Impacts of Geomagnetic storms on Trans-Canadian Grids

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ABSTRACT

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Induced “dc” currents due to geomagnetic storms have caused power system blackouts and transformer damages in the past. Statistically, large geomagnetic storms follow a 10-11 year sunspot cycle, but geomagnetic disturbances with significant impacts can occur at any time. The geomagnetically induced currents (GIC) have wide range of detrimental effects on otherwise normal operation of power systems, communication systems, railway systems, and can cause oil and gas pipeline corrosion. This thesis presents a method of estimating the magnitudes of terrestrial voltages; which is based on solving the magnetic diffusion equation. The method predicts the oft-quoted figure of “1 volt per kilometer” for the range of geomagnetic field variations (magnitudes and frequencies) and ground resistivity frequently encountered. The prediction formula has been validated by the plane wave method.

Geomagnetic storms have the tendency to disrupt the normal operation and even lead to major power outages depending upon the intensity of geomagnetic activity; whereas the major effects include transformer equipment damage, relay tripping, SVC failures resulting in minor or major power outages.

RÉSUMÉ

Impacts of Geomagnetic storms on Trans-Canadian Grids

Par le passé, les courants induits produits par des orages électromagnétiques ont causés des dommages à des transformateurs ainsi que des pannes de courant majeures (blackouts). Statistiquement, les orages géomagnétiques sévères suivent un cycle d'activité solaire de 10 à 11 ans. Cependant, des perturbations géomagnétiques peuvent avoir un impact important et peuvent apparaître à n'importe quel moment. Les courants induits géomagnétiques ont un large champ d'effets néfastes sur les réseaux électriques, les systèmes de communication, les systèmes ferroviaires et peuvent causer de la corrosion dans les oléoducs. Cette thèse présente une méthode pour estimer l'amplitude des tensions terrestres qui est basée sur les équations de diffusion magnétique. Cette méthode prédit la figure couramment utilisée de « 1 volt par kilomètre » pour une étendue de champs géomagnétiques (amplitudes et fréquences) et de résistances du sol fréquemment rencontrées. La formule de prédiction a été validée par la méthode d'onde plane.

Les orages géomagnétiques ont tendance à déranger les opérations normales et même à engendrer des pannes électriques majeures dépendamment de l'intensité de l'activité géomagnétique. Les principaux effets sont des dommages à l'équipement des transformateurs, des déclenchements de relais de protection, des défaillances des compensateurs statiques (SVC), ce qui causent parfois des pannes de courant mineures ou majeures.

DEDICATION

Dedicated to my respected parents, my beloved family, and precious friends

ACKNOWLEDGEMENT

I owe my deepest gratitude to my thesis supervisor, Prof. Boon Teck Ooi, for his guidance, support and continuous encouragement throughout my graduate studies and research.

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GLOSSARY

I. LIST OF SYMBOLS

Greek symbols:

δ	Skin depth (m)
μ_0	Permeability of free space (Henry/m)
ρ	Resistivity (ohm-m)
σ	Conductivity (Siemens per meter)
Φ	Scalar potential (volt)
ω	Angular frequency (rad/s)

Field Vector Symbols

$\boldsymbol{B}$	Magnetic Flux Density (Tesla)
$\boldsymbol{E}$	Electric Field Intensity (volt/m)
$\boldsymbol{H}$	Magnetic Field Intensity (A/m)
$\boldsymbol{J}$	Current Density (A/m^2)
$\boldsymbol{u}$	Directional Vector

Subscripts:

m	ground
s	magnetic diffusion coefficient

space	above ground
x,y,z	Cartesian coordinates
r,φ,z	Cylindrical coordinates

II. UNITS AND ABBREVATIONS USED

Units:

MW	Mega watts
KM	Kilometer
KV	Kilo-volt
ı	Degree Centigrade
Hz	Hertz
V	Volts

Abbreviations:

CME	Coronal mass ejections
GIC	Geomagnetically induced currents
D.C	Direct current
A.C	Alternating current
HVDC	High voltage direct current
CT	Current transformer

ESP	Earth surface potential
SVC	Static VAR Compensators
NASA	The National Aeronautics and Space Administration
NOAA	The National Oceanic and Atmospheric Administration
NERC	The North American Electric Reliability Council
EPRI	The Electric Power Research Institute
CSEM	The Centre for Space Environment Modeling team
OSO-7	The Seventh Orbiting Solar Observatory
ACE	Advanced Composition Explorer
TRACE	The Transition Region and Coronal Explorer
IMAGE	Imager for Magnetosphere to Auroral Global Exploration
HAARP	High Frequency Active Auroral Research Program
DSX	Demonstration and Science Experiment
ITWS	The Integrated Terminal Weather System
R&D	Research and Design

CHAPTER – 1

INTRODUCTION

1.1 Background

On March 13, 1989, The Hydro Quebec experienced a complete blackout of its power system due to the disturbances caused by the sun's solar activity. The entire province of Quebec was plunged into darkness, and power restoration took more than eight hours. Such solar disturbances are termed as "Geomagnetic storms", and they have the potential to cause fluctuations in the otherwise stable earth's magnetic field, leading to power system blackouts such as the one on March 13, 1989.

With the advancements in technology, society has become more and more dependent on electrical power. Electricity is considered to be a basic necessity; whether it is industrial sector, communications, water supply or general requirements of the society. There has been continual growth in the power utility sector: in terms of transmission and generation; improvement in power quality and reliability. Recently, security is considered to be important due to potential threats; both natural and terrorist inspired.

In the quest for greater economy and reliability, power utilities are interconnecting to form larger grids and there has been an interest in forming a Trans-Canadian Power Grid. In fact, the Power Research Group under the leadership of Professor F.D. Galiana is being funded by a Strategic Projects Research Grant of NSERC to research on "Design and Operations of Trans-Canadian Power Grids". Under the umbrella of this research, this thesis considers the threat from "geomagnetic storms". In the 1989 storm, the blackout was localized to Quebec and its neighbours. But the future interconnected system of Trans Canadian grids will be more vulnerable to geomagnetic disturbances. This will lead to extensive blackouts and system collapses.

The geomagnetic storm of 1989 in Quebec resulted not only in loss of revenues due to loss of 21,500 MW of electricity generation, but also the Quebec power industry suffered at large because it took nine hours to have the power restored. The destructive effect of Coronal Mass Ejections (CME) from the sun and Geomagnetically Induced Currents (GIC) around our planet, the earth, has put pipelines, cable systems, communications, and railway lines at risk. They increase pipeline and railway line corrosion. They cause navigational errors and disrupt the trajectories of communication satellites. The damage from geomagnetic storms is wide-ranging. This thesis focuses on the aspect which affects the electric power grid.

1.2 Objective

The objectives of this thesis are: (a) to review the impacts of geomagnetic storms on Trans Canadian grids and the entire power sector including pipelines, railway-lines, and communication systems; (b) to review the nature of the geomagnetic disturbances as reported in the literature; (c) to present a method of computing terrestrial voltages from geomagnetic storms based on solving the magnetic diffusion equation.

The thesis is organized as follows:

Chapter 1 is the brief introduction to the topic of geomagnetic storms. Chapter 2 presents a brief history of the solar storms as they affect the electric power industry. Their occurrences are in the form of very low frequency currents (so low that they have been reported as direct currents, DC) in the neutrals of wye connected transformers. They cause transformer core saturation and because DC is not expected they cause circuit breakers to open erroneously. Implicit in the flow of large dc currents is the existence of very high dc line-to-ground voltages. This voltage is of the order 1volt per km of transmission line. For the 1000 km

James Bay lines of the Hydro-Quebec, the line-to-ground voltage is 1000 kV. This chapter presents the effects of geomagnetically induced currents on power systems.

Chapter 3 presents a method of computing the terrestrial voltages (around 1 volt per km) by solving the magnetic diffusion equation. The method is validated by an existing method based on plane waves. Predictions useful to field engineers are presented in the graphs.

Chapter 4 deals with the methods and techniques implemented so far and under the phase of development used to mitigate the effects of geomagnetic storms, and prevent electrical power utilities from their detrimental effects. This chapter will throw some light on major organizations and power utilities becoming active in the field of research concerning geomagnetic storms, major technical breakthroughs, and response of the entire power sector to this alarming situation.

Chapter 5 presents the conclusions and suggestions for future research.

CHAPTER 2

HISTORY OF GEOMAGNETIC STORMS

2.1 Introduction

Geomagnetic disturbances termed as "Geomagnetic Storms" have affected the man-made electrical systems over the past 150 years. The first such incidence was noticed in the early 1840's on the telegraph equipment. It was noticed that significant deflections occurred in the needles of the electric telegraph in England in 1847 [1]. In 1859, under the influence of a brilliant aurora display, the communication systems of telegraphs were hardly working. Interruptions in communication system, telephone lines were noted in 1872-73 [1], and similar incidences were experienced in 1892 in various areas such as New York, Washington, France, Sweden, Austria, England, Switzerland and Turkey. Reaching back to the magnetic disturbances of 1840, they were the first recorded evidences of geomagnetic storms.

The effects of magnetic storms are increasing during the last few years. The electric power system, due to its large size is becoming very vulnerable to the interruptions caused by them.

This chapter presents an elementary picture of geomagnetic storms. It gives the definition, a brief history and the entire chain of processes that occur resulting in geomagnetic storms. Section 2.1 is a brief introduction. Section 2.2 describes the sun's solar activity, the key reasons behind solar disturbances, and the final phase of geomagnetic activities. Also, this section describes the various measurement indices implemented so far, which are used to measure the severity level of geomagnetic activity. Section 2.3 describes the history of the occurrences of geomagnetic storms. Section 2.4 presents the details of such events that have occurred so far in history. Section 2.5 contains a detailed explanation of the effects of geomagnetic storms on electric power utilities and other man-made structures. The area proximity and various other factors contributing to the severity of these geomagnetic disturbances are discussed in section 2.6 of this chapter.

2.2 The Solar activity and measuring indices for Geomagnetic Disturbances

Space weather, which is dynamically changing and highly unpredictable, is the result of a series of coupling processes between the earth and the sun, the magnetosphere, the interplanetary space and the ionosphere. Scientists and researchers focus on solar storms because terrestrial disturbances caused by them have affected both technology and humans.

2.2.1 The Sun's Solar Activity

The sun holds a key position in the solar system. Therefore solar activity, significantly the sunspots, the solar flares and the resulting Coronal Mass Ejections (CME) when properly oriented towards the earth, interact with the earth's magnetic field resulting in geomagnetic storms [2].

The solar activity of the sun is often linked to sunspot number [3].The sun has a cyclic pattern of occurrence of its solar activity defined by sunspot cycle i.e. every 10-11 years there occur major disturbances on the sun, which have their own minimum and maximum phase. The sunspots have an average temperature of around 4500▮, and a surrounding temperature of 6000▮. Solar flares are the result of release of tremendous amount of energy due to different processes occurring in and around the sunspot surface.

The solar activity has different phases: the declining or minimum phase and the phase with maximum solar activity. Similarly the solar, the interplanetary, the magnetospheric and the ionospheric processes that occur during these phases are different from one another, depending upon the phases. The activities during the maximum phase are the ones which lead to coronal mass ejections and coronal holes [3] . The high speed solar winds are the result of these coronal holes. The earth is surrounded by its terrestrial magnetic field which protects the surface of the earth from solar winds. The magnetosphere is the layer where the earth's terrestrial magnetic field exists. The charged particles from the solar wind distort this magnetic field of the earth. When the charged particles of the solar storms enter the magnetosphere, they cause variations in the magnetic field. The severity of these variations signifies the occurrence of geomagnetic storms.

The visual evidences of solar flares are the "Aurora borealis" and the "Aurora australis", the bright lights visible on the northern and the southern hemisphere of the earth; usually seen when there are disturbances in the earth's magnetic field. These auroral lights originate from a height of 100 kms or above and within a radius of 1100 kms. Figure 2.1 illustrates the effect of the sun-earth activities and solar flares which distort the magnetic field of the earth.

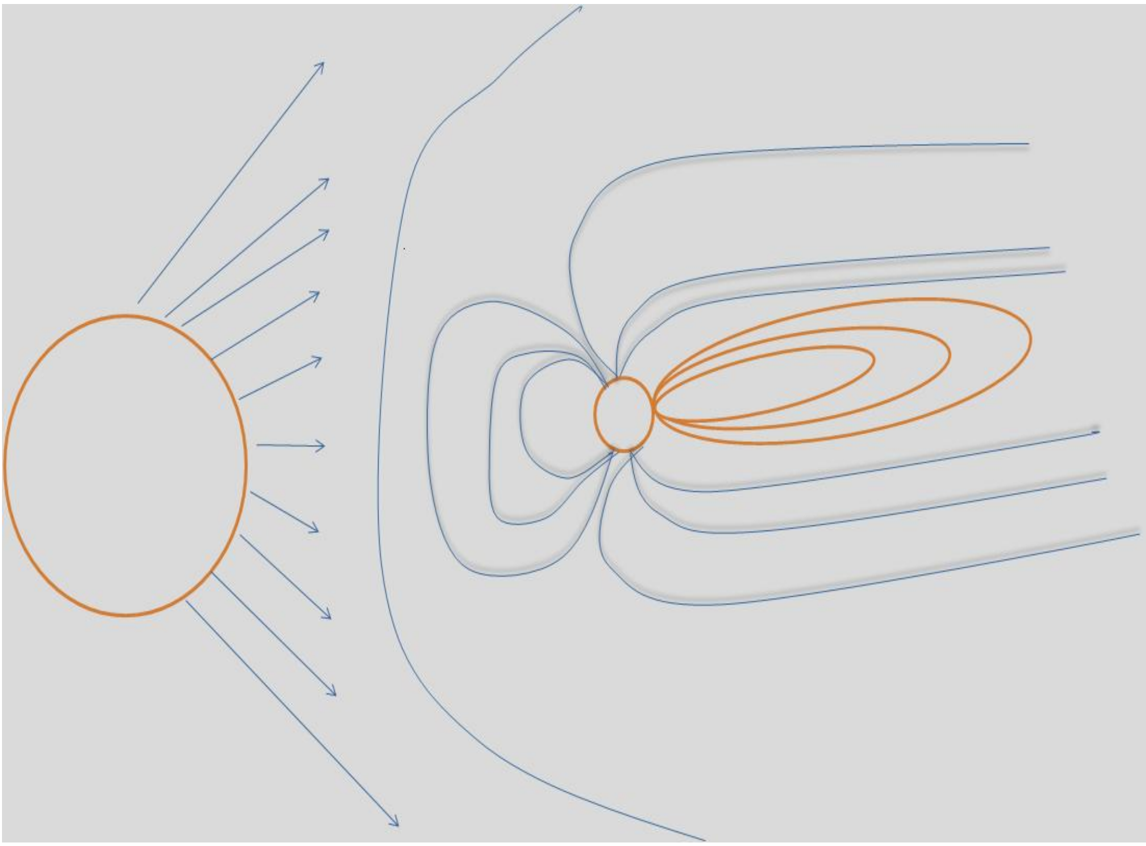

Figure 2.1 Diagram of solar flares distorting the earth's magnetic field

The slowly time-varying magnetic fields give rise to Geomagnetically Induced Currents (GIC), which have the capability to cause transformer core saturation, abnormalities in the functioning of circuit breakers and other power devices, and false tripping of relays leading to extensive power failures and blackouts.

