Geomagnetic Disturbances", Proceedings of Midwest Power Symposium. October 29 – 30, 1970.

Albertson, V. D. and J. A. Van Baelen. "Electric and Magnetic Fields at the Earth's Surface Due to Auroral Currents", IEEE Transactions on Power Apparatus and Systems. Vol. PAS-89, No. 4. April 1970.

Davidson, W. F. "The Magnetic Storm of March 24, 1940 – Effects in the Power System", Edison Electric Institute Bulletin. July 1940.

Fisher, E. D. "Influence of Solar Activity on Power Systems", Presented at a meeting of the Canadian Electrical Association. November 1970.

General Electric Company. "A Research Program to Study the Effects of Magnetic Storms on Electric Power Systems", Report on Phase I. July 1969.

Germaine, L. W. "The Magnetic Storm of March 24, 1940 – Effects in the Communication System", Edison Electric Institute Bulletin. July 1940.

Jacobs, G. and E. T. Martin. "The Dwindling High-Frequency Spectrum*", IRE Transactions on Communications Systems. pp. 399 – 408. 1961.

Lincoln, J. V. "Geomagnetic Indices", Physics of Geomagnetic Phenomena. Vol. I. Academic Press Inc., New York. 1967.

Manitoba Hydro Internal Report. "Effects of Magnetic Disturbance of August 4, 1972 on Manitoba Hydro Electrical System".

BIBLIOGRAPHY (Cont'd)

Masson, L. and J. R. Valotaire. "Hydro-Quebec Internal Report". Investigation of the Effects of Solar Induced D.C. In H.V. Power Transformers.

McNish, A. G. "Magnetic Storms", Edison Electric Institute Bulletin. pp. 361 – 370. July 1940.

Ontario Hydro Internal Report. "Solar Magnetic Disturbance – Friday, August 4, 1972". August 15, 1972.

Persson, P. O. State Power Board, Sweden. "Disturbances in Directly Earthed Transmission Systems Caused by Geomagnetic Storms".

Scott, R. L. "Utility System Effects of Space Plasmas", IEEE Spectrum. March 1968.

Slothower, J. C. and V. D. Albertson. "Effects of Solar Magnetic Activity on Electric Power Systems", Presented to the T & D Committee of EEI. January 1967.

Williams, D. "Magnetic Storm and Electric Power Line Disturbance Cycles", Journal of Cycle Research.

