Overview of Solar and Geomagnetic Storm Conditions and Impacts
October 24 – November 5, 2003

Quick Summary – Big Solar Flares, Not-So-Big Geomagnetic Storms

- Solar Flare and CME Activity predominantly from Active Region 486 reached intensity levels not before recorded from a single active region. On a historic basis, the recent activity has far exceeded intensity levels of the activity from the Active Region that spawned the March 1989 Superstorm. However that region did spawn more flare events in total.
- Two of the Superflares from this region were well positioned and it is estimated that most of the ejecta from these events would have been Earth-directed.
- Five Solar Wind Cloud Events (or CME's) arrived at Earth, but only two produced major Geomagnetic Storms (October 29 & October 30-31). The storm event on October 29, associated with the X +17 flare, produced the largest geomagnetic storm of this solar cycle. However, these storms were far less severe than a Superstorm status and resulting GICs that did occur could perhaps be a factor of 3 to 10 times larger in most regions than those observed. Regions of the US and Europe observed GICs between 50 and 100 amps or larger in a few isolated cases. It is also suspected that large GIC's were observed globally during the large shock around time 6 UT October 29, due to the arrival of the first large CME. The October 29 storm also may have caused extended periods of moderate intensity GIC, which could lead to large transformer overheating and perhaps premature loss of life.
- The NOAA K Indices (and newer G Indices derived from the K) again were inadequate for describing the storm severity for GIC Threats. These archaic indices, developed decades ago, all reached saturation levels of K9 and G5, even though these storms were far less severe than the March 1989 Superstorm. This classification is somewhat like a hurricane classification that would rate a hurricane with 75 mph wind speeds as being as severe as a hurricane with 150 mph wind speeds. This raises concerns that these K and G storm classifications tend to miss-lead about larger threats that infrastructures may face, and unfortunately builds complacency for those that need to be better prepared for larger threats that will at some point-in-time occur.
- Even with this perspective on overall geomagnetic storm intensity, some power system disruptions did occur. An outage in southern Sweden and transformer heating at a nearby nuclear plant were attributed to the events late on October 30. Anomalous voltage and power flow swings were reported in the US, but no major disruptions occurred. Other data on possible impacts is still trickling in.

Luck is perhaps the only explanation that can adequately describe how a Geomagnetic Superstorm was avoided during this period of extreme solar activity. In this Solar Cycle (Cycle 23), Earth is continuing on an incredible lucky streak in avoiding the occurrence of extremely large geomagnetic storms. Over the past ~70 years of consistent geomagnetic storm observations, superstorms typically happen at a rate of about once about every 5 years. It has not been over 14 years since the March 13-14, 1989 Superstorm. Luck, or fortunate circumstances prevailed as the X +17 Superflare of October 28, which directed the bulk of the CME plasma towards Earth, had much of the intense storm causing potential neutralized by northward oriented interplanetary magnetic fields when encountering the Earth's magnetic field. Luck also prevailed in that there was just enough timing (a matter of a few hours) between CME arrivals on October 29 and again on October 30 to moderate the overall storm intensity. Had these two CME's arrived with a few hours less separation, the storm momentum built up by the first CME passage (on Oct. 29) could have been used by the second CME passage (on Oct. 30) to produce an even larger storm, a process that Metatech suspects caused the March 13-14, 1989 storm to become a superstorm. Power grids also had some luck, in that the storms and activity occurred during a Fall minimum load season, so power systems did not have the combined stress of heavy summer or winter season peak loads combined with intense stresses due to a geomagnetic storm.

Luck in timing also played a part for the largest flare event observed (estimated to be greater than X +30) from the Active Region 486, which occurred on November 4 while the active region was on the far western edge of the solar disk. At this position, the bulk of the CME plasma was directed harmlessly out into interplanetary space. While good luck is always welcome, it is not something that can be counted upon for long-term risk management from future storm events. To prevent complacency, a sense of perspective is necessary. Indeed as this summary will describe, the scale of impacts for future storm events could be as much as a factor of 10 times larger than those resulting from any of these recent storm events.

Overview of Solar Activity Summary – October 24 – November 4, 2003

While several large active regions were present over this ~2 week period of time, Active Region 486 was the dominant feature and produced nearly all the major solar flares and CME events during the transit of this region across the solar disk. While the total number of large flares from this region was high, the most impressive aspect was the record number of extremely large flares and CME events from this region. The region produced three X+ Class flares including the largest ever observed. The largest was estimated by Metatech at a size of ~ X+30, which occurred on November 4 while at the western limb of the Sun, thereby sparing the Earth from most of the CME passage. Fortunately, this historically high level of solar activity did not result in extremely large geomagnetic storms at Earth, though that will not be a predictable outcome for any future episodes of extreme solar activity. This favorable result only occurred because of the polarity of the plasma cloud when it encountered the Earth, typically a 50/50 proposition. Hence, the odds for sustaining this present good fortune are not a likely outcome. The observation of these large flares certainly supports the possibility of historically large geomagnetic storms at some point-in-time in the future. For example, the X+ 30 flare of November 4, 2003 is more than 6 times larger than the X 4.5 flare that started the March 13-14, 1989 Superstorm.

