Properties of Geomagnetic Disturbances and How they Might Affect Power Systems: An Analysis of Past Geomagnetic Disturbances

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***Abstract*—Geomagnetic disturbances have been linked to power system damages in the past and its probable they'll continue to cause disturbances in the future. While geomagnetic disturbances have the potential to cause power system complications, it isn't clear what attributes of geomagnetic disturbances (GMDs) are most impactful to power systems. This paper identifies some of the pertinent characteristics of GMDs and their relation to power systems. Analysis of past storms has made evident some common identifiers of what composes a severe, impactful GMD. Identifying characteristics of storms that can potentially cause damage to power systems will be useful for creating synthetic GMD waveforms, which can be tested using grid models in simulators such as PowerWorld or Seimens PSSE. Thorough and exhaustive testing of grids using synthetic GMDs will allow power engineers to ensure their grid's resilience to large scale GMD occurrences.**

I. INTRODUCTION

The Carrington Event of 1859 is widely considered to be the most powerful geomagnetic storm in modern history[1]. The geomagnetic storm (GMD) that struck Earth on September 1st, 1859, bears the name of the amateur astronomer that first noticed the phenomenon, Richard Carrington. On the morning of September 1st, Carrington noticed an eruption of massive white flame from the Sun's surface. A few hours later, Earth's magnetosphere was rocked by one of the most powerful GMDs in modern history. This massive geomagnetic storm allowed for aurora lights, normally only visible at the Artic and Antarctic Circles, to be seen in places like Cuba, the Bahamas, and Hawaii in the tropics near the equator.

As noted in [1], perhaps the most interesting aspect of the Carrington Event is the effect it had on the telegraph communications systems of the 19th century. The storm severely disrupted or completely cutoff telegraph communication all over the world for its duration. There were reports of operators being electrically shocked by their telegraph machines and some instances of machines catching ablaze. Some operators also noticed that their telegraph machines could operate without being connected to their DC voltaic batteries. The cause of this strange behavior in telegraph systems was the geomagnetically induced currents (GICs) caused by the Carrington Event. The Carrington Event disrupted Earth's magnetosphere so much that it created large electrical fields that induced substantial geomagnetically induced currents (GICs) onto telegraph lines, the longest conductors of the day.

It is widely speculated that a GMD with the same magnitude as the Carrington Event would cause unprecedented damage to modern day power systems due to the high GICs that would be created. When predicting the effect the Carrington Event would have on Japanese Power Grids, [2] estimated that per-phase GIC flows would reach 89 ± 30 Amps at a minimum. GICs values of that magnitude can severely damage or destroy transformers and generators if unprotected and lead to catastrophic grid failure.

To prepare for such an event, electric grids need to be tested against large GMD events. By running GIC studies in power system simulation software like PowerWorld or PSSE, in-depth analysis can be done by simulating occurrences of various GMDs on real or synthetic grids. The difficulty is that there isn't a sufficient set of real GMD data to test grids against. The past 35 years has only seen two GMDs powerful enough to cause major power outages (Section III).

The purpose of this paper is to determine the principal characteristics of GMDs and identify which parts of these storms can cause problems for power grids. These characteristics can be used in the creation of various synthetic GMDs, hopefully allowing for the simulation of a storm with a magnitude matching the Carrington Event. Dr. Gannon and her team have synthesized a waveform that captures the potential behavior of the Carrington event, and we hope that our work will provide additional analysis of other storms for scaling or modifying her work [3].

TABLE I. NOMENCLATURE

GMD	Geomagnetic disturbance
GIC	Geomagnetically induced current
CME	Coronal mass ejection
X - Field	The X component of Earth's magnetic field pointing towards true north
Horizontal Field	The horizontal component of Earth's magnetic field that points towards magnetic north.
Substorm	An intense segment of a GMD
SSC	Sudden storm commencement

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II. CREATION OF GMDS

A. Solar Instability

GMDs are the consequences of violent space weather events that originate from the Sun. The Sun's magnetic field goes through an 11-year cycle, referred to as the solar cycle. At the height of this cycle, the solar maximum, the Sun's magnetic north and magnetic south poles switch places, resulting in a period of high instability. During this time, sunspots begin to appear on the Sun's surface. These sunspots can create solar flares, large eruptions of gas and fire spewing from the surface of the Sun. When the Sun is in this anarchic state during its solar maximum, occasionally one of its solar flares will shoot off a large ball of plasma and energy known as a coronal mass ejection, or CME. Along with an enormous amount of momentum, these CMEs contain their own powerful magnetic field. These "cannonballs" of plasma and magnetic field can travel in any direction and sometimes head straight for Earth.