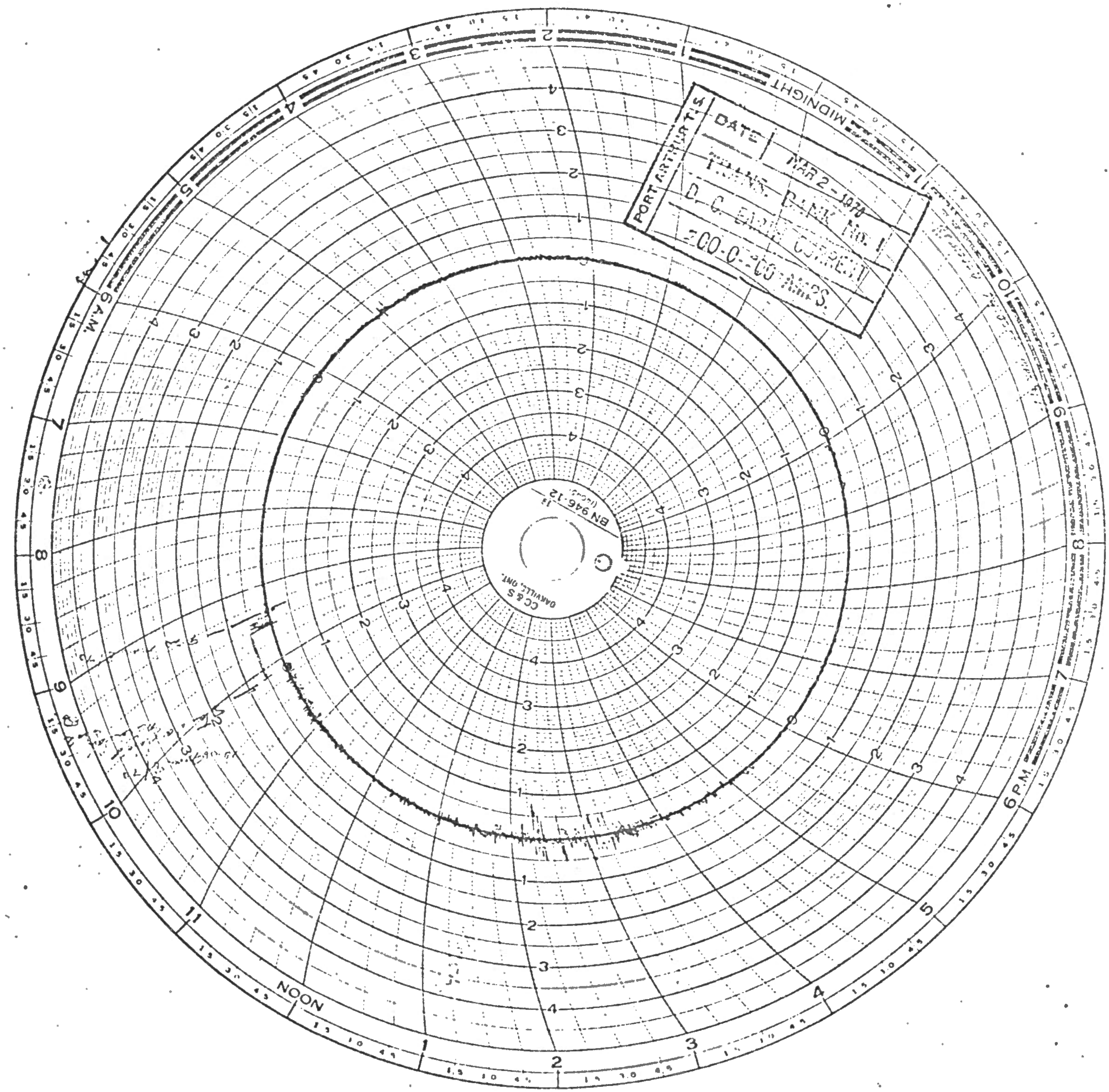

Figure 1
Neutral Current, Port Arthur
March 2, 1970

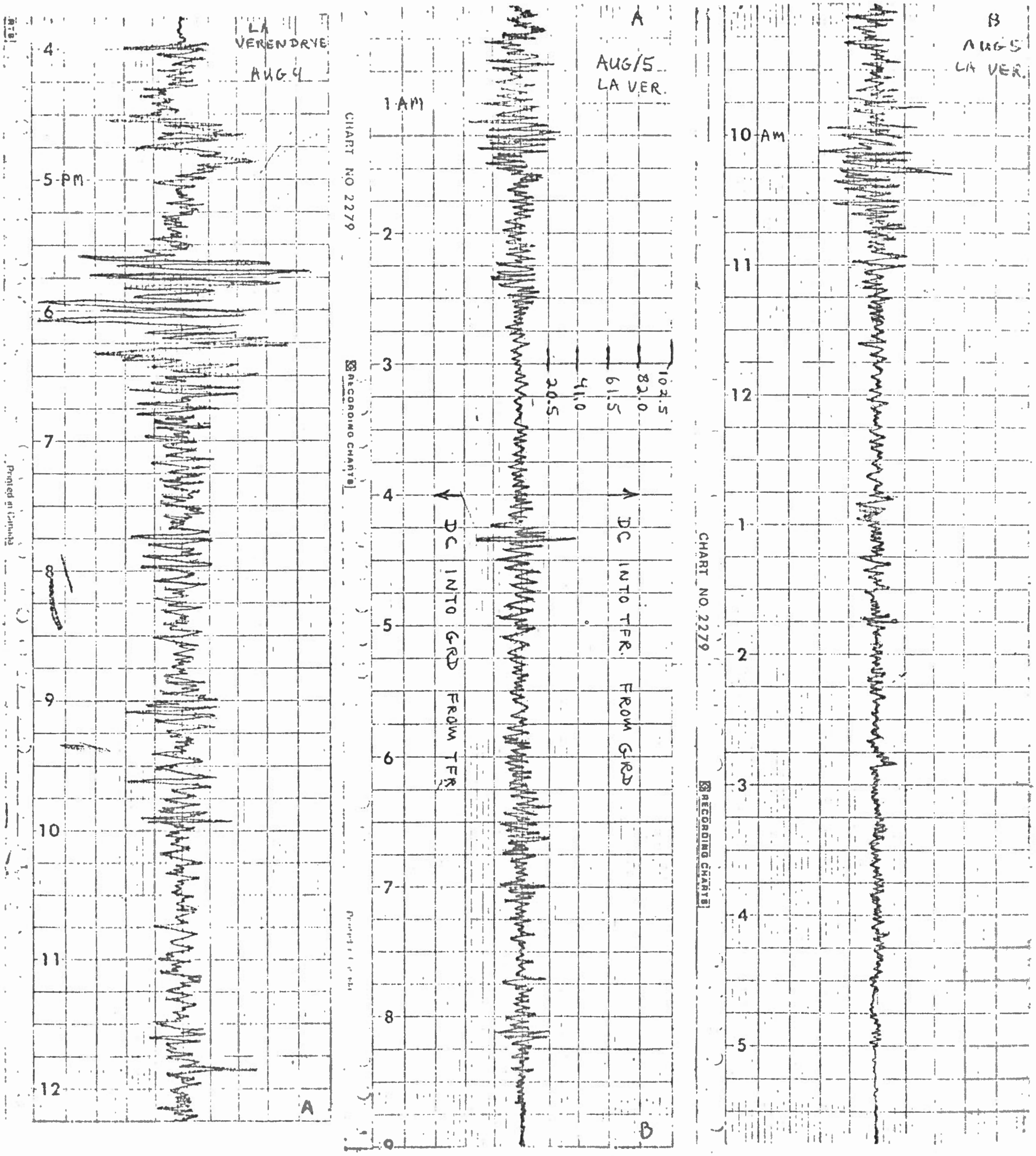

Figure 2
Manitoba Hydro — La Verendrye — D.C. Current Charts

APPENDIX A

CHECKLIST FOR GATHERING DATA FROM UTILITIES

1. For each of the outstanding storm periods recorded between 1970 and 1974, we want to determine whether the following have occurred:

(a) Excursion in transformer neutral currents (basically from SIC recorders) and tertiary winding currents.

(b) Abnormal variations in volts, watts, vars and frequency in the system, including generators and transmission lines.

(c) Undesired protective relay operation and non-operation.

(d) Phase current unbalances.

(e) Equipment failures; power transformers, shunt reactors, instrument transformers, etc.

(f) Temperature or gas alarms from the transformers coincident with SIC plus rotor heating in generator.

(g) Capacitor banks tripping from the harmonics generated by the transformers in saturation.

(h) Loss of load around the system.

(i) Communication, telemetering and supervisory alarm failures.

(j) Difficulties, failures and unusual excursions experienced on distribution systems.

(k) Any other unexplainable significant excursions.

2. General System Data

(a) System diagrams; geographical, single line, etc.