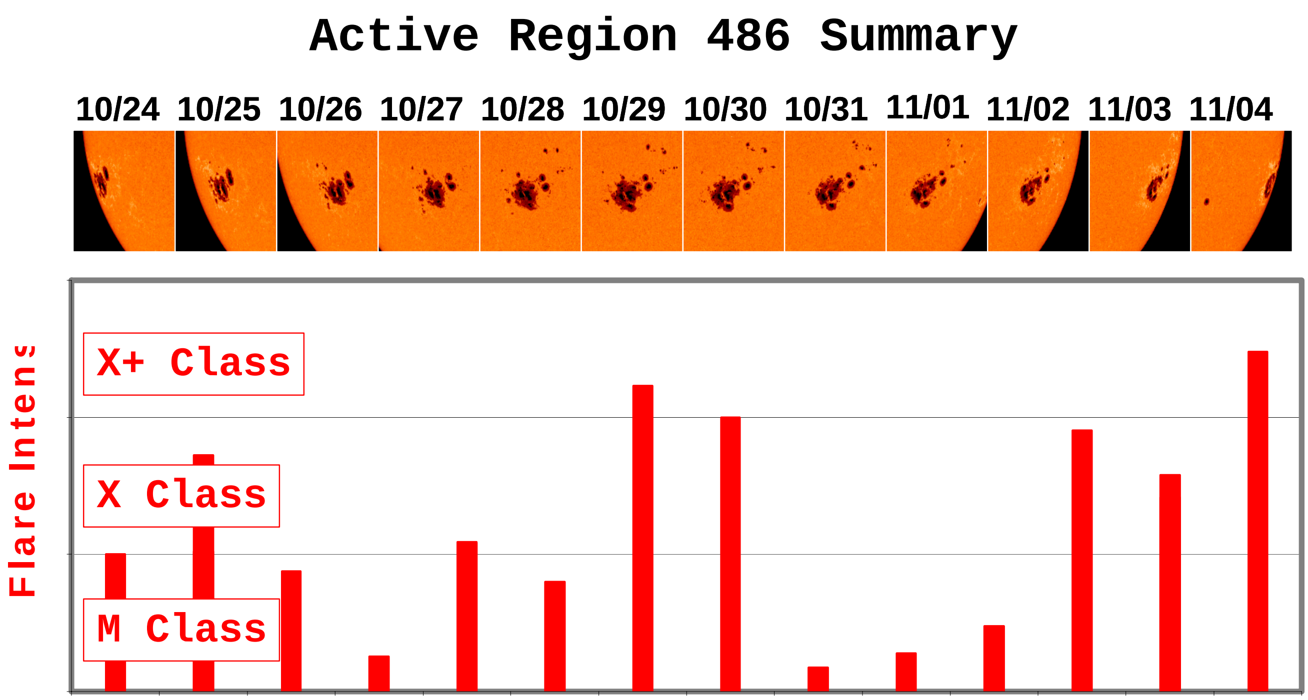

Figure 1 – Active Region 486 is summarized above from October 24 – November 4, 2003 during its transit of the solar disk. The top panel shows the spot size and location each day during the transit, while the bottom panel summarizes the major solar flare activity from this region during the same period of time. During the 12 days above, this region produced a total of 14 Flares of M-Class or larger in size, with three of these being X+ Class and the largest of November 4 going off-scale of X-Ray sensors. The X +17 Flare of October 28, when the region was near the center of the solar disk, resulted in the largest intensity geomagnetic storm of this Solar Cycle on October 29. Ironically the region exhibited the highest levels of activity near the west limb of the Sun Nov 4, when it produced an X +30 Super Flare.

These large flares likely produced significant radio frequency interference and disruptions to communication systems, HF, and wireless telephony. However, the nature of the geomagnetic storms that developed were large but not all that impressive in relative terms. Only a few minor changes in circumstances of how these events unfolded could easily have caused much larger resulting geomagnetic storm impacts at the Earth.

Overview of Geomagnetic Storm of October 29 and October 30-31, 2003

As we had advised with our Geomagnetic Storm Advisories on October 28 and October 30, geomagnetic storm conditions developed that varied from major to moderate in intensity. Two separate CME passages occurred, the first generated by a large X +17 flare on October 28 and the second CME passage due to a subsequent large X +11 flare on October 29, 2003.

Solar wind conditions produced very large energy transfers into the Earth's magnetosphere for brief periods of time that created optimal conditions for auroral precipitation and visible displays at relatively low-latitudes. The characteristics of the solar wind conditions were extremely intense on October 29 for several hours, but the polarity of the magnetic field was in the wrong direction to couple with the Earth's magnetosphere during much of this time period, which effectively diminished the resulting geomagnetic storm intensity. Despite these limitations, our measures of this storm rank it at the top of all CME or Solar Wind Cloud Events observed in this solar cycle. The resulting geomagnetic storm was also significantly smaller than the March 13-14, 1989 superstorm and much smaller than that of historically large storms which can be several times larger than even the March 1989 superstorm.