B. CMEs Link to GMDs

Whenever a CME hits Earth it can severely disrupt the planet's magnetic field for a number of days. CMEs collide with Earth's magnetosphere causing it to weaken due to the opposite alignment of the CME's magnetic field to Earth's. Earth's magnetic field lines point north, and the magnetic field lines of a large GMD typically point southward [4]. Since their magnetic fields are oppositely oriented, the magnetic field of the CME will cause the magnetic field of Earth's north component (horizontal component) to decrease in strength. Due to this sudden decrease in the magnetic field's horizontal component and the momentum of the CME, a geomagnetic storm, or GMD, is produced.

C. GICs and the Horizontal Magnetic Field

Earth's magnetic field can be described by several different components. Some of those include the X component that points true (geographic) north, the H component that points towards magnetic north, the Y component that points true east, and the Z component that points radially outward from the Earth's surface. The horizontal and X components are very similar, their only difference is that X points towards geographic north, what would be 90 ° N latitude and where Earth spins on its axis, and the horizontal component points to the actual magnetic pole, which is in Northern Canada a few hundred miles from the true north pole. Figure 1 shows the magnetic field lines of Earth and the relative locations of the magnetic and geographic North and South Pole.

When discussing the effect GMDs have on systems, typically only the horizontal (or X) component of the magnetic field is mentioned. This is because changes in the horizontal or X component of the magnetic field are the main force driving GIC flows [4]. Faraday's law of induction tells us that a changing magnetic field will create an electric field whose magnitude is proportional to the magnetic field's rate of change. These generated electric fields are what drive GIC flows and are almost completely dependent on the horizontal magnetic field's temporary changes. While the horizontal component is the best metric to use in GMD analysis, the use of the X component is sufficient and is typically used in GMD analysis due to data limitations. As a result, for the rest of the paper we will primarily reference the X or horizontal component of the magnetic field since they are the most directly tied to GIC flows.

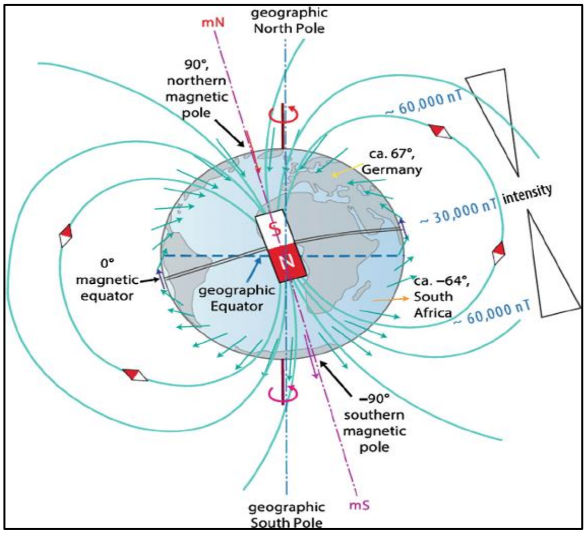

Fig. 1. Model of Earth's Magnetic Field, [5]

III. CLASSIFICATION AND HISTORY OF GMD EVENTS

A. Classifications of Storms by dst index

Before discussing some of the more technical characteristics of GMDs, it is important to understand how GMDs are categorized. Currently, the most common method for ranking GMDs is similar to the process that is used to rank hurricanes (Cat 1 to 5 based on windspeed). GMDs are ranked from G1 to G5 based on the severity of the disruptions they create. G1's and G2's are minor to moderate storms with little noticeable effects. G3s are major storms that can damage satellites and even cause some noticeable effects on power lines. G4s are severe storms that can destroy some satellites and cause serious issues to power systems. Storms of G4 magnitude have caused blackouts such as the Quebec Blackout of 1989 and the Sweden Blackout of 2003. Storms of magnitude G5 are extremely rare and are associated with the most intense storms like the one that caused the Carrington Event of 1859.