2.2.2 Measuring Indices for Geomagnetic Disturbances

The various North American and Canadian organizations such as the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the North American Electric Reliability Council (NERC), and the Centre for Space Environment Modelling team (CSEM), Hydro-Quebec, Manitoba and Minnesota power utilities and the entire power industry are interested in understanding geomagnetic disturbances. They need more accurate forecasting, to an accuracy of about 90%, so that the power utilities could get appropriate time to implement the safety procedures to ensure the smooth working of the power systems even during geomagnetic storms.

Most of the Canadian and the American power utilities use the K and A indices to indicate the intensity of geomagnetic disturbances [4]. K indices are magnetometer measurements of deviations in the earth's magnetic field for a particular geographical location. The geomagnetic variations, depending upon the latitude, auroral electrojet, geomagnetic field and particular geological location, are measured at the end of a three-hour activity. Geomagnetic variations are measured in units of nanoteslas. The K index is the integer value, ranging from 0-9, of the magnetic field measurements expressed in the quasi-logarithmic scale. The geomagnetic storm of March, 1989 was indexed as K=9. The index A is used to record 24 hour of solar activity. The A index uses the linear scale ranging from 0-400. In the same solar storm of March, 1989, the measurement was 248 on the A scale, indicating a high level of severity [5] - [6] .

But the K and A indices are not sufficiently accurate as indicators of intensity of geomagnetic disturbances. An important shortcoming is that neither K nor A index measures the rate of change of magnetic variation due to solar activity. For this reason, power utilities have faced false alarms in many cases. As will be seen from the conclusions of this thesis, the effect of a geomagnetic storm is also dependent on the earth's conductivity, and the rate of change of the magnetic field, so that K and A indices (which measure magnitudes alone) are not adequate.

The co-relation of K and A indices is shown in the table 2.1 as drawn:-

K INDEX	A INDEX	nT
0	0	0-4
1	3	5-9
2	7	10-19
3	15	20-39
4	27	40-69
5	48	70-119
6	80	120-199
7	140	200-329
8	240	330-499
9	400	>499

Table 2.1 K and A indices showing intensity of geomagnetic storms (From: N.O.A.A. Space environment laboratory)

Recently, NOAA introduced a five level G index for measuring the geomagnetic activity, and to communicate effectively the space weather conditions. The G index is an advanced measuring index recording a three hour geomagnetic activity, and also keeping the track of the rate of change of time of the earth's magnetic field, as it is a really important factor in measuring the geomagnetic activity [7] . Below is the table showing the G scale in co-relation with measuring index K

G index	Description	Physical Measure	Average frequency (1 cycle = 11 years
G-5	Extreme	K-9	4 per cycle (4 days per cycle)
G-4	Severe	K-8	100 per cycle (60 days per cycle)
G-3	Strong	K-7	200 per cycle (130 days per cycle)
G-2	Moderate	K-6	600 per cycle (360 days per cycle)
G-1	Minor	K-5	1700 per cycle (900 days per cycle)

Table 2.2 Showing G index co-relation to K index and measuring geomagnetic activity (From: N.O.A.A. Space environment laboratory)

Organisations such as NOAA are responsible for recording the activities on the sun on an hourly basis and present the day-to-day report. NOAA is responsible for raising an alarm in case of any significant change in day-to-day solar activity [8]. NOAA updates the entire solar activity using various monitoring and recording techniques. Data are available via www.spaceweather.com. This service keeps track of all ongoing solar and terrestrial activities in order to forestall outages due to geomagnetic storms.

2.3 History of occurrence of Geomagnetic Storms

Although geomagnetic storms have been reported for the past 150 years, they have gained importance only in the past few years. This is because the disruptions of the key technologies of modern society: electric power, telecommunication, railway transportation, pipelines, etc., which have been initiated by geomagnetic storms, are very expensive economically. Section 2.4 gives the history of geomagnetic disturbances which have occurred in last few decades in detail. This part of the section includes the geomagnetic events occurring in the era of 1840's, and ranging into the 20th century. Section 2.5 presents the impacts and effects of geomagnetic storms on the electric power industry, communication systems, railway systems and pipelines. The detrimental effects of geomagnetic disturbances are addressed thoroughly and explained with help of details from various events that have occurred so far.

2.4 Some Geomagnetic Storms reported in Literature

This section lists some of the geomagnetic disturbances found in literature search. Each sub-section contains a brief summary of the reports of those disturbances. They affected the man-made structures in early 1840's and the detrimental effects were clear as the time lapsed by. Telluric currents started effecting electric equipments in the 1920's and the electric community was alerted about the dynamic and unpredictable phenomenon of geomagnetic storms.

Varley observed the auroral lights in 1840 and presented the reports about this visual phenomenon which occurred in England in 1873 [1] . Since then, the power utilities have been working hard on developing techniques to predict and monitor these geomagnetic variations ahead of times.

2.4.1 Year 1847

The entire telecommunications system in England either stopped working or experienced problems; when “northern lights” were visible in the northern hemisphere of the earth. This coincidence of interruptions in telegraphic system and visibility of aurora, led to the conclusion that telluric currents were the reason behind these disturbances all through the year 1847-48.

The attractive phenomenon of auroral lights is shown in figure 2.2 below.

Figure 2.2 Auroral lights or “Northern lights” visible in sky during the years 2007 and 2009 in Norway (Image credit; www.digitalsky.org.uk)

Many such disturbances were reported in the telegraph and communication systems in various areas such as New York, Washington, Philadelphia, Massachusetts, Sweden, France as well as other regions of Canada and North America, when these beautiful “auroral lights” were seen in many parts of northern hemisphere.

2.4.2 Years 1870 to 1894

The phenomenon of telluric currents kept interrupting the telegraphic communication in years 1870-72-73 A series of disturbances were noticed on the Western Union lines between New York and Buffalo, New York to Elizabeth and New Jersey. Very similar incidences were reported in year 1894 as well.

2.4.3 Year 1940

The first ever reported incident of effects of geomagnetic disturbances on power systems occurred on March 24, 1940 [1].There were noticeable voltage surges, relay tripping and reactive power swings in Northern United States and Canada. Among the reported disruptions: transformers tripped out at Ontario Hydro, Port Arthur and Crow River Ontario, power disruptions in submarine cables, abnormal power flows in Minnesota. Many such activities were observed in areas such as Toronto, Norway, Sweden and U.S in consecutive years of 1957 and 58. Severe disturbances were reported during these years which affected the communication system, power systems, railways, cables and pipelines.

2.4.4 Year 1989

Scientists claimed that there were a series of major solar processes occurring between March 6, 1989 and March 12, 1989 on the surface of the sun. According to the reports [6] published on “Geomagnetic Storm of 1989”, scientists spotted major solar flares heading towards the earth on March 9, 1989 with a speed of a million miles per hour and hit the earth on March 13, 1989 causing major disturbances in the earth's magnetic field [9].

It took only 1 minute and 10 seconds for these solar disturbances to blackout Hydro-Quebec. The blackout lasted around 8 hours and this storm led to the loss of 21,500 MW of electricity generation and damaged equipment, with the replacement cost reaching to millions of dollars.

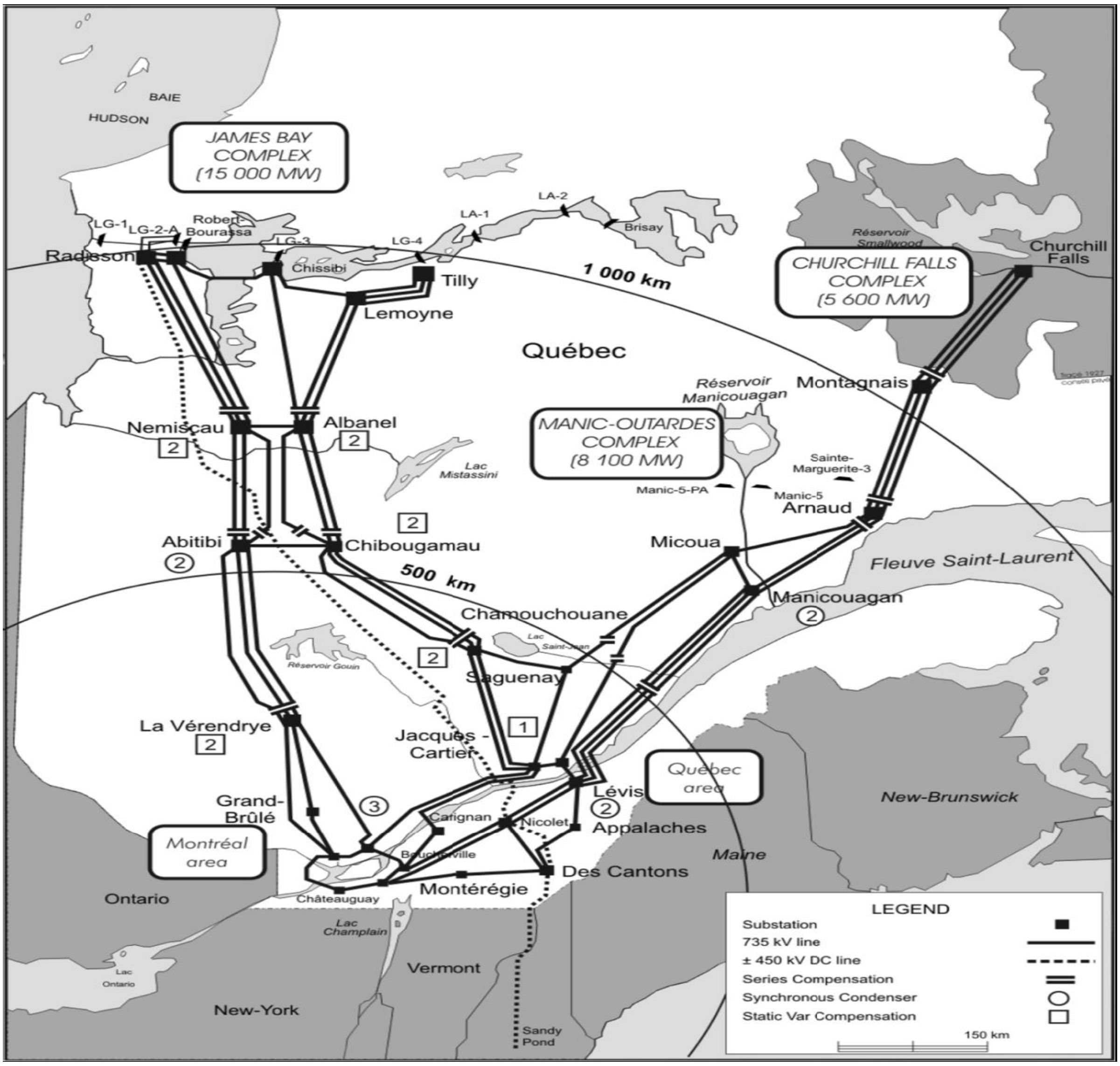

Figure 2.3 Diagram of the Hydro - Quebec's 735-KV transmission network –one of the extensive and complex network systems of North America. (Figure credit: Hydro-Quebec)

The Hydro-Quebec transmission system is a complex and extensive system (see Fig. 2.3) consisting of 735 KV transmission lines of lengths in the order of 1000 km's. The geomagnetic disturbances were strong enough to cause the tripping of seven static compensators-the device necessary for the entire voltage control, on the La-Grande transmission network. By the time the voltage dropped, the frequency increased, and the La-Grande transmission network was separated from the main grid.

The electrojets induced a voltage gradient in the earth's crust which caused transformer core saturation, and frequency relay tripping. Within a few seconds of the separation of the La-Grande network, power swings and tripping caused the separation of the Churchill Falls network from the main grid too. The entire grid system collapsed within a few seconds resulting in a major power blackout.

With the collaboration of the geomagnetic laboratory, Hydro-Quebec measured electric field at five sites, covering 250 km of the distance. The electric field was measured at larger than 1volt/km. this is the "oft quoted figure" which aptly matches the figure calculated in the results presented in Chapter 3, to calculate the terrestrial voltages of geomagnetic storms using the magnetic diffusion equation.

2.4.5 Year 1991

Geomagnetically induced currents (GIC) interrupted the power systems during the years 1991-92, in the U.S and Canadian provinces especially in GIC susceptible regions. Failure of various equipments including the interruptions in HVDC links was reported. Major outages occurred such as the Quebec-New England DC line tripped, the New Mexico HVDC terminal tripped, various transformers and capacitor banks were tripped out of service in the U.S. [10]

2.4.6 Year 2001-2002 (The 23rd sunspot cycle)

For the 23rd sunspot cycle in 2001-2002, the coupling processes between the sun and the earth were monitored using latest advancement in space technology. The solar disturbances of 2003 were called the “Halloween Magnetic Storm”. It kindled new areas of research and new attention was paid to space weather and the impacts of geomagnetic disturbances on power systems.