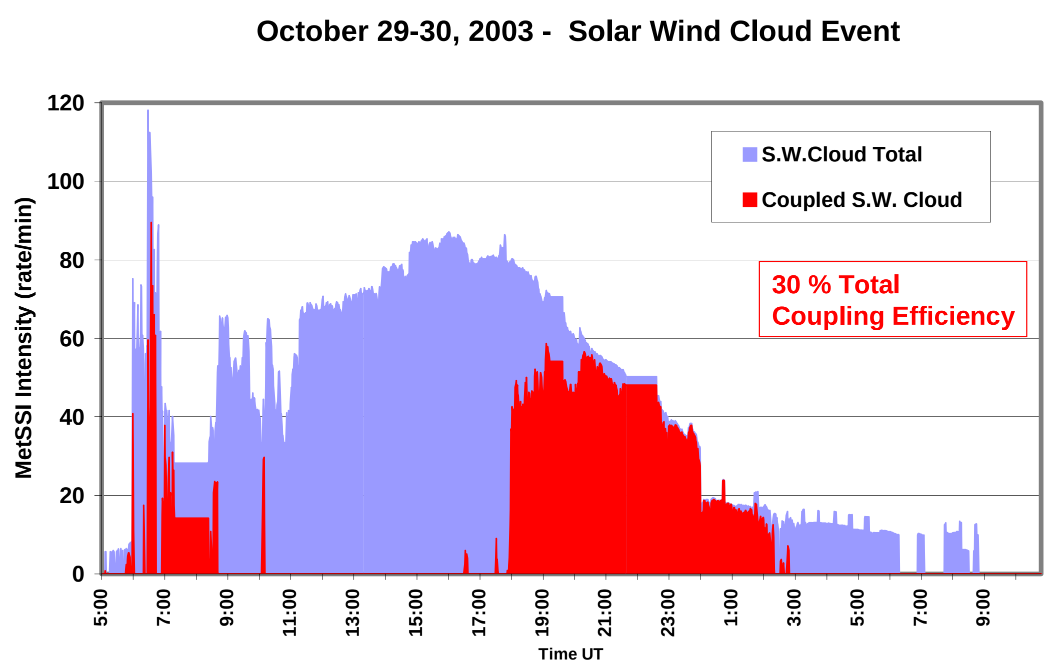

Figure 2 – MetSSI Solar Wind Cloud Event chart for solar wind and geomagnetic storm conditions starting 6:00UT, October 29 through 9:00UT October 30, 2003. The total storm causing potential of the CME passage is shown as blue, while the fraction of the cloud that coupled with the Earth's magnetosphere to produce geomagnetic storm activity is shown in red. The large CME Shock arrival and SSC began at ~ 6:00 UT at L1 and due to extremely high speed, a large shock from the interplanetary pressure pulse arrived at Earth at 6:10UT. Favorable coupling (red portion of plotted regions above) only existed for a brief period of time resulting in low overall transfer of plasma from solar wind to the magnetosphere (~30% coupling efficiency) and limiting the overall storm size. Still with this limited coupling, the resulting storm was slightly larger in intensity than the July 15, 2000 storm, which was previously the largest CME-caused storm of this solar cycle.

No simple means of classifying geomagnetic storm intensity can fully describe all the complex regional and time specific geomagnetic field disturbance intensities. Therefore a summary will be provided of global conditions and then supplemented with specifics on regional activities levels and times of important storm intensifications for production of GIC in power grids. Our evaluation of global solar wind potential and coupling or input from the solar wind into the Earth's magnetosphere is provided in Figure 2 for the first large Solar Wind Cloud Event on October 29 and in Figure 3 for the smaller cloud event arrival on October 30. As indicated by comparison of Figures 2 and 3, the first cloud passage on October 29 was much larger in total potential than the second passage on October 30. In general, the red regions on both plots show time periods in which locally intense geomagnetic field disturbances would have been observed due to geomagnetic storm activity caused by the passage. .

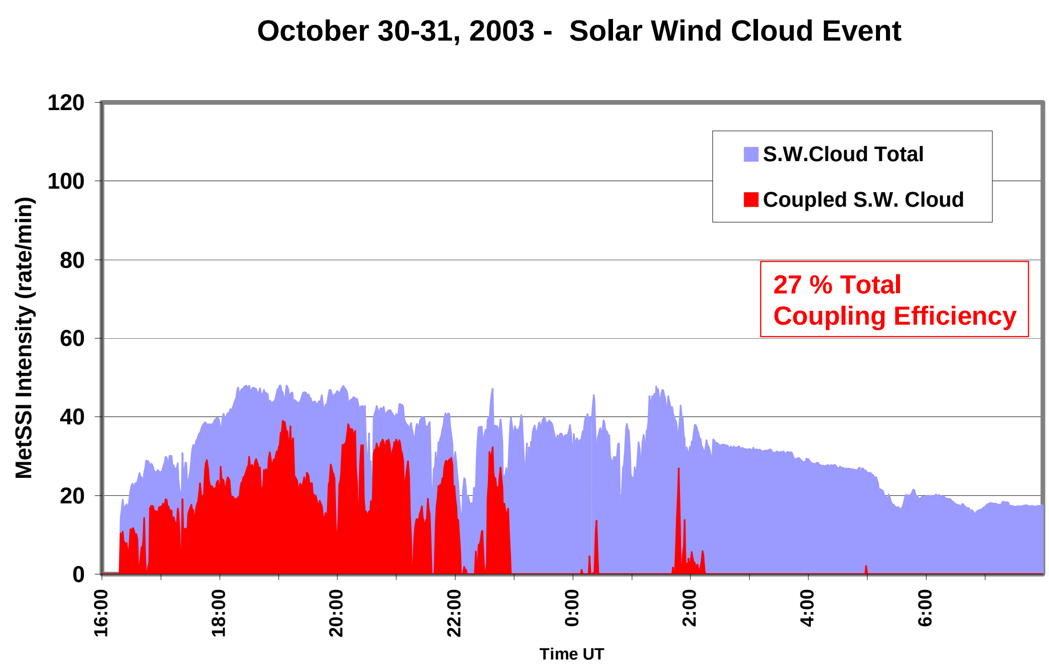

Figure 3 – MetSSI Solar Wind Cloud Event chart for solar wind and geomagnetic storm conditions starting 16:20UT, October 30through 8:00UT October 31, 2003. The total storm causing potential of the CME passage is shown as blue, while the fraction of the cloud that coupled with the Earth's magnetosphere to produce geomagnetic storm activity is shown in red. This CME was smaller in total size than the October 29 event and also had low overall coupling efficiency (~27%) similar to the October 29 CME event. Favorable coupling (red portion of plotted regions above) only existed for a brief period of time resulting in low overall transfer of plasma from solar wind to the magnetosphere (~30% coupling efficiency) and limiting the overall storm size.