An important distinction between the two categories is that hurricanes are ranked solely on their wind speeds while GMDs are ranked based on the Kp index, which is derived algorithmically from multiple factors from stations all over the world. Some components of the Kp index are solar wind speed and westward magnetic ring current (a band electrons in space that circle Earth). While the Kp scale provides a good measure for the general strength of a storm, it isn't always best suited for determining its impact on power systems. Figure 2 shows the average deviation and standard deviation of the X-field magnetic component for several storms, G1 through G4, for magnetometers in Barrow, Alaska, and the Stennis Space Center in Louisiana. While standard and average deviation both generally increase as the G rating increases, there are a few exceptions. G1A and G3B are two such cases where the volatility of a storm doesn't necessarily increase with the G rating.

Another component of the Kp number, the Dst index, gives us a more quantitative metric of how a GMD effects Earth's magnetic field. The Disturbance storm time (Dst) Index is a measure of the amount of change in the Earth's horizontal magnetic field around the equator that is produced by the WDC for Geomagnetism in Kyoto, Japan [6]. The severity of a global storm can be measured by the amount of dip indicated in the Dst index. Figure 3 shows an example of how storms are classified using the Dst index.

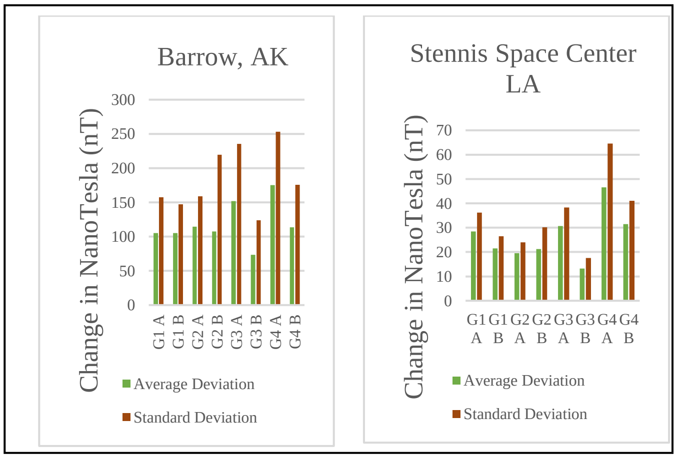

Fig. 2. Magnetic Deviation by G Rating

A substantial and sudden dip in the Dst index, like the ones seen at day 29 and 31 in Figure 3, would signal the most extreme parts of a GMD. The unit of measurement in the Y-axis are nanoteslas and the X-axis is time in days. A Dst reading of approximately -100nT indicates a mild storm while a Dst of less that -300nT indicates a more extreme storm. GICs are created by electric fields induced by changes in Earth's magnetic field and the Dst index better quantifies magnetic field variations. Therefore, we believe the Dst index is a very useful metric to use when examining GMDs and their propensity to create GIC flows.

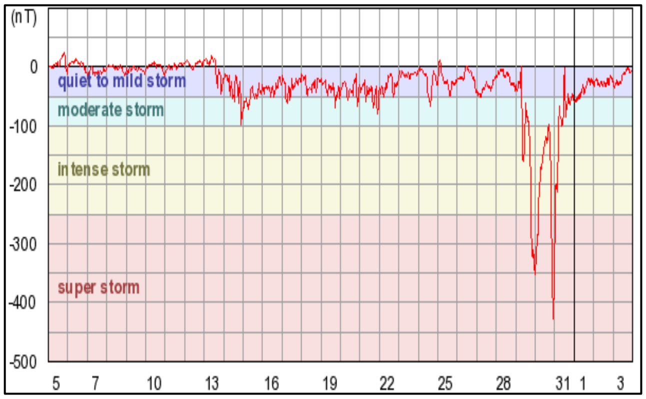

Fig. 3. Dst Index Example, [6]

A. *Historical analysis of GMD-induced blackouts*

In the past 35 years there have been two preeminent cases of blackouts caused by GMDs. The first is the 1989 Hydro-Quebec Blackout.