Before 2003, the mid-latitude regions were not considered as geomagnetic susceptible areas. It has been noticed that geomagnetic disturbances of 2003 affected not only the North America but also Europe and South Africa [11]. The “Halloween Storm” was reported to be the reason behind the tripping of transformers in Manitoba power station and Lethabo Power station in November 2004 located in mid and low latitude regions.

More than 30 years of research into the subject of geomagnetic activities has enabled the power industry to have a better understanding of the earth-sun connection. Power utilities have been preparing defense plans, working towards mitigation techniques and developing monitoring and data collection techniques to be better prepared for every aspect of geomagnetic storms.

2.5 Impacts of Geomagnetic storms on power utilities and other man-made structures

The potential threat of GIC on power system networks was fully appreciated after the complete blackout of March 13, 1989 in Quebec and some parts of North America. The geomagnetic variations in the earth’s magnetic field induce voltages which produce GIC, quasi dc currents which have very slow variation in the frequency range of 1 Hz or less. GIC enter the grounded neutral of wye connected transformers causing transformer core cycle saturation. Frequency relays, which are not prepared for quasi dc currents trip circuit breakers, and disrupt the normal power system operations.

The sub-sections below summarize some records of how GIC has led to disruptions in power systems.

2.5.1 General Faults

The transmission network is becoming much more vulnerable to the effects of geomagnetic storms due to the large interconnected systems spanning over large geographical areas. These large interconnected networks are exposed to induced voltages ranging between 1-6 V/Km, driving high geomagnetically induced currents.

Fig. 2.4 below shows the link from solar activity to potential malfunctioning of man-made equipment.

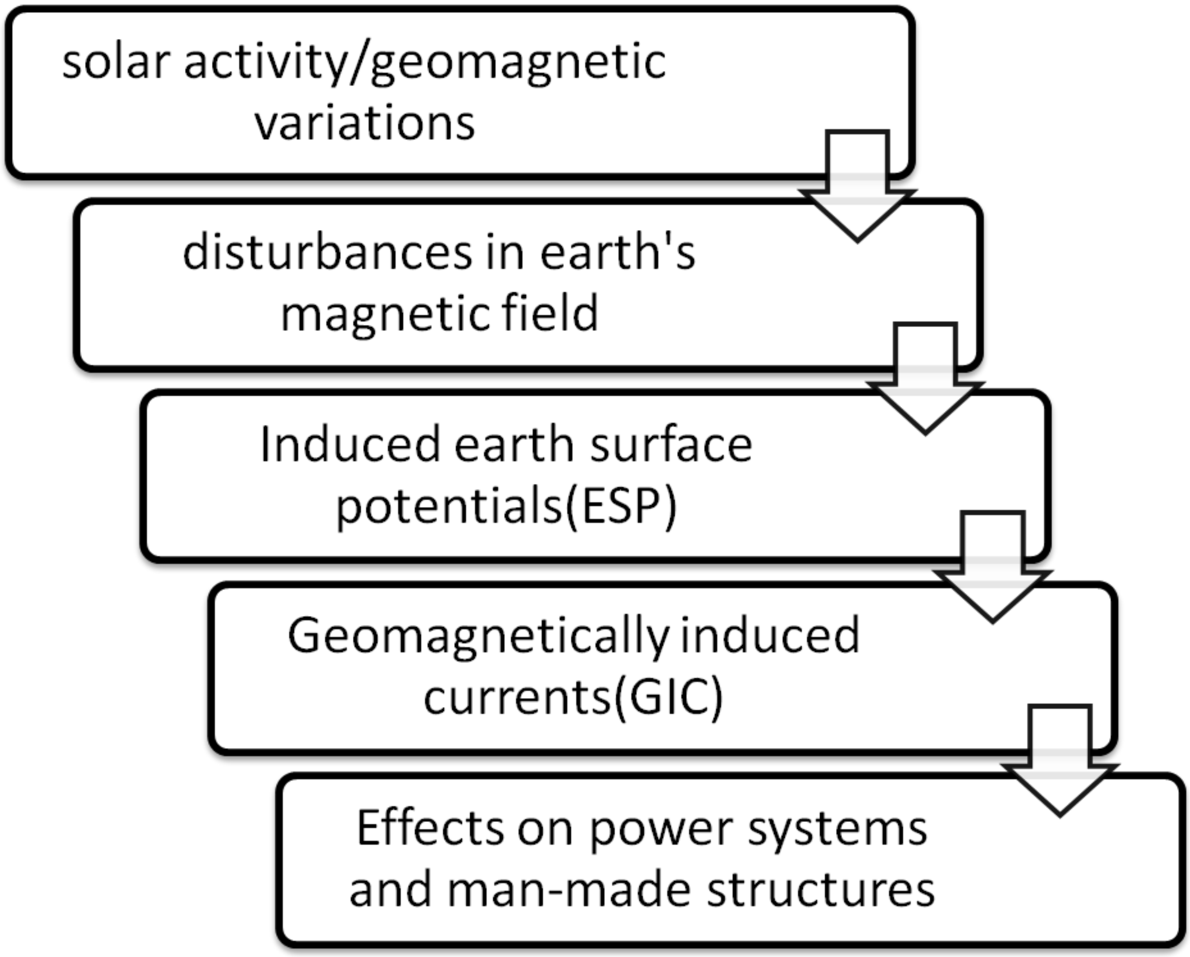

Figure 2.4 Flow chart showing the entire process of geomagnetic effects

Samples from reports which give an idea of the nature of the damage caused are:

(1) In the 1940 storm, transformer fuses blew up in New England, New York, Minnesota, Ontario and Quebec.

(2) In the 1989 storm, increased VAR demands led to voltage collapse. (Recent trends to generate and transmit electrical energy over larger distances have reduced voltage stability and transient stability margins).

(3) As GIC is quasi-dc, half cycle saturation in transformers occurs.

(4) False frequency relay tripping because quasi-dc current is unexpected.

Moreover the equipment damage due to geomagnetic disturbances is an important consideration in terms of re-usability, restoration and cost. Many electric power utilities experienced generator trips during intense geomagnetic activity. Generators are prone to harmonics and voltage imbalance due to transformer half cycle saturation. Hence the equipments such as generators and turbines are effected indirectly by heating and mechanical vibrations including the harmonic distortion leading to lesser lifespan and interruptions in normal operation.

2.5.2 Effects on Transformer Equipment

Transformers are heavily affected by the geomagnetically induced currents resulting in interrupting the power supply, and leading to major power system breakdowns. It takes only a low level of GIC, probably tens of amperes to drive transformers into half cycle saturation. Saturation results in distorted transformer exciting current which is full of harmonics, leading to eddy currents causing transformer heating [12]

The effects of geomagnetically induced currents on transformers are:

i) Transformer core saturation

ii) Harmonic generation

iii) Excessive transformer heating

iv) VAR consumption

v) And Noise

Transformers driven into half cycle saturation are bound to consume more VARS leading to decrease in capability of AC transmission systems Transformer half cycle saturation is the major cause of all the sequence of power failure events which occurred in the Hydro Quebec transmission network [13]. Transformers are normally made to operate near saturation limit, and GIC, if present, can offset the magnetic flux of transformer, and transformer is saturated over a half cycle. This is called transformer half cycle saturation.

GIC enters the grounded neutral of wye-connected transformers as shown in Figure 2.3. Because GIC is quasi-dc, it saturates the iron core of the transformer.

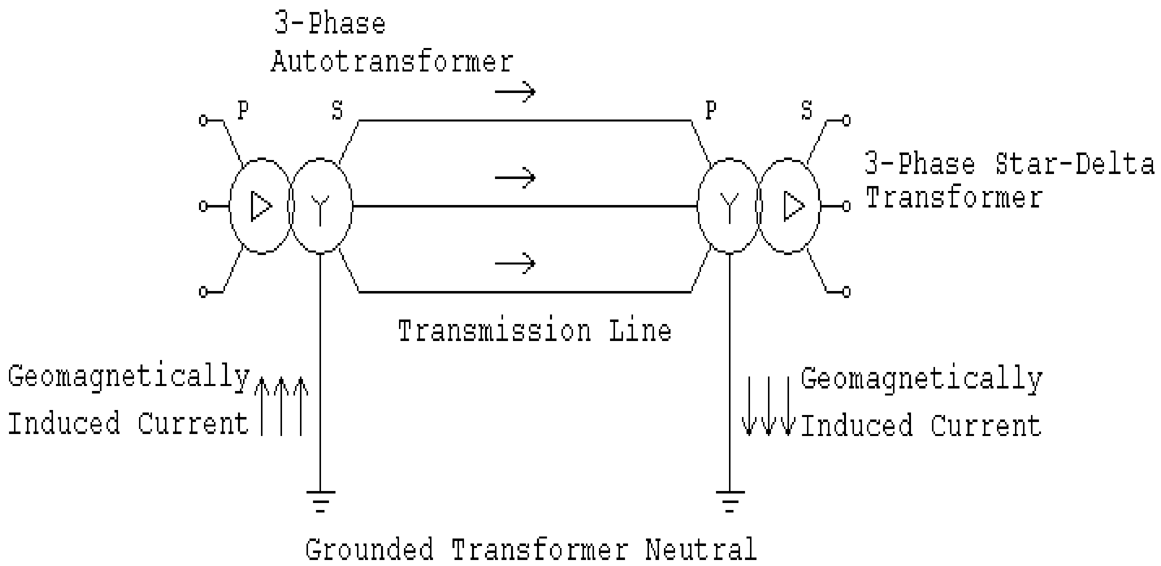

Figure 2.5 Diagram of GIC flowing through the grounded neutrals of wye connected transformers

Transformer half cycle saturation also results in increased VAR consumption, and increase in harmonics. Iron core saturation can cause equipment damage, due to harmonics and overheating. During transformer half cycle saturation the stray flux flows through paths other than the transformer core, and induces the circulating eddy currents, resulting in transformer heating. Transformer heating could have damaging effects on transformer winding insulation and can result in damage to the equipment. As a result of the March, 1989 geomagnetic storm, there was failure due to an overheated transformer at the Potomac Edison Meadow Brook Substation, Virginia. Transformer half cycle saturation when persistent results in audible noise due to steel vibrations and vibrations of the transformer tanks.

All these cumulative effects of GIC on transformers are very complicated and differ with transformer type and design. The susceptibility of transformers to GIC induced saturation is really type dependent, for example, the three-phase and single-phase shell form and single-phase core form are highly susceptible; whereas the three-phase three-core form is not. The load tap-changing transformers are vulnerable and GIC leads to an increase in VAR consumption and thus voltage collapse. Frequently GIC just initiate the processes leading to damage. After initiation, the stray magnetic flux, equipment overheating, excessive gas evolution in transformer oil tanks and mechanical vibrations can bring about transformer failure, and transformer failure led to power system failure in the case of the Hydro Quebec.

2.5.3 Faults in Relay Protection System, Circuit Breakers and VAR Compensators (SVC)

During the geomagnetic storm of March 1989, the power utilities at Minnesota and Manitoba reported faulty circuit breaker tripping. The GIC caused transformer quasi-dc neutral current which led to transformer half cycle saturation, etc. The protective relays misinterpret the current imbalance and harmonics. They mistakenly sent signals to open circuit breakers. Apart from current distortions due to half-cycle power transformer saturation by GIC's, the Current Transformers (CT) of the differential protection system themselves can be saturated by GIC. The differential protection uses the secondary currents of the CT and because of saturation they yield unreliable information from which relays have been activated to trip circuit breakers wrongfully [11]. Examples of protection malfunction due to GIC leading to circuit breaker tripping are: (i) Sept. 1957, tripping of 230 KV circuit breaker in Jamestown, North Dakota; (ii) 1960 in Sweden [14]; (iii) 1980 in Manitoba and Minnesota. Circuit breaker malfunctioning is directly related to the secondary arc currents for single pole switching on three phase networks. Since the presence of geomagnetically induced currents increases the secondary arc current by many fold due to the increased harmonic content, thus increasing the fault detection time.

The Seven Static VAR Compensators (SVC) on the La-Grande network of the Hydro-Quebec were tripped by the solar storm of March, 1989.The SVC were used for the voltage control and regulation, and reactive power compensation. The geomagnetic storm of 1989 resulted in tripping of seven static compensators causing voltage instability and increased frequency leading to the major power outage of the century. Within a few seconds, the 735 KV lines began tripping due to prevailing low voltage conditions. The major networks, the La Grande and the Churchill Falls, were separated from the main Hydro-Quebec network, thus plunging Quebec and many regions in North America into darkness. As mentioned, the initial cause was the tripping of circuit breakers by protective relays in detecting the harmonics and quasi-dc currents due to half cycle saturation of transformer by the GIC. Undesirable tripping of the 230 KV capacitor banks at the Forbes substation and 30 MVAR capacitor bank at Nashwauk were the other recorded events indicating malfunctioning due to GIC in 1989.

2.5.4 Communication Problems

Communication systems such as wire communication, radio communication, and satellites are also affected due to intense geomagnetic activity [15]. Although to date there have been no major impacts of geomagnetic storms on communication systems reported, but power industry and R& D organizations have been alerted on the same grounds.

As already mentioned in the section 2.1 the first ever event reported was on the telegraph systems in 1840’s. The telegraph system in England experienced interruptions in normal operation which coincides with the visible auroral lights in northern hemisphere. The visible auroral electrojet was the result of a series of coupling activities between the sun and the earth. The telluric currents caused due to intense geomagnetic activities reportedly caused fluctuations in needles of telegraphs and danger to telegraphic equipment. Even the submarine cables were reported to be affected by these magnetic disturbances. The solar flares narrow the useable range of frequency resulting in the interruption of radio-transmission and satellite communication.