A comparison is provided in Figure 4 of these two events along with other large events observed in Solar Cycle 23 (current solar cycle). As indicated by this comparison (or red bars), the October 29-30 storm slightly surpassed the previously largest storm of this solar cycle of July 15, 2000. In contrast, a comparison of blue bars (or total cloud potential) indicates that the October 29-30 CME passage was ~70% larger than the July 15, 2000 CME passage. Had a higher coupling efficiency occurred (for example levels over 60% have been observed for other CME's, rather than 30% for this passage), a very much larger geomagnetic storm would have occurred. The October 30-31 storm was also one of the largest of this solar cycle. Some power system problems were reported in the Pacific NW regions of the US during the brief storm activity of October 30-31, the most intense disturbance occurred in that region at time 20:05 UT, October 30 continuing through 2:30UT on October 31. Power system problems were also reported in southern Sweden coincident with this same event. These reports included the short time outage to ~50,000 customers in the city of Malmo. The two small cloud passages of October 24, 2003 and November 3, 2003 are also shown in this comparison, both were small events with little coupling.

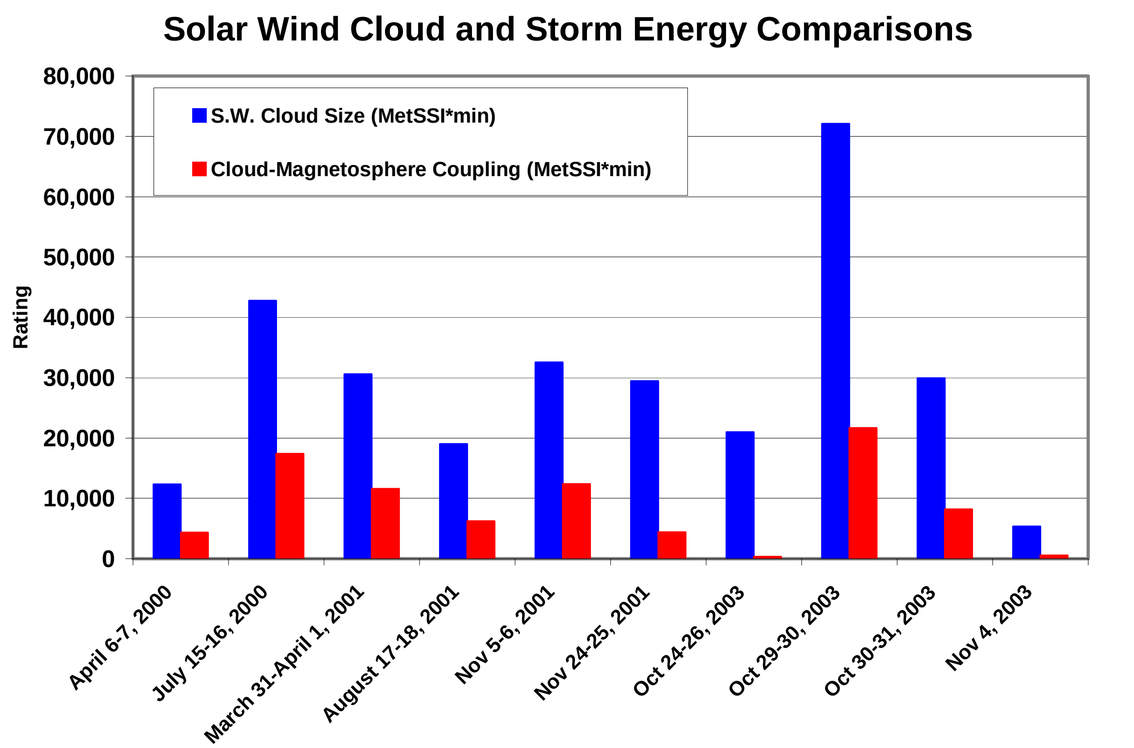

Figure 4 – Comparing total MetSSI cloud and geo-coupled energy content provides further information on relative storm intensities. The recent October 29-30, 2003 geomagnetic storm slightly surpasses the July 15-16, 2000 storm as the largest storm of Solar Cycle 23. The storm of October 30-31, 2003 is the fourth largest of this solar cycle. As suggested by the size of the blue bars, the October 30 storm could have been substantially larger (as much as a factor of 3) had a higher coupling efficiency prevailed during the passage.

Metatech's method of ranking Solar Wind Cloud Events agrees very well with the Space Weather community indice to measure total geomagnetic storm intensity, the familiar Dst Index. For example, the Dst index rated the geomagnetic storm activity on October 30 as reaching a peak of -347. In comparison, the July 15-16, 2000 storm reached a peak of only -301, approximately the same ranking as shown by the red bars in Figure 4. However, our method provides an indication of the potential available in the cloud passage that was not utilized (the blue bars), indicating the plausible "what if" scenarios under less favorable orientations of the solar wind fields. These "what if's" include larger storms such as the March 1989 superstorm which reached a Dst index peak of -589 (~70% larger than the October 30, 2003 storm) or estimated Dst of ~-1700 for historically large storms such as that in 1859, a level more than 3 times larger than the March 1989 superstorm. To further supplement the global perspectives provided in Figures 2-4, a brief overview of various regional and time-specific disturbance events for the geomagnetic storms on October 29 and October 30-31 is also provided.