The Quebec Blackout of 1989 is the greatest modern example of a GMD induced blackout. Based on information provided by [7], we were able to thoroughly analyze this massive GMD and the blackout it caused. On March 13th, 1989, large solar flares were observed on the sun and a large CME slammed into Earth shortly after. Less than two minutes after the CME hit Earth, the entire Hydro-Quebec power grid completely failed. For 9 hours following, millions of people in Quebec found themselves without heating, lighting, or cellular communication.

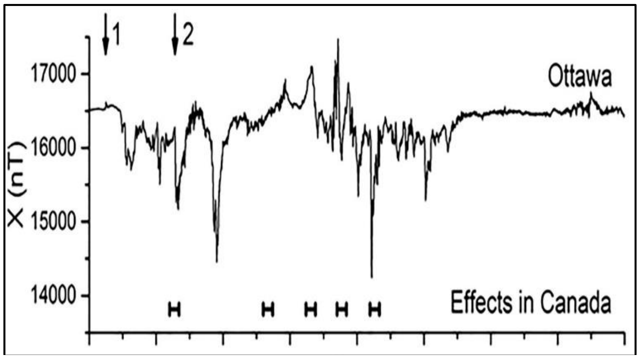

Fig 4. Ottawa, Canada Magnetometer Data March 1989 [7]

The Dst index measured for this storm decreased as low as -589nT, greater than any storm measured in the past century. But what is interesting about the blackout caused by the storm is that it didn't occur at the most extreme moment in the GMD. At the time of the blackout, 7:45 UT, the Dst index was at -138nT. Arrow 2 on Figure 4 corresponds to the magnetic dip observed at the time of the blackout. Still a considerable Dst value but quite smaller than the Dst values produced later. More severe swings in the magnetosphere occurred later in the storm but did not induce more blackouts in Canada. Power system complications farther south in the United States and United Kingdom were associated with the more extreme Dst values that occurred later in the storm. However, it is still unclear why Canada didn't experience worse power system damage in the most extreme parts of the storm. We speculate this is because the storm had already pushed the auroral oval, the magnetic belt around the poles that causes the polar lights, south from Quebec at the more extreme times of the storms which kept the GMD from effecting Canada as severely for the continued duration of the storm.

The second blackout causing GMD is the 2003 Swedish Halloween Storm [8]. The Halloween geomagnetic storm of 2003 was an especially "scary" GMD caused by a CME that disrupted the Earth's magnetic field from October 27th to November 3rd of 2003. This storm is the most recent example of a blackout caused by a GMD. The Halloween Storm of 2003 was a surprise to many because it happened during a period of expected solar stability. This geomagnetic storm was large enough to knock out the power grid of Southern Sweden for several hours on October 30th of 2003. Along with power knocked out in Sweden, many NASA and European Space Agency satellites were damaged or destroyed.

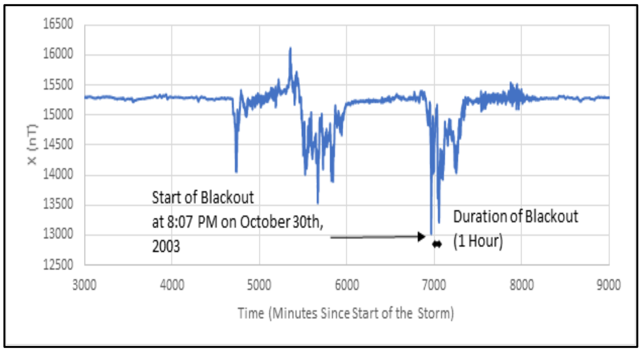

Fig. 5. Lovon, Sweden Magnetometer Data October 2003

Magnetometer Data from Lovon, Sweden during the Halloween Storm of 2003 confirms the observations present in the Quebec Blackout data from earlier. As can be seen in Figure 5, the magnetic field around Lovon goes through a dramatic dip, which caused the Swedish power grid to blackout for more than an hour. The Dst index was measured to be down to -383nT at 8:07 UT on October 30th, the time of the blackout. According to [9], GICs as high as 42A were recorded in Scotland. It would be reasonable to speculate that GICs of equal or greater magnitude occurred in Sweden which led to the brief blackout.