2.5.5 Problems in Pipelines and Railway Systems

Up to this section, the solar activities of interest have been those of the 10 or 11-year cycle whose intensity and rate of change induce GIC’s which result in false tripping of circuit breakers in electric power grids. Less intense geomagnetic activities also cause GIC which over decades affect pipelines and railway lines by enhancing the corrosion process in them, thereby decreasing their lifespan. Recently, the development of very long oil and gas pipelines has increased concerns about their vulnerability to geomagnetically induced currents. This has aroused interests in corrosion control, protection techniques and pipeline surveys [16]. Pipeline corrosion occurs when the induced geomagnetic currents flow through the pipe and soil with the induced electric potentials in the earth surface. The conducting pipe serves as a long conductor which samples the earth’s electric field at grounded locations such as the bends and turns in a pipeline, causing the induced current to flow between these different potential points. The process occurring is similar to electrolytic process in which water molecules break down into H^+ and ions making common rust at the anode. Hence the rate of corrosion is directly dependent on the flow of induced current through the pipe. The rate of corrosion is also affected by frequency of current oscillations and chemical composition of the soil at the contact point.

In order to understand the effects of geomagnetically induced currents on pipeline corrosion, companies, such as the Finnish natural gas pipeline, continuously monitor on site, the magnitude and the frequency variations of GIC and develop a data bank of the earth soil conductivity and chemical composition. From better knowledge, the expectation is that better counter-measures can be developed.

Recently, there were claims that geomagnetic activities have reportedly been affecting the railway system. During the geomagnetic storms of 2000 and 2003, there had been malfunctioning in the otherwise smooth operation of Signalization, Centralization and Blockage (SCB) systems of railways especially in high latitude areas [17]. To be more specific, the Russian and the Swedish railway systems experienced false blockages in railway systems, voltage instability which caused malfunctioning of traffic lights and false employments of rail tracks. This malfunctioning coincided with the period of high geomagnetic activity. The railway automation and telemetry systems in Siberia were experiencing similar technical failures. Whether the intense geomagnetic activity was the sole reason for all these malfunctions or whether it was a sheer coincidence, is open to further research for confirmation.

2.5.6 Effects on HVDC Transmission Systems and HVDC Converters

Intense geomagnetic activity may also cause GIC to flow through a high voltage direct current (HVDC) transmission network [18], inducing non characteristic harmonic current to flow on the AC side of converter, which increases noise level, and temperature of converter transformer. Increase in harmonic currents not only distorts the voltage waveform but can also lead to overloaded shunt capacitors and filters. GIC flow in converter transformer also causes transformer saturation leading to a series of faulty operations.

Recent advancements in the power industry, like expanded HVDC transmission lines in countries like China, Canada and regions of North America are much more prone to geomagnetically induced currents. Mid latitude and high latitude regions which have HVDC transmission lines extending to 1000 kms and in favored east-west direction of auroral electrojet currents require immediate attention towards the effects of geomagnetic currents on them.

2.6 Directional Sensitivities of Geomagnetic Disturbances and Area Proximity

Key factors affecting the probability of GIC occurrence and vulnerability are:

i) Geographical and topographical locations

ii) The Earth conductivity and igneous rocks

iii) Physical factors such as equipment length and type

iv) Directional sensitivity of auroral electrojet

High latitude areas such as Canada, Finland, and North America are much more prone to solar disturbances [19]. The Electric Power Research Institute in Canada issued a GIC hazard map of Canada and North America which assigned vulnerability percentages of GIC in different areas. But recent studies have indicated that even the mid latitude and low latitude regions have some potential risk to geomagnetically induced currents [20]. Recent reports of transformer equipment damage, relay tripping and other faults in power systems in South Africa [11] and China [21], Malaysia [22], areas reasonably far from auroral zone, contradict conventional thinking. In year 2001, mid-latitude regions experienced intense solar activity. A high value of geomagnetically induced currents recorded there, confirmed the effect of geomagnetic disturbances in mid and low latitude areas. Hence network topology gained importance as far as geomagnetic disturbances are concerned.

Geographical conditions are highly responsible for GIC effects on power systems and equipments. The complex and vast span of the North American grid system is easy prey to intense geomagnetic disturbances. Variable conductivities and rock formations increase the vulnerability trend. The geomagnetic disturbances are more pronounced in areas located around the igneous rock formations [23]. The conductivity of the earth and geo-electric field is interrelated. The igneous rock formations with high resistivity and low conductivity are highly prone to geomagnetic disturbances.

Also power system orientation, equipment types especially in transformers, transformer type and connections, length of transmission and distribution network, and electrical resistance are a few physical factors defining the GIC susceptibility and vulnerability. The long transmission lines, extended over large distances to transmit more and more power, are more vulnerable to GIC flow during geomagnetic storms. The spanned network of long transmission lines induces voltages in grounded neutrals of wye connected transformers, leading to half cycle saturation in transformers, relay tripping, voltage imbalance and series of faulty operations leading to major power outages.

Since half cycle saturation is the major cause of faulty operation, transformer manufacturers are claiming that their new designs are based on three limb core type which may be highly insensitive to geomagnetic disturbances. Analysis of the recorded data of the March, 1989 GIC disturbances in the Hydro-Quebec 735 KV grid system indicates that the GIC had directional sensitivity [24]: its effects were more pronounced in the east-west power transmission lines than the north-south transmission lines. This is because the east–west auroral electrojet caused fluctuations in north-south component of earth’s magnetic field resulting in east-west direction earth surface potentials.

All these factors make the dynamically changing geomagnetic disturbances even more complex and difficult to predict. The space weather organizations especially NOAA are working on space weather predictions and forecasts which will help the power utilities to be better prepared for GIC.

CHAPTER -3

TERRESTRIAL VOLTAGES OF GEOMAGNETIC STORMS SOLVED FROM MAGNETIC DIFFUSION EQUATION

3.1 OverviewEquation Chapter (Next) Section 3

Geomagnetic storms occur as a result of the sun's solar activity**.** They involve solar mass ejection and its orientation towards the earth, solar rotation, the speed of the solar winds, etc. These solar winds flow at the rate of 400km/s in normal and up to 800km/s at peak conditions. In coupling through interplanetary magnetic fields, they modify the upper atmosphere currents flowing in the ionosphere at about 100 km altitude. The strong auroral currents have been given the name, "electrojets". Although GIC are generally considered to be random, according to [1] data collected over several decades indicate certain statistical regularities: 10-11-year period of higher solar activities; maxima occurring during the equinoxes; a clear diurnal variation of the amplitudes with the most frequently observed times seen around the sun rise and the sun set. Their occurrences are not limited to high latitudes (50 degrees North) [25], [26] as earlier believed, because they have made appearances in South Africa, Brazil and China (33.4°N) [21].

At one point in time, they were considered as a part of space weather and were deemed harmless. Thus very little attention was paid to them. But it was realized after experiencing blackouts on many occasions in North America and Europe, that geomagnetic storms have the potential to significantly disrupt normal operation of power utilities, phone cables and other communication systems. They have been known to increase corrosion in oil and gas pipelines, railway lines and to give rise to electric shocks.

The geomagnetically induced DC currents **(GIC)** that occur due to geomagnetic storms [2]-[27] appear as quasi static “dc currents” which have very slow variation in frequency range of 1 Hz or less. The alerted electrical engineering community accordingly has examined their implications on protective relaying [12]-[25], load flow studies [28], HVDC [29], [30] and power quality [31]. GIC can also affect pipelines [16] and railway lines [17]

The engineering research on GIC reported to date, for example [14], [27]-[32] and [13]-[21], assumes that the stages related to solar activity, propagation of the solar wind and the magnetospheric processes can be omitted and research can focus on the “geo-electric stage”, i.e. from the magnetic field of the electrojets. The computation methodology is mainly based on the plane wave method pioneered by Louis Cagniard [33] for magnetotelluric prospecting. Electrical engineers begin at the level of the measured magnetic fields and look for methods to relate the magnetic fields to the induced electrical voltages.

So this chapter of the thesis sums up the research undergone at McGill University, explaining the predictive method of computing terrestrial voltages from geomagnetic storms based on solving the Magnetic Diffusion Equation. Also this chapter is an attempt towards summarizing the entire process, description and computed results obtained. As will be shown, voltages around “1volt per kilometer” can be predicted from the magnetic field density deviation, periodicity and ground resistivity values generally encountered. This method is a useful addition to the other excellent methods already developed. [16]-[34].

This chapter presents a method of estimating the magnitudes of terrestrial voltages which is based on solving the magnetic diffusion equation. The method predicts the oft-quoted figure of “1 volt per kilometer” for the range of geomagnetic field variations (magnitudes and frequencies) and ground resistivity frequently encountered. The prediction formula has been validated by the plane wave method.

This chapter is organized as follows: After the brief overview above, in section 3.1; Section 3.2 is formal introduction, explaining the basis on which the magnetic diffusion method is used to compute terrestrial voltages from geomagnetic storms. Section 3.3 briefly presents the derivation of the magnetic diffusion equation, which is available in text books [35], [36]. The derivation is summarized here for completeness. Section 3.4 models the magnetic field density from the electrojets in the space above the ground of the planet earth and solves the magnetic diffusion equation in the ground as a boundary value problem. The computed results are presented in Section 3.5. Section 3.6 shows that the formula of terrestrial electric field intensity E_m derived from the magnetic diffusion equation is the same as the equation (2) of [16] which has been derived by the plane wave method. Section 3.7 outlines how the derived formula is applied in the power grid. Section 3.8 is a brief conclusion to the chapter, an effort to show that the method explained is a predictive tool, helpful for engineers and researchers to have clear understanding of geomagnetic storms, and to protect electric power systems from further risks of geomagnetic storms.

3.2 Quasi-Static Approximation to Maxwell's Equations

This section introduces the method of the magnetic diffusion equation, used to calculate the terrestrial voltages from geomagnetic storms. Starting with the formal introduction, this section of the chapter presents the magneto-quasi-static approximation of Maxwell's Equations [37]-[38] wherein there is no wave propagation. Developing from the magneto-quasi-static approximation, the terrestrial voltages from geomagnetic storms are obtained by solving the magnetic diffusion equation [35], [36], [39].

The method predicts voltages of around "1 volt per kilometre" from the range of ground resistivity, magnetic field densities and periodicities reported during magnetic storms. In addition, the derived prediction formula on magnitude is the same as equation (2) in [16] which has been derived by the plane-wave method.

In this section, the starting point is the magnetic field density, $\boldsymbol{B}_{space}$, as measured at ground level. Amongst other researchers, the authors of [27], [32] and [34] have pointed out that it is the time derivative of the magnetic field density which is significant, i.e. the measured GIC come from the induced electric field $\boldsymbol{E}_m$ of Faraday's Law of Electromagnetic Induction.

For GIC with very low frequency, $\boldsymbol{E}_m$ is also varying slowly with time. The very slow time variation, together with the small number $\varepsilon_0=8.854x10^{-12}$ farad/m, means that $\partial\mathbf{D}/\partial t=\partial\varepsilon_0\boldsymbol{E}_m/\partial t$ in the Maxwell's equation, $\nabla\times\boldsymbol{H}=\boldsymbol{J}+\partial\mathbf{D}/\partial t$, can be dropped so that the wave propagation equation does not have to be used.

The omission of $\partial\mathbf{D}/\partial t$ enables the magneto-quasi-static approximation to Maxwell's equations to be assumed. One criterion for determining the validity of using the approximation is that spatial dimensions of interest are much smaller than the quarter-wavelength (wavelength=velocity of light/frequency in Hz) of the propagation frequency [36]-[37]. For GIC with frequencies as low as *1* cycle per second, *1* cycle per minute or *1* cycle per hour, the quarter-wavelengths are $0.75x10^6$ km, $4.5x10^6$ km and $270x10^6$ km respectively. As the altitude of the electrojet and the diameter of the earth are of the order of *100* km and *6000* km respectively, GIC of such low frequencies qualify for treatment by the magneto-quasi-static approximations of Maxwell's equations. The set of magneto-quasi-static equations are:

$$\nabla\times\mathbf{H}=\mathbf{J} \tag{3.1}$$

$$\nabla\cdot\mathbf{B}=\mathbf{0} \tag{3.2}$$

$$\nabla\cdot\mathbf{J}=0 \tag{3.3}$$

$$\nabla\times\mathbf{E_m}=-\partial\mathbf{B}/\partial t \tag{3.4}$$

The geoelectric stage is treated by solving the magnetic field in the Magnetic Diffusion equation which embodies ground conductivity together with equations (3.1) to (3.4). After solving $\boldsymbol{B}$ in the magnetic diffusion equation, $\boldsymbol{J}$ is obtained from (3.1) where $\boldsymbol{H}=\boldsymbol{B}/\mu_0$. As the ground is assumed to be homogenous with electric conductivity σ (Siemens per meter, reciprocal of resistivity ρ in ohm- meter), the electric field $\boldsymbol{E_m}$ is found from Ohms Law, $\boldsymbol{E_m}=\boldsymbol{J_m}/\sigma$.

The terrestrial voltage, Φ_{m-n} between any two ground points, m and n, is obtained by evaluating the line integral of the magnetically induced electric field [13].

$$\Phi_{m-n} = \int_m^n \mathbf{E_m} \cdot d\mathbf{s} \tag{3.5}$$

As the orientation of the $\boldsymbol{B}$-field changes with geomagnetic storm, the direction of the electric field $\boldsymbol{E_m}$ changes and so does Φ_{m-n}.

3.3 Derivation and Solution of Magnetic Diffusion Equation

This section presents the complete derivation of the magnetic diffusion equation.