Region and Time Specific Review of Storm Activity

As described by the red regions in Figures 2 and 3, the global geomagnetic storm conditions exhibited several important phases that would have the possibility for impacts on power system operations. The times and regional intensities of these impacts can be summarized as follows:

Storm Sudden Commencement (SSC) – October 29 from times ~6:12 – 7:00 UT

At ~ 6:00 UT, the solar wind monitoring satellite detected the arrival of a large high-speed solar wind shock front. This large pressure pulse produced a wide spread, but short-duration geomagnetic field disturbance which was observed starting at approximately 6:12 UT around the world. A brief period of storm intensification immediately followed causing large GIC's to be observed in some regions until at least ~7 UT. One of the regions of highest-intensity would have been centered over the Pacific.

Even though North America and Europe where located quite distant from the highest impact regions, sizable shocks would have resulted in these regions, which various monitors confirmed as producing large but brief GIC's.

Storm Intensifications – October 29

In Western Europe, the most intense levels of geomagnetic field disturbance occurred around 7 UT and again around 14-16 UT and from 20UT into the early hours of October 31. The peak intensity of disturbances ranged from only ~300 nT/min over the Baltic regions down to levels of ~160 nT/min across mid-latitude regions of the European continent (i.e. France-Germany for instance). These levels are nearly a factor of 10 below the ~2000 nT/min disturbance levels observed over Northern Europe in March 1989 and the ~2700 nT/min levels observed in a July 1982 geomagnetic storm.

Over North America, the most intense periods of activity also occurred around 6 UT, and 14-16 UT and into the early hours of October 31. There was also a period of intense activity observed around 9 UT.

Storm Intensifications – October 30

In many European and North American locations, the regional intensity of geomagnetic field disturbances were at times more intense than those observed on October 29, even though the Oct. 29 cloud event was much larger. This paradox is due to the gain in momentum caused by the arrival of the second large cloud on October 30, while the Earth's magnetosphere had considerable energy storage from the earlier cloud passage starting Oct. 29 and was still in a mode of slowly dissipating that stored energy. Had this second cloud or CME passage started a few hours earlier, an even larger resulting geomagnetic storm is likely to have occurred, a process that is suspected as the combination that may have produced the March 13-14, 1989 superstorm.

The regional intensities in Western Europe ranged from 600 to 700 nT/min in the Baltic region and northern Germany, with these peaks generally occurring between times 20:00 to 22:00 UT. It was this impulsive event that appears to have triggered the blackout in southern Sweden and associated transformer heating problems at a nearby nuclear plant.

Many North American locations also experienced disturbance intensity levels during the 19:00-23:00 UT time period that exceeded those observed on October 29. There were several reports of GIC's approaching peaks of 100 amps down through mid-Atlantic regions of the US coincident with these observed disturbance conditions. Again, because of limited solar wind coupling, the length of the storm was very short, lasting only a few hours in most locations. This period of activity may have been the source of some reported minor problems on the transmission network in the Pacific NW portions of the US.

Long Duration/Low Level Disturbances – October 29. 2003

Because of the extremely high speed of the solar wind, a considerable amount of buffeting occurred to the Earth's magnetosphere (a process called Kelvin-Helmholtz shearing, which is similar to how ocean waves can be kicked up by high surface winds). This causes sustained pulsations of the geomagnetic field. For most CME passages, these are normally small disturbances but became large enough due to the extreme nature of the event on October 29 to cause sustained GIC currents at many locations around the world. This disturbance can occur even without a southward orientation in the solar wind magnetic field which produces a favorable coupling to the magnetosphere. This mode is the likely explanation for some of the geomagnetic field disturbance intensity peaks that were observed starting around 14:00UT, when the CME passage reached peak intensity, though not coupling with the magnetosphere at that time. For power grids, this would have meant that very long duration GIC's would have persisted over the entire period of the October 29 CME passage. Figure 5 provides an example of observed GIC over the course of the day and would have been typical of what would have been observed in many other locations. The very long duration and sustained intensity of the GIC flow (over nearly 20 hours) would raise concerns for transformer internal heating and loss-of-life of winding insulation due to the sustained core saturation of

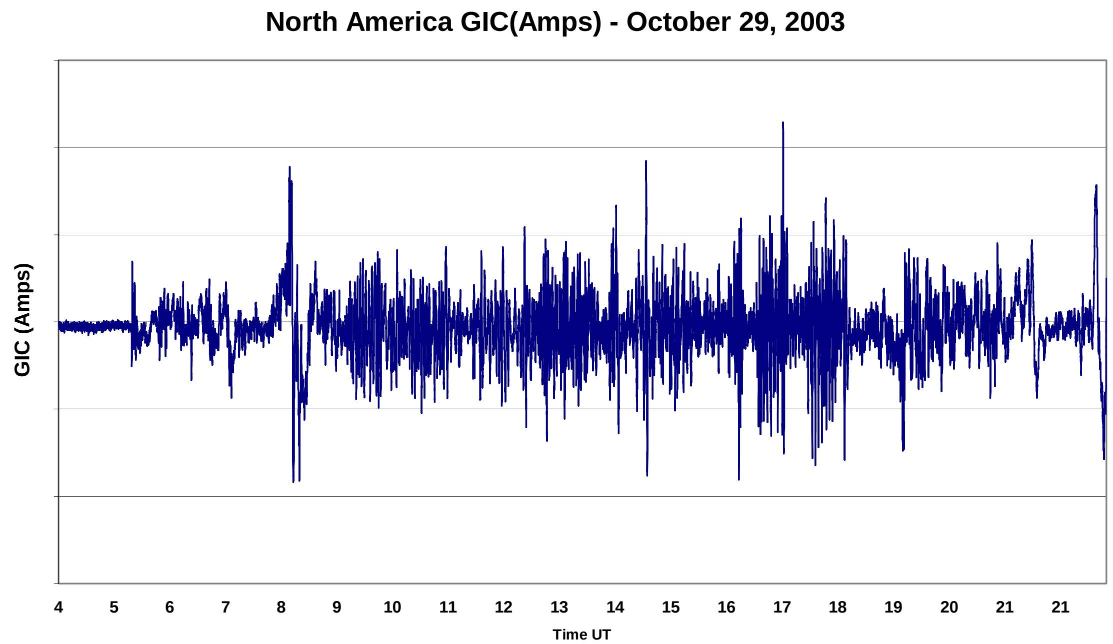

Figure 5 – Observed Transformer GIC at a North American location on October 29, 2003. The long duration and sustained intensity of the GIC would have the potential to cause transformer internal heating and loss of life of winding insulation.

exposed transformers. As a result, it may prove to be a root-cause explanation for transformer damage or future subsequent transformer failures.