While the relationship between changes in the Dst index and power system disruptions is not perfectly correlated, the data indicates that a strong relationship is present. In both the 2003 Halloween Storm and the 1989 Hydro-Quebec Storm, the Dst index reached incredibly low values, which corresponded with substantial, sudden dips in the magnetic field at the blackout's respective locations. It is impossible to predict future weather with 100% accuracy, space weather is no exception. However, we would strongly expect the next GMD capable of causing power system failures to have a considerable Dst index that will correspond with substantial dips in magnetic field strength in many locations based on our analysis of past storms.

IV. GMD VARIANCE BY LOCATION

Geomagnetic disturbance are global events and can be felt anywhere on Earth. However, these events are not felt to the same degree uniformly across the Globe. Differences in longitude and latitude have substantial effects on the magnetic field of a certain location and play a large role in determining the extent which a GMD effects are experienced. In our research, we compared the effects of several GMDs on many different US locations using magnetometer data provided by USGS magnetometers [10] with data gathered from Intermagnet, [11]. Table 2 shows a list of the locations used in our analysis and their abbreviations.

A. Regular Magnetic Field and Latitude

TABLE II. ABBREVIATIONS OF LOCATIONS

Abbreviation	**Location**
HON	Honolulu, Hawaii
SJG	San Juan, Puerto Rico
BSL	Stennis Space Center, Mississippi
TUC	Tucson, Arizona
FRD	Fredericksburg, Virginia
FRN	Fresno, California
BOU	Boulder, Colorado
NEW	Newport, Washington
BRW	Barrow, Alaska
DED	Deadhorse, Alaska
CMO	College, Alaska
DEL	Del Rio, Texas

We noticed in our analysis that the regular X magnetic field component, the magnetic field strength observed in any typical day without a GMD occurrence, varied from location to location. More precisely, we found that the X magnetic field component strength was mostly dependent on latitude. As can be seen in Figure 6, the horizontal magnetic field at a particular location tends to decline the farther away from the equator you get in a quadratic trend.

This trend holds quite well for North America as can be seen in Figure 6. Locations close to the equator like San Juan, Puerto Rico (SJG) and Honolulu, Hawaii (HON) have a strong X magnetic field component while places in Alaska like Burrow (BRW) and Deadhorse (DED) have a substantially weaker X component. This is because Earth's horizontal magnetic field, and its X component, tends to decrease as one moves toward the poles. This makes sense when we look back at the magnetic field diagram shown in Figure 1. While it is true that the magnitude of Earth's magnetic field is strongest at the poles, it is almost entirely composed of its vertical component, Z-field, and the horizontal and X component becomes negligible.

However, it should be noted that there seems to be hardly any discernible correlation between latitude and X-field magnetic strength when looking at many South American locations. We suspect this is due to the South Atlantic Anomaly, which causes Earth's magnetosphere to be weaker at a point over the South Atlantic Ocean and is inconsistent with the ideal dipole that typically characterizes Earth's magnetic field.