3.3.1 Magnetic Diffusion Equation

The derivation to Magnetic Diffusion equation is well known [35]-[36] but as it is central to this work of research at McGill University; related to effects of geomagnetic disturbances on Trans Canadian grids, as summed in this thesis, its derivation is summarized here for completeness. This method, based on solving the magnetic diffusion equation is successfully used to compute the terrestrial voltages from geomagnetic storms,

It is assumed that the conductivity σ of the ground is homogeneous and the permeability everywhere is $\mu_0= 4\pi\times10^{-7}$ Henry/m. When the magnetic field density $\boldsymbol{B_m}$ from the magnetic storm has time variation, an electric field $\boldsymbol{E_m}$ is induced because of (3.4). As the ground has conductivityσ, $\boldsymbol{E_m}$ produces a ground current density $\boldsymbol{J_m}=\sigma \boldsymbol{E_m}$. Multiplying (3.4) by σ and substituting $\boldsymbol{J_m}=\sigma\boldsymbol{E_m}$, one has:

$$\nabla \times \mathbf{J_m} = -\sigma \partial \mathbf{B_m} / \partial t \tag{3.6}$$

Substituting (3.1) in (3.6)

$$\nabla \times (\nabla \times \mathbf{H_m}) = -\sigma \partial \mathbf{B_m} / \partial t \tag{3.7}$$

Multiplying (3.7) by μ_0 and because $\boldsymbol{B_m}=\mu_0 \boldsymbol{H_m}$

$$\nabla \times (\nabla \times \mathbf{B_m}) = -\sigma \mu_0 \partial \mathbf{B_m} / \partial t \tag{3.8}$$

From vector identity, the left hand side of (3.8) is

$$\nabla \times (\nabla \times \mathbf{B_m}) = \nabla (\nabla \cdot \mathbf{B_m}) - \nabla^2 \mathbf{B_m} \tag{3.9}$$

Substituting (3.9) in (3.8) and thereafter (3.2), one arrives at the Magnetic Diffusion Equation

$$\nabla^2 \mathbf{B_m} = \sigma \mu_0 \partial \mathbf{B_m} / \partial t \tag{3.10}$$

3.4 Model of Electrojet and the Solution of Magnetic Diffusion Equation

This section of the chapter presents the solution to Magnetic Diffusion equation focusing on the objective of the research. This section summarizes the modeled magnetic field density of the earth due to the electrojet of high speed electrons, and explains the solution of Magnetic Diffusion equation as a boundary value problem to compute the desired results as presented in section 3.5 of this chapter.

3.4.1 Static Magnetic Field Due to Direct Current in Infinitely Long Conductor

From (3.1), the magnetic field intensity H, at radius r from the axis of an infinitely long line carrying a direct current I, is a field vector with magnitude $H=I/2\pi r$ and with the directional vector u_φ of cylindrical coordinates, whose z-axis coincides with the infinitely long line.

3.4.2 Magneto-Quasi-Static B-field

When the current of the line has an angular frequency variation of ω radian/s, it is described as $Im\ Ie^{j\omega t}$ where "*Im*" designates the imaginary part of a complex number. Its magnetic field density in space for $r > 0$ is:

$$\mathbf{B}_{space} = \mathbf{u}_{\varphi}\mathrm{Im}(\frac{\mathrm{B}_{\varphi-space}}{r}e^{j\omega t}) \tag{3.11}$$

Where $B_{\varphi\text{-}space}=I\mu_0/2\pi$.

3.4.3 Magnetic Field Density of an Electrojet

Figure 3.1 models an electrojet at a height above the earth. The electrojet is represented by the infinitely long line of slowly time varying current described in Section 3.4.1 above. The *B*-field of (3.11) is illustrated as concentric circles in Fig. 3.1 As the height of an electrojet is of the order of 100 km and the diameter of the earth is around 6000 km, Figure 3.1 cannot be drawn to scale. The surface of the earth is depicted by an arc of a large radius.

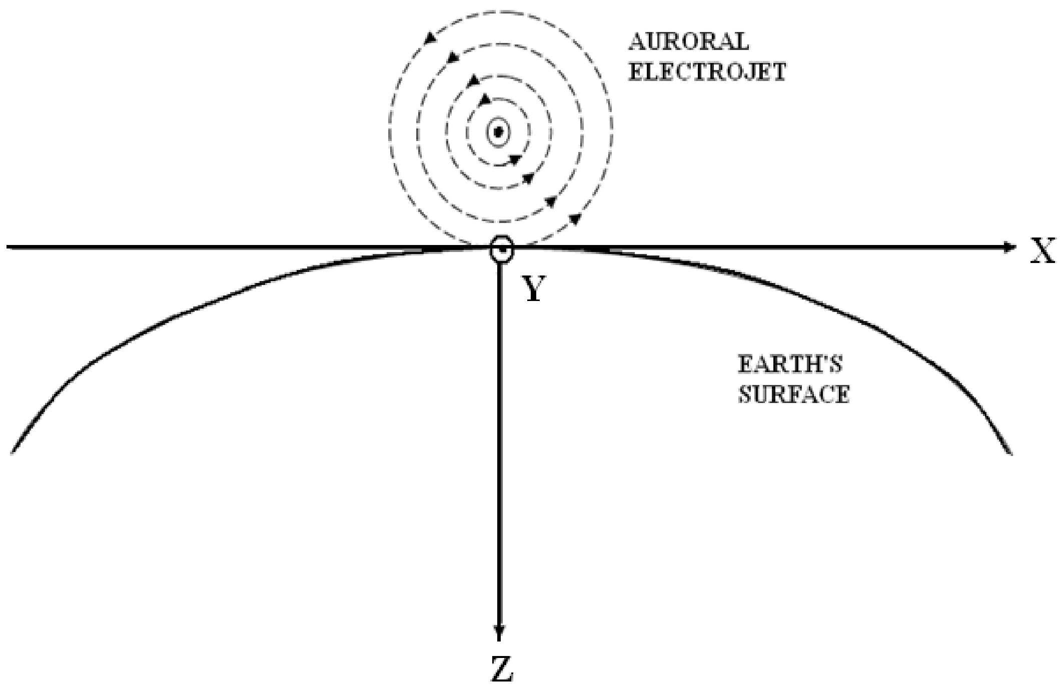

Figure 3.1 Diagram of ***B***-field due to an auroral Electrojet current above the earth surface.

3.4.4 Cartesian Co-ordinate Frame

Notwithstanding that B_{space} should be modeled by cylindrical coordinates and the earth by spherical coordinates, for mathematical simplicity the Cartesian *x-y-z* rectangular co-ordinate system is adopted and positioned as shown in Fig. 3.1. The earth's surface is the *x-y* plane at z=0 with the z axis pointing downwards. The Cartesian frame is orientated so that the directional vector u_φ of (3.11) lies in the x-z plane. It is assumed that $z=0_+$

$$\mathbf{B}_{space} = \mathbf{u_x}\mathrm{Im}(\mathrm{B}_{space}e^{j\omega t}) \tag{3.12}$$

where B_{space} approximates $B_{\varphi\text{-}space}/r$ on the surface of the earth.

3.4.5 Objective of Analysis

The objective of the research is to derive a formula which predicts the voltage of the GIC from knowledge of: - B_{space}, an angular frequency ω and the ground conductivity σ. It is assumed that in the ground, $z \geq 0$, and in the vicinity of the region of interest, B_m is independent of x and y and has a direction vector of u_x only, i.e.

$$\mathbf{B_m} = \mathbf{u_x}B_x(z,t) \tag{3.13}$$

From the modeling assumptions, the solutions of the analysis are valid in a small region close to the surface of the earth in the vicinity of the electrojet.

3.4.6 Solutions of the Magnetic Diffusion Equation

For the reduced dimension of B_m in (3.13), the Magnetic Diffusion Equation of (3.10) simplifies to:

$$\frac{\partial^2 B_x}{\partial z^2} = \sigma\mu_0 \frac{\partial B_x}{\partial t} \tag{3.14}$$

The well known solution of (3.14) from [35], [36], and [39] is:

$$B_x(z,t) = \mathrm{Im}\, B_m e^{sz} e^{j\omega t} \tag{3.15}$$

Where B_m is the peak value of the ground magnetic flux density and s is the coefficient of z which is obtained by substituting (3.15) in (3.14) and equating the left hand-side to the right hand-side. The equality yields

$$(s)^2 = j\omega\sigma\mu_0 \tag{3.16}$$

$$\text{As } \sqrt{j} = \pm\frac{(1+j)}{\sqrt{2}} \tag{3.17}$$

The 2 complex solutions of s are:

$$s = \pm\frac{(1+j)}{\sqrt{2}}\sqrt{\omega\sigma\mu_0} \tag{3.18}$$

3.5 Results

This section summarizes the results obtained by solving the magnetic diffusion equation, used to compute the terrestrial voltages from geomagnetic storms. The solution of the magnetic diffusion equation as a boundary value problem is used to obtain the "oft quoted figure of 1 V/Km" in a transmission line as obtained by the power utilities after the geomagnetic storm of March, 1989.

3.5.1 Matching Boundary Conditions

The solution B_m of the Magnetic Diffusion equation in the ground is related to B_{space} above it by satisfying the continuity of the B-fields at z=0. By equating (3.12) to (3.15)

$$B_m = B_{space} \tag{3.19}$$

As it is required that $B_x\ (z, t) \rightarrow 0$ when $z \rightarrow +\infty$, one chooses the s which has negative real part.

3.5.2 Ground Current

The ground current is $\boldsymbol{J_m} = \boldsymbol{u_y} J_{my} + \boldsymbol{u_z} J_z$ and is obtained by substituting (3.13) in (3.1), i.e.

$$\mathbf{J_m} = \nabla \times (\mathbf{B_m} / \mu_0) \tag{3.20}$$

Since B_m=B_{space} because of (3.19), the y and z components of the magnetic ground current are:

$$J_{my} = \text{Im} \frac{\frac{(-1-j)}{\sqrt{2}} \sqrt{\omega\sigma\mu_0}}{\mu_0} B_{space} e^{\frac{(-1-j)}{\sqrt{2}}\sqrt{\omega\sigma\mu_0}z + j\omega t} \tag{3.21}$$

$$J_{mz} = 0 \tag{3.22}$$

Since

$$J_{my} = \sigma E_y \tag{3.23}$$

$$E_y = -\text{Im}[\frac{(1+j)}{\sqrt{2}} \sqrt{[\frac{\omega}{\sigma\mu_0}]} B_{space} e^{j\omega t} \tag{3.24}$$

Although the key physical process is (3.4) (Faraday's Law), the electric field is modified by the magnetic diffusion process so that E_y is dependent on the square root of frequency and resistivity. In addition, the phase shift is *45°* and not *90°*.

Eq. (1.24) yields the ratio:

$$\left| \frac{E_y}{B_{space}} \right| = \sqrt{\frac{\omega}{\sigma\mu_0}} \tag{3.25}$$

3.5.3 Terrestrial Voltage

The engineers and power utilities are concerned as to whether their power systems are at risk during solar storms; Fig. 3.2 presents graphs of the conditions when the transmission line will encounter voltages of "1 volt per kilometer". The y-axis of Fig. 3.2 is for cyclic period *N* (hours). The x-axis is for resistivity ρ (ohms-m). The graphs are for different magnetic field densities B_{space} (nanoteslas). Fig. 3.2 displays the formula:

$$N = [\frac{2\pi\rho}{3600\mu_0} \cdot (\frac{B_{space}y}{\Phi_p})^2] \tag{3.26}$$

Which is obtained from (3.25) by substituting ($\omega=2\pi/(3600N)$ rad/s, $\mu_0=4\pi.10^{-7}$, B_{space} (nanoteslas), y (meters), $\sigma=1/\rho$ (Siemens per meter). In Fig. 3.2, the peak voltage $\Phi p=1$ volt and $y=1000$m.

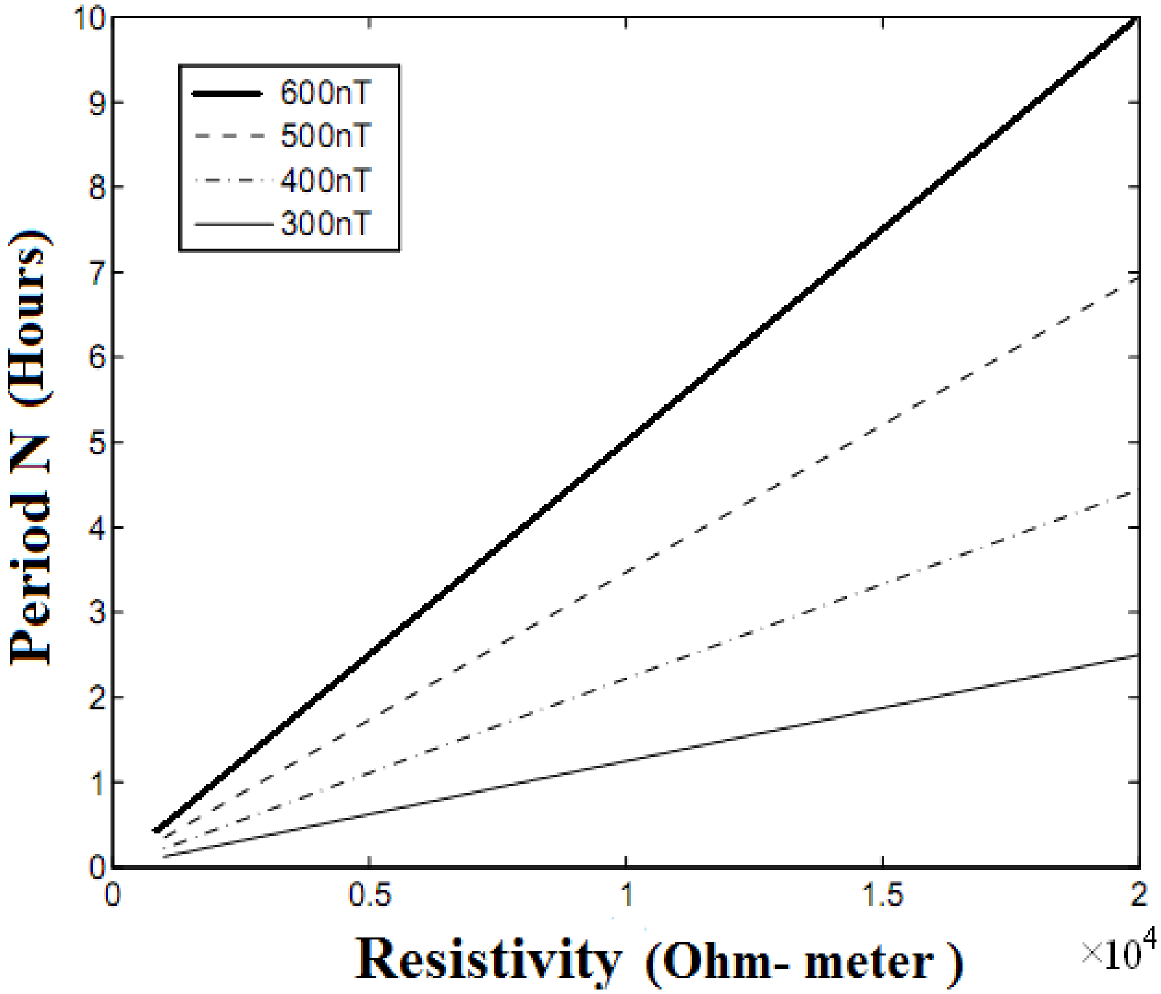

Figure 3.2 Parameter combinations (peak magnetic field (nanoteslas), cyclic period N (hours), ground resistivity ρ (ohms-m) which produce peak terrestrial voltage of 1 volt/kilometer.