An Overview of Power System Operational Response – October29, 2003 and Large Storm Scenarios

The timing and location specifics are very important in determining the impacts that storms may have upon critical infrastructures like power grids. K Index alerts provided by NOAA are based upon 3-hour time blocks and are planetary in coverage. Rather than define the physical location of complex Space Weather disturbances, K indices average and therefore badly blur the important location and temporal characteristics of this rapid and dynamic phenomena. Space Weather should and has been provided by Metatech similar to the way that ordinary weather is provided via satellite imagery or radar display. It would be unacceptable to the operator of any power grid to substitute high-quality terrestrial weather information with vague, planetary, two character, 3 hour indices to cover the diversity of rain, snow, wind, thunderstorm, temperature, or lightning activity that can impact operations of these infrastructures. Metatech has now implemented the same level of quality for space weather and geomagnetic storm forecasting services that have long been available in terrestrial weather.

To illustrate further, a brief case study can be provided showing the important differences between the storm of October 29 and the geomagnetic superstorm of March 13-14, 19889, all of these storms have received K9 or highest NOAA designation. However, they also have had far different local intensifications and impacts on critical infrastructures. To illustrate these differences, Metatech has developed improved geomagnetic storm climatology methods for regional assessments of storm intensities, by the development of the RGIC (Regional GIC Index). For this example, the US Mid-Atlantic Region RGIC will be compared for the recent October 29, 2003 storm event with the March 13-14, 1989 storm event. Figure 6 provides a map showing this region. While, Metatech models have the capability to calculate the GIC flows at each minute through the entire power grid and in each of the EHV network transformers, the RGIC provides a simple way of making comparisons between storms and possible impacts of those storm events at each minute and for a specific region. Figure 7 provides the RGIC observed for each minute in the US Mid-Atlantic for the October 29, 2003 storm. The RGIC Intensity scale is provided on the left hand axis (a scale from 0 to 400 is used for comparison purposes), while the intensity variation over time is plotted horizontally. While it is not possible using this alone to estimate GIC flows in any specific transformer from the RGIC, it is possible to generally estimate GIC levels and impacts on systems. As the RGIC reaches higher levels, the relative levels of GIC and impacts in the system proportionately increase. Also shown in Figure 7 are the noted times when the PJM-ISO commenced and ended System Alerts due to the storm.

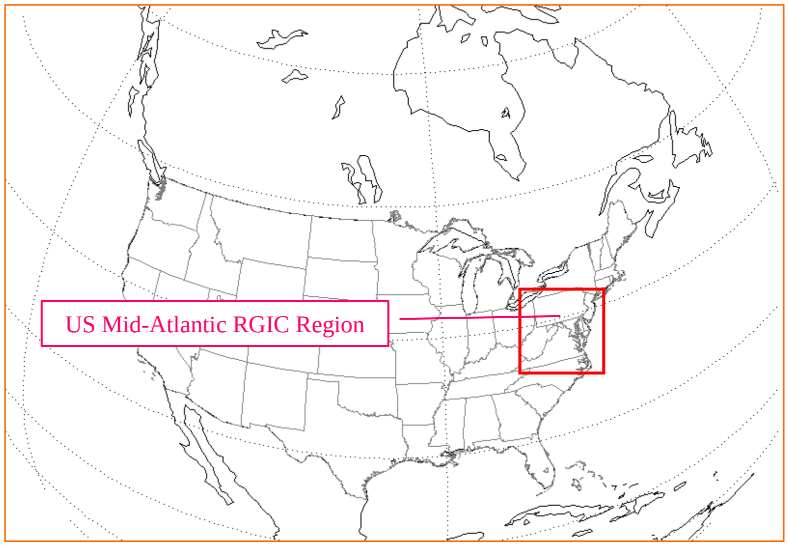

Figure 6 – Map of US Mid-Atlantic Region for Regional GIC Index (RGIC) that will be discussed for several geomagnetic storms.

As indicated by the decisions of the PJM-ISO, they were consistently late in making decisions to start their Alert Procedures twice this day and only went into alert conditions after each of the two peak intensity events of the day occured. As a result, it is evident that the start and end times for the Alert conditions issued by PJM-ISO did little to meaningfully improve network reliability.