(b) Topology and length of the transmission lines involved in GMS disturbance.

(c) Parameters, including grounding points, for the power and instrument transformers and shunt reactors involved in GMS disturbance.

APPENDIX B

SUMMARY OF GEOMAGNETIC STORM OF AUGUST 4, 1972

1. Newfoundland and Labrador Power Commission,
St. John's, Newfoundland, Canada

The Corner Brook transformer tripped on differential relay (IAC, no harmonic restraint) and was returned to service several times as follows:

> 8/4/72: 2012 – 2112 hours; 2230 – 2243 hours; 2332 – 2349 hours NST.
>
> 8/5/72: 0022 – 0032 hours; 0131 – 0140 hours; 1245 – 1812 hours NST.

Long Harbour Terminal tripped as above at the following times:

> 8/4/72: 2012 – 2152 hours; 0022 – 0058 hours NST.
>
> (Note: NST is 1-1/2 hours ahead of CDT.)

False alarms on power line carrier circuits on August 5, 1972, at approximately 2210 hours NST.

SIC's at Corner Brook started at about 20 amp at 03/2330 hours NST and for the next 5 hours fluctuated between plus 100 to minus 100 amp. It varied around 10 amp until 04/1812 hours NST when excursions over 100 amp, plus and minus, took place. This lasted until around 05/0500 hours when it dropped to half until 05/1000 hours when the chart ran out. At 04/1850 hours SIC was near 100 amp and stayed at the same polarity for nearly 30 minutes.