Table 3.1 lists the resistivity of common ground material, many of which are taken from [38]. Apart from igneous rocks, regions with dense limestone and metamorphic rocks are also at risk.

TABLE 3.1

RESISTIVITY OF EARTH MATERIALS	
MATERIAL	***RESISTIVITY IN OHM-METER***
Clay	1-100
Sand	1-1,000
Shale	20-2,000
Limestone	50-10,000,000
Igneous rocks	100-1,000,000
Metamorphic rocks	50-1,000,000

Table 3.1 listing the resistivity of various earth materials

3.5.4 Terrestrial voltage dependence on distance and ground resistivity

Substituting (3.24) in the line integral of (3.5), the dependence of the peak voltage Φ_p on distance y is plotted in Fig. 3.3 for B_{space}=400 nanoteslas, cyclic period of N=1 hour and for a range of resistivity: ρ=100 to 100, 000 ohm-m. Voltage is a relative measure and it is the difference of potential between two points measured in the direction of y (perpendicular to the direction of B). Ref. [13] has called attention to the importance of directional sensitivity.

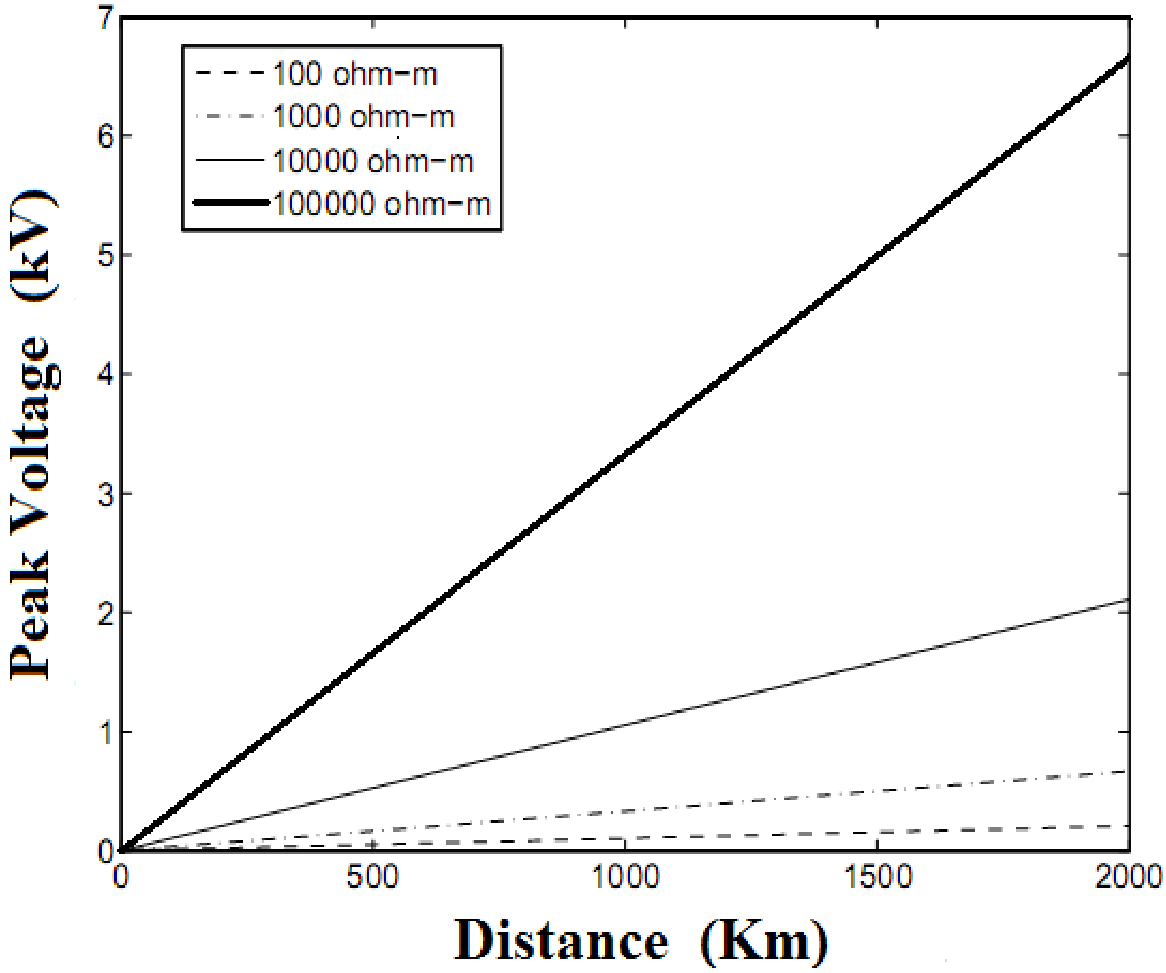

Figure 3.3 Φp, peak voltage, plotted as function of distance y. (=*400* nanoteslas, cyclic period $N=1$ hour).

3.5.5 Ground Current from Magnetic Diffusion

Fig. 3.4 displays J_{my} of (3.21) as a function of z for different time instants (ωt is measured as degrees of the $N=1$ hour period). The ground resistivity is $\rho=1000\ \Omega\text{-}m$.

In the magnetic diffusion process, $\boldsymbol{J_m}$ flows in a direction opposite to the penetration of the magnetic field (Lenz's Law) so that both $\boldsymbol{B_m}$ and $\boldsymbol{J_m}$ attenuate exponentially to zero at $y\rightarrow+\infty$. The attenuation is determined by $e^{-z/\delta}$ where δ is the skin depth whose formula, from [35], [36], and [39], is:

$$\delta = \sqrt{2\rho / \omega\mu_0} \qquad (3.27)$$

The skin depth for Fig. 3.4 ($N=1$ hour period, $\rho=1000$ Ω-m) is $\delta=0.96\times10^6 m$.

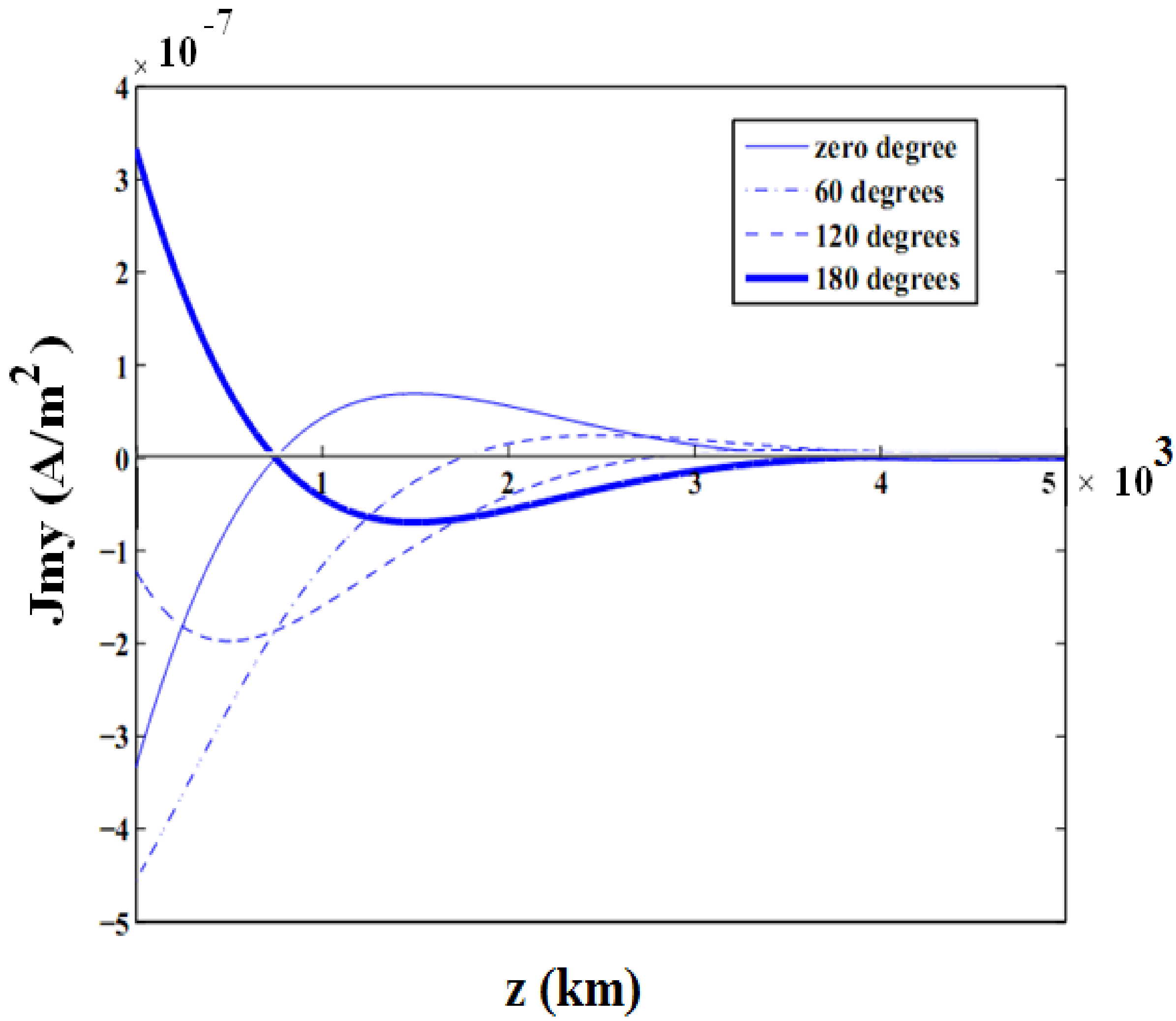

Figure 3.4 Magnetic diffusion current density *Jmy* plotted as the function of z for ωt measured in degrees of $N=1$ hour period. $\rho=1000$ Ω-m. Skin depth= 0.96×10^6 m

3.6 Comparison with the Plane – Wave Method

This section comprises of the agreement and validation of the method of solving the magnetic diffusion equation, used in research; with the plane wave method. Furthermore the assumptions and approximations used in this predictive tool are completely justified.

3.6.1 Agreement with the Plane-Wave Method

This section supports the independent validation of (3.25) in equation (3.2) of page 247 in [16]. This formula is reproduced here intact as:

$$\left|\frac{B_y}{E_x}\right| = \sqrt{12\sigma T} \tag{3.28}$$

In equation (3.28), B_y is given in nanotesla and T is the oscillatory period in minutes. Except for differences in Cartesian axes orientation, the choice of units and the fact that (3.25) is the inverse of (3.28), (3.25) of this section is the same as (3.28).

In order to highlight the agreement, Fig. 12 of page 249 of Campbell's paper [16] is re-plotted as the heavy line in Fig. 3.5. The light line is based on (3.25). As Campbell used a "very simple layered Earth conductivity model", discrepancy is expected. As [16] used $\sigma=0.007exp\ (0.007d)$ Siemens/m where d is depth in km, whereas the value of sigma being used is $\sigma=0.01008$ Siemens/m for estimated depth of $d=52.09$ km which gives a good fit.

The agreement is remarkable because the magnetic diffusion method does not model wave propagation. On the other hand, the results of [16] are based on the plane wave method, pioneered by Louis Cagniard [33]. The agreement with the phase plane method lends validity to the magnetic diffusion method.

Figure 3.5 below shows the agreement of the Magnetic Diffusion Method (the line graph) with the Plane-Wave Method (the Point Symbols summed as the Campbell curve with dark line graph) which is from Fig. 12 of [Campbell] where the value of σ=0.94 Siemens-m.