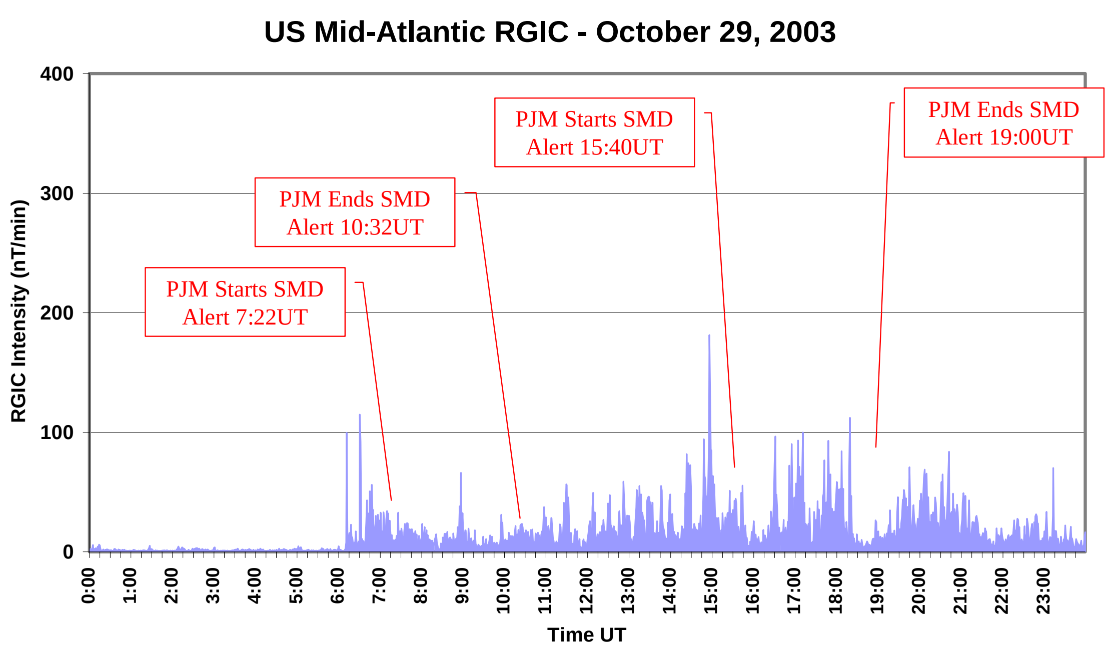

Figure 7 – RGIC for US Mid-Atlantic Region for October 29, 2003 Geomagnetic Storm. Also shown are time periods when PJM started and ended storm (SMD) emergency procedures. .

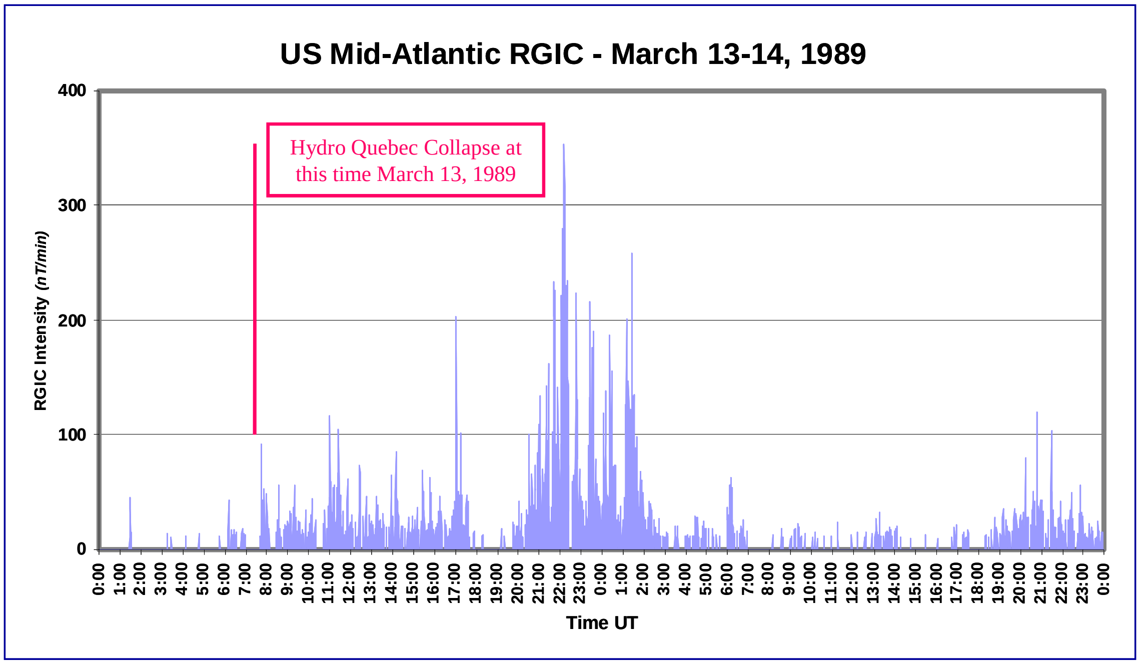

Figure 8 – RGIC for US Mid-Atlantic for March 13-14, 1989 Superstorm. Significant power system impacts were observed across this region over the course of the storm. RGIC intensity levels are generally 3 to 4 times larger for this storm compared to recent storms of October 29, 2003 storm. Also the duration of the storm is more than twice as long as the October 29, 2003 storm.

In contrast, Figure 8 provides a plot for the same region of the storm intensity conditions associated with the March 13-14, 1989 superstorm. This storm produced intensities across the US that generally ranged from 300 to 600 nT/min. A very large number (~200) of noteworthy power system problems were reported across North America and in this region over the course of the storm. As shown, the RGIC for this storm is generally 3 to 4 times larger than for the October 29, 2003 storm, with proportionately higher levels of GIC and power system impacts as well. One of the more significant events caused by this storm was the collapse of the Hydro Quebec network located north of the US Mid-Atlantic Region at time 7:44UT. In addition to the intensity, the duration of the storm is noteworthy as well. Using contemporary operational restrictions, many hours of network alert and conservation operation would have been necessary for this storm.