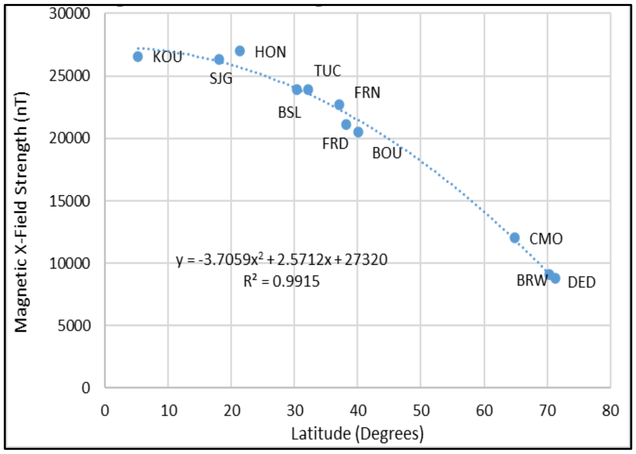

Fig. 6. Regular Magnetic X- Field vs Latitude

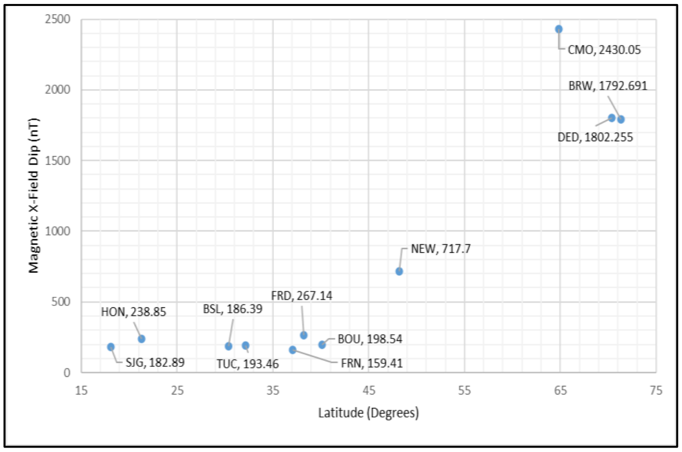

Fig. 7. Maximum Deviation

B. *Latitude and GMD Storm Severity*

Due to the locational variations in the horizontal magnetic field component, GMDs effects differ with latitude. Generally, as the horizontal magnetic field gets weaker the farther north we went, the more intense the GMD tended to be experienced.

When examining the difference between the minimum value measured and the average of the magnetic X-field component for GMDs, or the "dip" in the magnetic field, we observed that the dip increased the farther north we went. Figure 7 shows the difference between the lowest measured magnetic field value and the average, or "dip", for a powerful storm that occurred in September of 2017 for several different North American Locations. For locations with a latitude less than 45 º, the amount of dip seemed to fairly insignificant, but for locations farther north, like Newport and the Alaska locations, the dip became quite substantial. Along with the maximum dip in the magnetic field, we also noticed that the volatility of the storm increased dramatically the farther north we went. Figure 8 shows the absolute value of the rate of change in the magnetic field X component for several different locations. The rate of change, or derivative, of the X-field magnetic component gives a good idea of how sporadic the magnetic field is during a GMD. We used the absolute value of the rate of change to make it easier to visualize how the instability of the storm changes throughout its duration. Since large, sudden changes in the magnetic field are what create electric fields, high volatility can be a cause for concern for power systems. For Del Rio, Texas (DLR), the greatest rate of change in the magnetic field was about 25 nanoteslas per minute.

As we move farther north to Boulder, Colorado (BOU), the volatility of the storm increases by a sizeable amount. The maximum rate of change recorded from the Boulder magnetometer was about twice that of the Del Rio location at about 49.6 nanoteslas per minute. While the volatility of these two locations might seem large, they are completely eclipsed by the rate of change recorded for College, Alaska (CMO) during the storm. The maximum rate of change recorded for the Alaska location was 740.1 nanoteslas per minute, more than 14 times than what was recorded at Boulder.