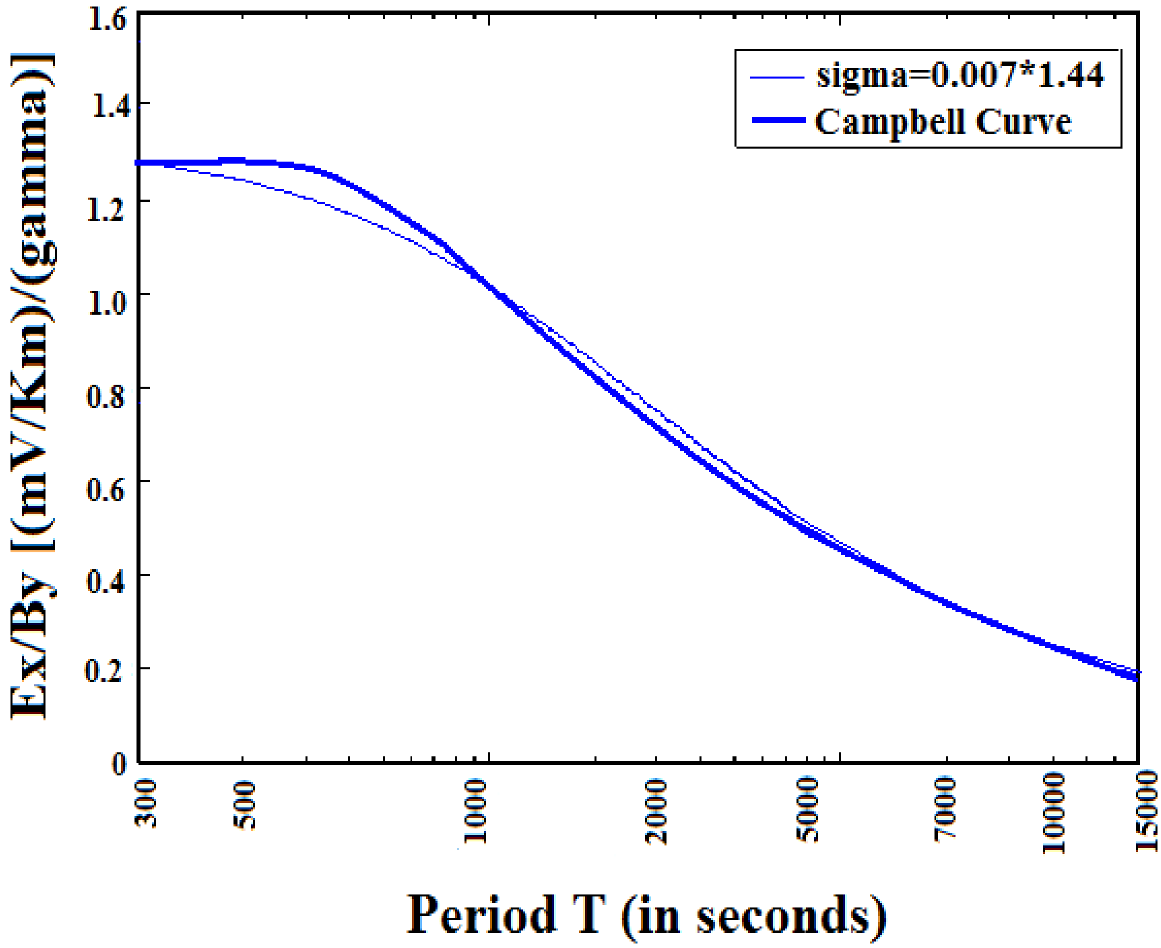

Figure 3.5 Agreement of the Magnetic Diffusion Method (line graph) with the Plane-Wave Method (Point Symbols) which is from Fig. 12 of [Campbell] σ=0.94 Siemens-m.

3.6.2 Validity of the Plane-Wave Method

In Section 3.2, it is being argued and explicitly stated that GIC with very low frequencies have quarter-wavelengths which justify the application of magneto-quasi-static approximations of Maxwell's equations. If wave propagation is to be included, the electrojet of Fig. 3.1 must be treated as an antenna. Antenna theory [40] classifies the fields surrounding the antenna into:-

(i) Reactive Near Field

(ii) Radiating Near Field or Fresnel Region and

(iii)Far Field or Fraunhofer Region. The criteria for the classifications are not precise. Generally, the region of Far Field is where $r \gg \lambda$ (wavelength). Another guideline for classifying the Far Field is

$$r \geq \frac{2D^2}{\lambda} \tag{3.29}$$

where D is the maximum linear dimension of the antenna.

The subject of Far Field is raised here because plane waves belong to the Far Field region. The ***E***- and ***H***- fields of plane waves (which belong to Far Field region) are orthogonal to each other and to the direction of propagation but they are in time phase.

Since the wavelengths for the very low frequencies of GIC are of the order of 10^6 km and the propagation distances are of the order of *100* km, is it valid to apply the plane-wave method to very low frequency GIC problems? The imprecision in the classification criteria can be clarified from experimental evidences.

The experimental evidences, in [27], [32], and [34] and [41] for example, show that Faraday's Law of Electromagnetic Induction plays a central role in a very low frequency GIC. From the time derivative in (3.4) which embodies Faraday's Law, the vectors ***E*** and ***H*** must have a 90 degrees phase shift between them. In antenna theory, the ***E***- and ***H***- fields in the Reactive near Field are out of time phase by 90 degrees. This fact reinforces the classification of very low frequency GIC as belonging to the Near Field zone. (When ground resistivity is included in the interaction, (3.24) predicts a phase shift of 45°.) As the ***E***- and ***H***- fields of plane waves are in time phase, it means that the plane wave method is an approximate method.

3.6.3 Time Series Prediction

In the time domain, the induced electric field is time shifted with respect to the magnetic field. Because the magnetic diffusion method models the phase shift of the Near Field region, researchers in Geophysics Laboratories who possess time-synchronized data on magnetic field density $B_{space}(t)$ and electric field $E_y(t)$ for $P \geq t \geq 0$, can apply the method to correlate the geoelectric stage of GIC. This consists of expanding $B_{space}(t)$ as a Fourier series of periodicity P, i.e.

$$B_{space}(t) = \sum_{k=1}^{k=K} \overline{B_{s,k}} e^{jk2\pi/P} \tag{3.30}$$

Where $\overline{B_{s,k}}$, $k=1, 2...K$ are complex Fourier series coefficients. The electric field is found by assuming that $E_y(t)$ is another Fourier series of the same form, i.e.

$$E_y(t) = \sum_{k=1}^{k=K} \overline{E_{y,k}} e^{jk2\pi/P} \tag{3.31}$$

Where $\overline{E_{y,k}}$, $k=1, 2...K$ are complex Fourier series coefficients. For each term of integer k whose frequency is $\omega=2\pi k/P$, following the same procedure of this chapter one has from (3.24)

$$\overline{E_{y,k}} = \frac{1+j}{\sqrt{2}} \sqrt{\frac{2\pi k/P}{\sigma\mu_0}} \overline{B_{s,k}} \tag{3.32}$$

Applying superposition, $E_y(t)$ is the sum of all the terms of $k=1, 2...K$ in (3.31), where $\overline{E_{y,k}}$ is obtained from (3.32).

3.6.4 Inaccuracies from Assumptions and Approximations

For as complicated a problem as GIC, simplifying assumptions and approximations are resorted to in order to make analysis tractable. Although the agreement between (3.25) and

(3.28) shows that both methods support each other in their claims of accuracy, both methods share one common underlying approximation. In the plane-wave method, it is in the flattening of the cylindrical wave-front to a planar wave-front. In the magnetic diffusion method, the approximation lies in changing $\boldsymbol{B}_{space}$ of (3.11) which is in cylindrical coordinates to $\boldsymbol{B}_{space}$ of (3.12) which is in Cartesian coordinates.

3.7 Application of Results in a Power Grid

This section presents the applications of the computed results to the Trans Canadian Grids and supports the key result obtained.

3.7.1 GIC Voltages

The key result of this research about geomagnetic storms and computing terrestrial voltages employing the Magnetic Diffusion equation method is the equation (3.25) as listed in this chapter. The magnetic storm is characterized by its magnetic flux density B_{space} (Tesla) and angular frequency ω (radian/s). The other information needed is the conductivity σ (Siemens per meter) of the terrain. The requisite information is the electric field (volt/m) E_m and this is obtained from (3.25). The direction of E_m is perpendicular to that of B_{space}.

If the distance between two grounded points m and n is L and θ is the angle between the direction vector of E_m with that of the straight line joining m and n, then according to (3.5) and[13], the voltage between them is:

$$\Phi_{m-n} = |\mathbf{E_m}| L \cos\theta \qquad (3.33)$$

As the direction of $\boldsymbol{B}_{space}$ varies from storm to storm, it is necessary to consider the range of all possible values of θ.

3.7.2 GIC in a Power Grid

Having obtained Φ_{m-n} from electromagnetic field analysis, power engineers need only to return to circuit theory where the power system network is represented by lumped parameter and R, L, C elements using the procedures outlined in [13] and [42] as an example. The sources of GIC are represented by ideal voltage sources similar to Φ_{m-n} of (3.5) or (3.33) at all grounded points of the network model. Every grounded point has its grounding resistance which must be included in the network. The magnitudes of GIC in the transmission lines are solved by applying Kirchhoff's Voltage and Current Laws to the lump parameter network model.

3.8 Conclusion

This chapter has presented the magnetic diffusion method of estimating terrestrial voltages from magnetic storms whose frequency are so low that the GIC's have been taken to be "dc". As the derived formulas (3.25) and (3.26) predict "ball park figures" of around 1 volt/km for the range of parameters generally encountered in magnetic storms, it can be used with confidence.

In addition, the formula (3.25) has been validated by the plane wave method [16]. Because the formula has been validated by an independent theoretical method it can be used with greater confidence.

The recent research at McGill University is humble contribution by the McGill power group towards the efforts made so far by various Canadian and North American power utilities to immunize the electric power industry from detrimental effects of geomagnetic storms.

The formulas will be useful to engineers in assessing if their projects of long distance transmission lines, railway lines, or pipe lines (located in regions of known ground resistivity), are at risk from magnetic storms.

Ongoing research on predictions by other researchers is found in [43]. Continuing work by the National Academy of Sciences Report on Severe Geomagnetic Storms and Power Grid Impacts is found in [44].

CHAPTER – 4

MITIGATION TECHNIQUES

As mentioned in Chapter 2, the geomagnetic disturbances have been affecting the power systems, communication systems, pipelines and railways systems in one way or another for past 150 years. This chapter presents a few tested methodologies which have been implemented by power utilities and organizations such as Hydro Quebec, power utilities of Minnesota and Manitoba, NASA, EPRI and NOAA to mitigate the effects of geomagnetic disturbances on the power industry. Break down of Canadian and North American power industries had a serious negative economic impact as their annual revenues are around $250 billion each.

The chapter is organized as follows: - Section 4.1 gives a general overview of the monitoring and data collection programs materialized with a purpose to gain a better understanding of geomagnetic disturbances. Section 4.2 presents the mitigation techniques developed and implemented by various Canadian and North American power utilities to mitigate the effects of geomagnetically induced currents on power system grids. Section 4.3 concludes by discussing the forecast improvements and future plans in developing the mitigation and monitoring techniques.

4.1 General Overview of Monitoring Programs used for better understanding of Solar Storms

After experiencing the power failures such as the one in North America in March 1989, power utilities are becoming more sensitive and alert to data collection and monitoring techniques related to geomagnetic disturbances. There have been improvements in the technologies for collecting and aggregating data from magnetometers and space satellites.

Real time data collection by NASA, NOAA and EPRI is making forecasts of GIC more reliable and is boosting the monitoring and mitigation strategies.

NASA has launched satellites to monitor the sun-earth activity and track changes which affect the magnetic field of the earth. In 1973 OSO-7 started recording the solar flares and solar wind along with Coronal Mass Ejection (CME's). Satellites like ACE and WIND were launched to study the coupling activities between the sun and the earth, and give details about the effects on the earth's magnetic field due to solar flares. The SOHO satellite, launched in 1995, was set to keep the track of solar activities [8]. TRACE (The Transition Region and Coronal Explorer) satellite was launched in 1998 to have the finest detail on the earth's magnetic field and to record changes due to solar activity. In February 2000, IMAGE (Imager for Magnetosphere to Auroral Global Exploration) was launched to track very minute space weather changes.

Through correlation of data from the GIC measurements, the K and A, and later G indices were formulated by NOAA to assess sun activity on a daily basis. The indices are considered to be among the most important achievements.

Information regarding space weather is now readily available on the internet. There is an enhanced interactive program which provides documented data and plots about the sun-earth activities received from the ACE and WIND satellites.

Electric power and other utilities [2] have access to numerical models from monitoring projects (SUNBURST, POWER CAST, ESP Model) which enable them to make assessments about the severity of the impending geomagnetic storms and take appropriate pre-emptive measures.

The SUNBURST project which began in 1991 involves participating substation authorities installing passive measuring devices along with transformer equipment and sending GIC current measurements to the SUNBURST headquarters in Pittsburgh. Because GIC are measured in hundreds of locations spread across North America and Europe, they provide continuous monitoring which is used as a warning indicator in case alarming data shows up in GIC measurements.[45]

The ESP model for estimating GIC in electric power systems is being used extensively. It is comprised of a voltage source between two grounded neutrals of wye connected transformers or autotransformers, located at opposite ends of a long transmission line. [3]

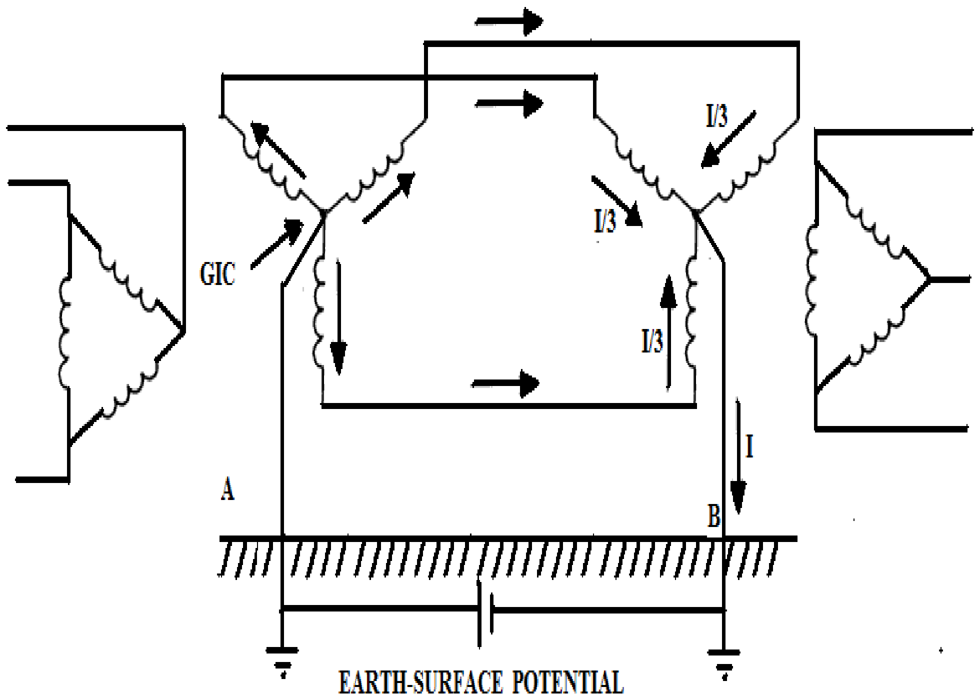

Figure 4.1 shows the ESP model used to estimate GIC between the grounded neutrals of wye connected transformers.