Of considerable concern is that much larger intensity disturbances can occur in these same regions and operational practices such as those exhibited for the recent October 29 event would not be implemented in time to counter the impacts brought on by a sudden 2000 nT/min or larger disturbance across the region. These are relatively rare events, but have been observed world wide on a approximate 1 in 10 year frequency, though they have not occurred over North America since August of 1972. There is also evidence that disturbance intensities approaching ~5000 nT/min are possible and have occurred in prior storms at these latitudes. This increase in storm intensity causes a nearly proportional increase in resulting stress to power grid operations. As cited in recent Congressional testimony, a number of studies have been done to investigate the potential impact to the US Electric Grid infrastructure for such an extreme disturbance scenario. These storms also have a footprint that can simultaneously threaten large geographic regions. Figure 9 shows one of many possible scenarios for how a large storm could unfold. As illustrated, a large region of power system collapse is projected for severe geomagnetic disturbance scenarios. Depending on the morphology of the geomagnetic disturbance, it would be conceivable that a power blackout could readily impact areas and populations larger than those of the recent August 14, 2003 blackout. As this analysis suggests, large geomagnetic storms may well surpass more familiar natural hazard phenomena in the capacity to threaten the integrity of high voltage power grids.

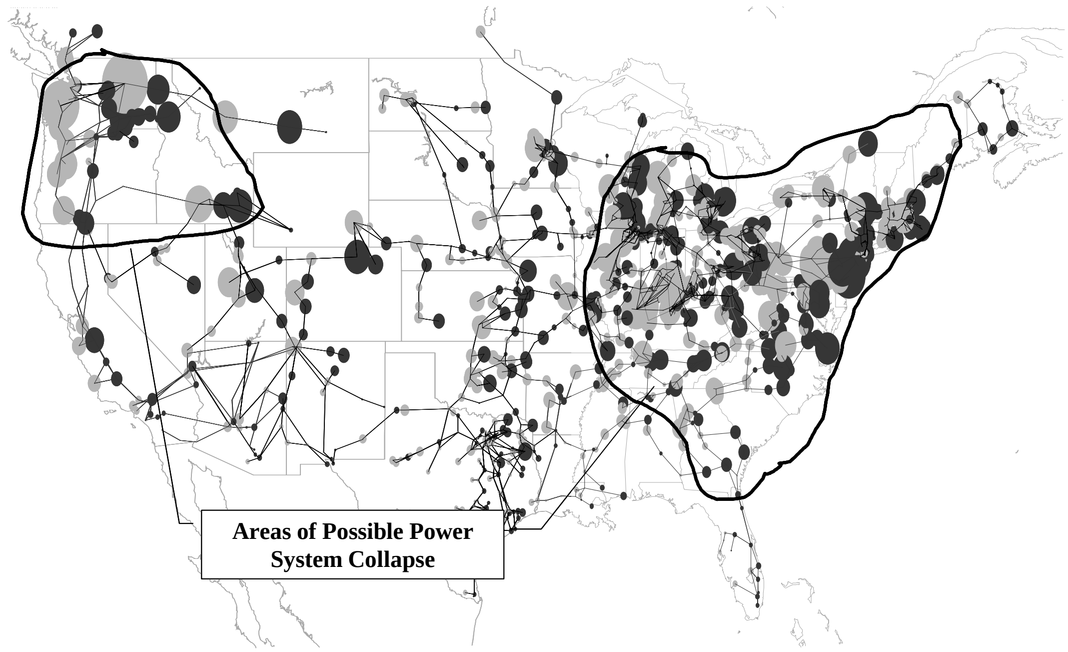

Figure 9 – US Electric Power Grid simulation results showing regions of large GIC flows and possible power system collapse due to a 4800 nT/min disturbance scenario. Other scenarios changing the location or the disturbance footprint could lead to differing regions of power system collapse.

Conditions Needed for a Superstorm

Many of the basic factors needed to produce a large storm were present during these instances of large solar activity and CME passage. However, a large geomagnetic storm did not occur due to just a few minor circumstances which could readily change in the future. The solar flare activity leading up to and the CME passages associated with the October 29 and October 30 storm event illustrated the potential that these events may have in the future should less favorable solar wind magnetic field orientations persist. Even the resulting moderate intensity geomagnetic storms had impacts in spite of advance notice and preparations by many power grid operators. While these storms were rated a K9 intensity at most times from October 29-31, the more objective measure of the storm for GIC impacts comes from reviewing specific impulse intensities and locations, as discussed earlier. As noted in this review, disturbance intensities could be a factor of 5 to 10 times higher at many locations than those caused by any of these storms. The primary solar wind conditions that determine the storm characteristics are both intensity and direction of the interplanetary magnetic field and the speed of the solar wind. Intensity was high but the direction or polarity was generally unfavorable to produce large geomagnetic storms. Both cloud or CME passages happened to have generally unfavorable orientations of the solar wind polarity, especially at times of peak intensity of the CME passage. This was the largest single factor in limiting overall storm intensity, is very unpredictable and can vary significantly for future events. Speed was very high for the October 29 storm, but has been observed to be somewhat higher. The strength of the interplanetary magnetic field could also increase compared to intensities observed and suspected in other historically larger storm events. Another key factor was the duration and/or a successive passage of 2 or more CME's within short intervals of time. As previously discussed the second CME passage on October 30 (though much smaller in size) produced more intense geomagnetic field disturbances because it was able to build on the momentum of the earlier CME passage. Had the second CME arrive a few hours sooner, the storm could have been even more intense. The power industry was also fortunate in the timing of the event during the fall season, when load demands on the network drop substantially from summer peak load conditions.

The major X+ Class flares of the past few days illustrate that Earth has also been avoiding just the right combination of small and easily variable factors that would produce the "perfect" geomagnetic storm. Long-term climatology indicates that we have experienced on average ~2 Superstorms per solar cycle (or every 11 years). It has now been over 14 years since the last Superstorm of March 13-14, 1989.
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