2. Hydro-Quebec,
Montreal, Quebec, Canada

Mw variations of a few per cent. Bersimis No. 2, on power-frequency control, had Mw variation of 90 per cent.

Significant variations of Mvars at all generating stations.

Voltage variations of 3.6 per cent (735 kv sending end) to 5.7 per cent (315 kv receiving end).

Shunt capacitor bank tripped off by overload protection at 1852 hours EDT on August 4, 1972.

Many intermittent alarms caused by fading on microwave systems.

Loss of telemetering system of the La Gabelle generating station at 2026 hours EDT on August 4, 1972.

3. Ontario Hydro,
Toronto, Ontario, Canada

Ontario–Michigan interconnection	540 to 480 Mw
Ontario–New York State interconnection	310 to 280 Mw
Pinard 500-kv bus	2 per cent voltage change
Richview 230-kv bus	236 to 234 kv (1 per cent)
Essa 115-kv bus	4 per cent voltage change
Lakehead 115-kv bus	120 to 118 kv (2 per cent)
Atikokan 115-kv bus	119 to 115 kv (4 per cent)
Kenora 115-kv bus	125 to 115 kv (8 per cent)
System frequency	60.00 to 60.03 hertz
System load increase	150 Mw

Flaggings (no tripping) of the Burlington T12 (230/115 kv) autotransformer tertiary ground relay occurred.

4. Manitoba Hydro
Winnipeg, Manitoba, Canada

U.S.A. Tie Line (La Verendrye)	120 to 164 to 44 Mw
U.S.A. Tie Line (La Verendrye)	+25 to –100 Mvar
Grand Rapids 230-kv bus	295 to 336 to 295 to 340 Mw
Grand Rapids 230-kv bus	40 to 250 Mvar
Grand Rapids 230-kv bus	237 to 220 to 247 kv
La Verendrye 115-kv bus	114 to 96 to 116 kv
Morden 115-kv bus	112 to 96 kv
Parkdale 115-kv bus	113 to 96 kv
Selkirk 115-kv bus	116 to 100 kv
System Voltage	111 to 90 kv

At La Verendrye, SIC > ± 100 amp in neutral of 230/115-kv transformer No. 2.

At Grand Rapids, SIC ~ ± 100 amp in neutral of 13.8/230-kv transformer No. 1.

System Frequency	60.00 to 59.95 to 60.08 hertz

Seven Sisters Unit No. 2 (25 Mw) tripped by generator field ground and overcurrent time A and C phase relays.

Slave Falls Unit No. 3 (9 Mw) tripped by undervoltage relay.

Grand Rapids reported phase unbalanced annunciations on Units No. 1, 2, 3 and 4.

Kettle Rapids reported phase unbalance annunciations on Units No. 2 and 5 (R24G line).

Grand Rapids and Kettle units went to maximum var output at 1740 hours CDT, August 4, 1972.

Load Dispatch requested all generator units to maximum voltage boost at 1755 hours CDT, hoping to prevent loss of additional generator units.

No transformers tripped out by differential relay operations.

Per cent amp current observed through the disconnect which was closed to by-pass HVDC valve.

5. Saskatchewan Power Corporation,
Saskatchewan, Canada

1413 – 1430 hours Boundary Dam – Estevan line (BIE) started with a 5-Mvar oscillation and built to 13-Mvar oscillation — 17-Mw swing

Boundary Dam – Peebles – Yorkton (BIY) line – 4-Mw oscillation

Boundary Dam – Reston (R7B) line – 12-Mw oscillation

Worst oscillation occurred at 1642 hours and lasted about 1 minute

Estevan Area Control Centre frequency varied 59.92 to 60.12 hertz

Grid Management Centre at Regina frequency varied 59.89 to 60.10 hertz

Manitoba – Saskatchewan Tie Line – 44-Mw and 48-Mw oscillation

Boundary Dam – Estevan line (BIE) – 31-Mw swing with 8-Mvar oscillation

Boundary Dam – Peebles – Yorkton (BIY) line – 4-Mvar oscillation

Boundary Dam No. 1 and No. 2 units swung from 40 Mw to 36 Mw to 40 Mw

Boundary Dam No. 3 – no Mw swing, but Mvar increased by 20 Mvar.