The ESP model (see fig. 4.1) estimates GIC, but factors like the earth conductivity, and other geological properties also affect the accuracy of ESP measurements.

“Power cast” – a predictive and forecasting method currently employed in Great Britain, developed by John Kappenmen; has the capability to forecast transformer or any other power equipment’s response in case of major or minor geomagnetic disturbances[46].

4.2 Mitigation Techniques implemented by various power utilities

There have always been some consistent and reliable guidelines for every power utility to transport electricity to the society. But in recent times few geomagnetic disturbances have brought the entire highly reliable and otherwise stable operation of power systems to a halt. After the recent solar storms and resulting power outages, power utilities are working on a number of mitigation and forecast techniques to avert such consequences in the future. Hence, several R&D projects are underway especially with the geological laboratories, EPRI, NASA, and Hydro-Quebec, Minnesota and Manitoba power units, the power systems units in Ontario and other regions of North America.

4.2.1 GIC Mitigation Techniques

Geomagnetically induced currents (GIC) are the prime cause of major and minor power outages from geomagnetic storms in the years 1989, 1993 and 2003. The Hydro-Quebec power system was the worst hit by geomagnetic disturbances which resulted in large economic losses as well as the power loss of more than 21,500 MW. Since then Canadian and North American power utilities have launched different GIC monitoring and data collection programs as discussed in section 4.1. Also various GIC blocking devices and GIC measuring techniques have been tested and implemented so far.

With the long term expertise in space weather, the earth’s geology and electrical power transmission network, power utilities have been able to understand GIC to an extent, and also the factors affecting it. The Electric power utilities and research groups have summarized a few important facts which need to be clear before working towards GIC mitigation techniques.[47]

i) Sunspot numbers are the basis of solar activity and define the maximum and minimum phases of solar activity. The intensity of solar activity is a further defining criterion for GIC

ii) The interplanetary, the magnetospheric and the ionospheric processes define the latitudinal variation of GIC. Hence the GIC study involves the latitude factor in determining the GIC susceptible areas.

iii) The Earth’s conductivity and igneous rock geology are two of the significant factors defining the GIC prone areas and concerned mitigation strategies

iv) Transformer equipment type and design affect the GIC occurrence in various types of transformers.

v) Power system orientation and direction of long transmission lines affect the GIC occurrence in many electrical power systems.

vi) Last but not the least, the time rate of change of the earth’s magnetic field is the most important factor concerning the accurate prediction of GIC in electrical power system.

Along with all the efforts by power utilities to understand GIC, various GIC blocking devices are being used to cope with the power failures and shutdowns due to GIC occurrence. The very basic mitigation technique employed is use of the linear and non-linear resistors in the transformer neutral. This helps in reducing GIC magnitude, while ensuring transient voltages to remain in acceptable limits.

The GIC hazards in the Hydro – Quebec power system were the best example to indicate severity level of the damage they can cause. Since then Hydro-Quebec has been working on various methods and strategies to fight with the detrimental effects of GIC. Hydro – Quebec has opted for series capacitor compensation to protect the long transmission lines and transformer equipments from damage. The series capacitors are installed in the 735 KV long transmission lines from the Churchill Falls and the La-Grande Complex [18]. Major action plans and strategies have been worked out and are still going on in the complex Hydro-Quebec power grid to deal with harsh space weather effects and the dynamic and unpredictable nature of geomagnetic storms. The new defense techniques focus on the mechanisms which could help avoid any major contingencies as far as the complexity and diversity of the power network is concerned.

The effects of geomagnetic storms are now cascading beyond provincial borders. Even the power utilities in Ontario, Manitoba and Minnesota have come across the detrimental effects in the form of relay tripping, circuit breaker tripping and separation of one unit from others due to one fault or another. The Power utilities at Manitoba and Minnesota have taken a new approach and are working on evaluating a microprocessor based relay, to avoid undesirable tripping of capacitor banks during such geomagnetic disturbances. NBGD (Neutral Blocking and Grounding Devices) is also among the mitigation techniques being worked on by Manitoba power utility, to save transformer equipment from any further damage. However the installation cost of the neutral blocking and grounding devices limits its use on equipments at high risk.

4.2.2 Operations and Planning Guidelines

Besides all these mitigation techniques and defence plans, there need to be well defined operational strategies and operation and planning guidelines for every power utility to prepare them for geomagnetic storms to come.

This section of the thesis focuses on various operational and planning guidelines any power system authorities usually should follow before, after and even during the geomagnetic storms, to have a safe and reliable operation.[47].

Many such guidelines have been proposed by various power utilities, to overcome the destructive nature of geomagnetic disturbances. A few of these guidelines are:

i) Ensure that the system voltage is balanced; perform timely reviews of the voltages across long transmission lines and HVDC links, and areas operating under full load conditions.

ii) Possibly reduce the number of switching operations on the system which helps reducing harmonics and avoid instability.

iii) There should be better supervisory control over the relay settings. Adjustment of negative sequence current relay settings, harmonic imbalance, and false trips should be reviewed. Timely adjustments and actions could prevent discrepancies.

iv) Reduce loading on transmission lines, HVDC lines to free more VAR's

v) Install GIC blocking devices, Monitoring devices in transformer neutrals to have better understanding of GIC and geomagnetic activity.

vi) If possible, appropriate transformer types and designs which are less susceptible to GIC, should be implemented in highly prone areas.

vii) Risk management, such as removing equipments under high risk, load shedding, reducing key transformer loadings are considered to be key and timely decisions in cases of severe geomagnetic disturbances.

viii) Last, but not the least, electrical power systems must be designed to cope with large voltage swings and appropriate inspection and human intervention is highly needed and appreciated.

4.3 Forecast Improvements and Future Work

"Experience is a hard teacher, because she gives the test first and lesson afterwards", something like this defines the nature of geomagnetic storms. The history of geomagnetic storms discussed in Chapter 2, along with its effects on power systems and other man-made structures has helped the power utilities to learn much more about this space phenomenon after their occurrence in all these years. With continuous hard work, integrated research and complete analysis of geomagnetic activities in past years, power utilities and concerned organizations have achieved a great deal of success in understanding the nature of geomagnetic disturbances, the earth sun activities, and they have developed good monitoring and mitigation techniques and forecasting of the space weather.

Forecasting the space weather is really important to win over the uncertainty factor related to geomagnetic disturbances, which has always made the geomagnetic storms a difficult problem to deal with. However the organizations like NASA, NOAA, EPRI and many more are working on forecasting projects to get rid of this uncertainty factor. Reliable advance warnings, lessening of false alarms and data collection of geomagnetic activity and the sun-earth activity on an hourly basis, are few steps to increase our ability to understand the impacts of geomagnetic storms.

Recently even the Air Force wing of the U.S. armed forces sensed the effects of geomagnetic disturbances on aircrafts, radar systems and other important communication systems that are must to continue to work safely and securely. Hence the armed forces have stepped forward and sponsored two major projects in space weather forecasting[48].

High Frequency Active Auroral Research Program (HAARP) located in Gakona, Alaska is one of the major projects launched to gain a better understanding of the space weather. This program makes use of radio waves to keep the track of changes occurring in the earth's ionosphere, the major solar activities occurring in space.

The other big project is the launch of a satellite named “Demonstration and Science Experiment” (DSX) Satellite whose purpose is to record the effects of solar flares and high energy electrons on the space satellites. This is just another example of the technological advances being implemented for a better understanding of space weather.

With the advancement in real data monitoring from using satellites like ACE and SOHO, R & D organizations and power utilities have been motivated to go ahead with the hybrid techniques in mitigation and forecasting by making use of artificial intelligence, fuzzy logic and expert systems [49]. Although very few of these expert systems are really in use, as far as we know, the Integrated Terminal Weather System (ITWS) is just the one such hybrid system being implemented and tested.

A lot has been done and many major projects are underway to provide better forecasting methods and mitigation techniques to help us understand these dynamic and frequently changing geomagnetic storms. In last 150 years , the power industry has had advances in terms of predicting geomagnetic disturbances, understanding GIC better, developing new and advanced mitigation techniques and finally to accomplish the basic mission of transmitting electric energy to their customers, by maintaining safety, security and reliability standards.

CHAPTER – 5

CONCLUSION

This thesis summarizes the causes, effects and mitigation techniques being adopted by the electrical utilities to avert the embarrassment of blackouts. The vulnerability of electrical power systems to geomagnetic storms is bound to increase in the coming 10-20 years because of the trends of transmitting large blocks of electrical power over longer and longer distances, such as the Trans-Canadian Grid.

No doubt, the blackout of March 1989 in Quebec did not cascade beyond the province borders. But the impacts of the geomagnetic storms on the Trans-Canadian Grids and electrical utilities connected to it would cause more extensive damage.

In order to prepare against such disruptions, it is first necessary to estimate the magnitude of the terrestrial voltages caused by magnetic storms. The research of this thesis has presented the magnetic diffusion method which, for the first time, (as far as the author's knowledge) yields the ball park figure of "1 volt per km" for magnetic field, periodicity and ground resistance. Considering the large spread of decimal places of the parameters involved (for example $\mu_0=4\pi x10^{-7}$, $B_{m-s}=400x10^{-9}$ teslas, $\rho=10^4$ *ohm-m*, $\omega=1.74x10^{-3}$ *rad/s*), the ability to estimate the terrestrial voltage close to observations reported is a good claim to the adequacy of the magnetic diffusion solving method.

The Trans-Canadian Grid is sensitive to magnetic storms because: (i) It is an east-west connection; (ii) It is in the high latitudes (55^o to 70^o, see hatched area in Fig 5.1); (iii) Much of the territory is in igneous regions (see shaded area in Fig. 5.1).

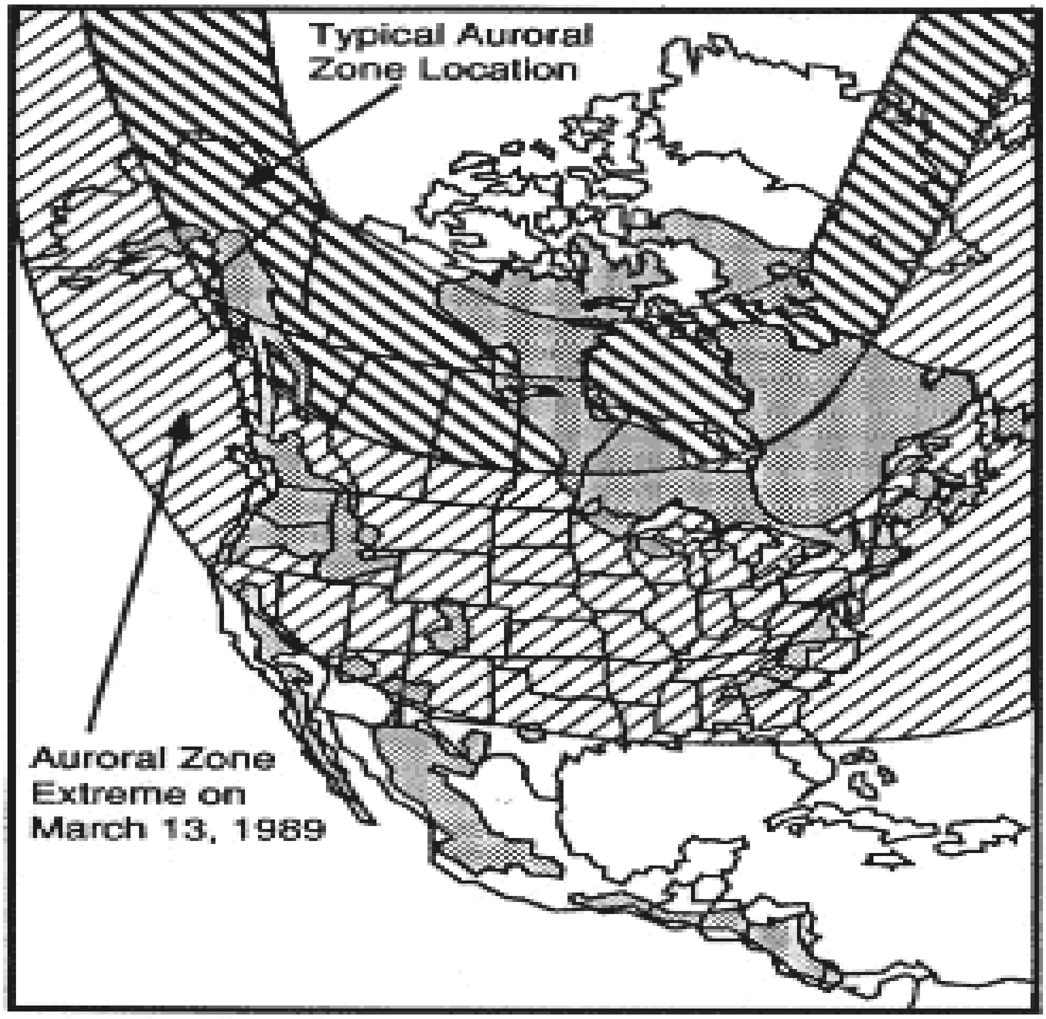

Figure 5.1 Diagram showing areas of igneous rocks overlapping with auroral zone.

FUTURE WORK

Various scientific institutes such as, NOAA, NASA, Meta-Tech Canada, Minnesota Power, Manitoba Power, Hydro Quebec, EPRI 'S SUNBURST program are pursuing research towards understanding geomagnetic storms and mitigating their effects on engineering systems. From the contribution of this thesis, more work can follow in extending the magnetic field diffusion method to finite element methods. Research in the effect of non-homogeneous ground resistance is relevant.

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