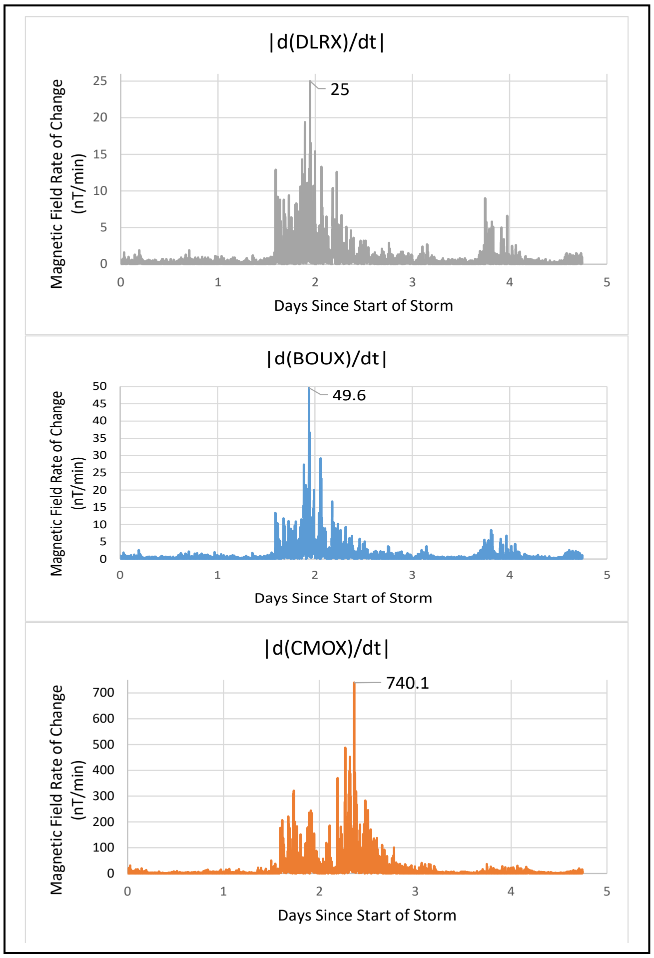

Fig. 8. Volatility of Storms at Different Locations

The general trends shown in Figure 7 and Figure 8 were present in other GMDs that we analyzed. When re-evaluating the Hydro-Quebec Blackout of 1989 and the Swedish Blackout of 2003, the relationships between location and GMDs are apparent. Both blackout causing GMDs had a large difference between the average and minimum magnetic x- field, or dip, and both were highly volatile events. These GMD characteristics are what we'd expect from northern locations. Since the horizontal magnetic field is much smaller in northern places like Quebec and Sweden than it is in places like Texas, northern locations are much more susceptible to dramatic dips and erratic behavior in their magnetic field. These dramatic dips and fast swings in the magnetic field, like the ones seen in 1989 and 2003 can lead to power system disturbances and even blackouts for these northern locations.

V. OTHER CHARACTERISTICS OF GMDS

A. GMD Substorms

While geomagnetic disturbances typically last several days, their intensity is not uniform across their duration. Instead, GMDs can often be divided into several substorms. Substorms typically last from a few hours to a day and are where the most severe stages of a GMD occur. When looking at the 2003 Halloween Storm in Figure 5, you can clearly see several substorms throughout the GMD. There is a substorm that accompanies the arrival of the GMD and the beginning of a later substorm is linked to the blackout in Sweden. Substorms are also visible in the Hydro-Quebec storm in Figure 4, with the start of a severe substorm happening at the same time as the Hydro-Quebec voltage collapse. In our research, we found that the duration, intensity, and number of substorms seems to be unique to each GMD. However, the presence of substorms was found in all the GMDs we analyzed.

B. Sudden Storm Commencement

The sudden storm commencement or SSC is a small, quick increase in the magnetic field that often indicates the arrival of a GMD. In Figure 4, arrow 1 indicates an SSC that indicated the arrival of the GMD that caused the Hydro-Quebec blackout. SSCs are not present in all GMDs and not all SSCs indicate the arrival of a storm. However, SSCs can serve as an early warning that a possible GMD is imminent.

VI. CONCLUSIONS AND RECCOMENDATIONS

In brief, GMDs are the result of solar instability that can cause Earth's magnetic field to be disturbed for several days. Severe disturbances can create GIC flows that have the potential to damage power systems and cause blackouts. Characteristics of a bad GMD are high volatility and sudden dips in the horizontal component or X component of Earth's magnetic field. The Dst index is a good metric to use when ranking GMDs and their effects on power systems because it quantitatively describes the strength of Earth's magnetic field at any given point in time. GMDs tend to be worse the further north you travel, both GMD induced blackouts discussed happened in places with high latitudes. We believe this is because the horizontal component of the magnetic field gets smaller the farther north you go, allowing GMDs to have more influence on the magnetic activity in those regions.

With the GMD characteristics described in this paper, we believe it would be possible to generate a completely synthetic GMD to test against power grids. However, we also realize that creating a GMD from scratch would be time consuming and mentally exhausting. As a first order approximation for simulating the effects of a GMD on a synthetic power grid in a place like Texas, we would recommend choosing a large GMD from a northern location, like Alaska or Canada, and scaling the regular or baseline horizontal magnetic field component down to what it would be in the desired location. Following the trend line in Figure 6 to adjust the regular X–field strength, a massive GMD from Alaska could be moved to Texas in a few simple steps. While we know this approach is not necessarily true to life, it is a quick and straightforward way to create a powerful GMD in a location where GMDs of great intensity have never been recorded. This would allow Texas grid ISOs, to test the durability of Texas's massive grid against a substantial geomagnetic storm. We are far from completely understanding the nature of GMDs and further work should be done to examine these powerful phenomena.

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