Review of March 31, 2001 Geomagnetic Storm Activity

As we had advised on March 29, the storm that occurred on March 31 had an intensity (on a planetary level) that was less intense than the March 13-14, 1989 Superstorm but a bit more intense than the April 6-7, 2000 Storm. Figure 1 shows a plot comparing these three storms by measuring the DST readings near the equator. The DST reading gives a proxy for the amount of energy deposition that occurs over time into the Earth's magnetosphere. As shown, this storm started off with a rapid level of growth compared to the other storm events. However, solar wind conditions did not sustain for long-enough durations to continue building the intensity of the storm. Some aspects of the storm produced regional intensifications that had power system operational impacts. In general terms, this storm was strong, but storms can and have occurred that could be a factor of 5 to 10 times more intense. Only minor enhancements in solar wind conditions would have been necessary to create a significantly higher intensity storm scenario.

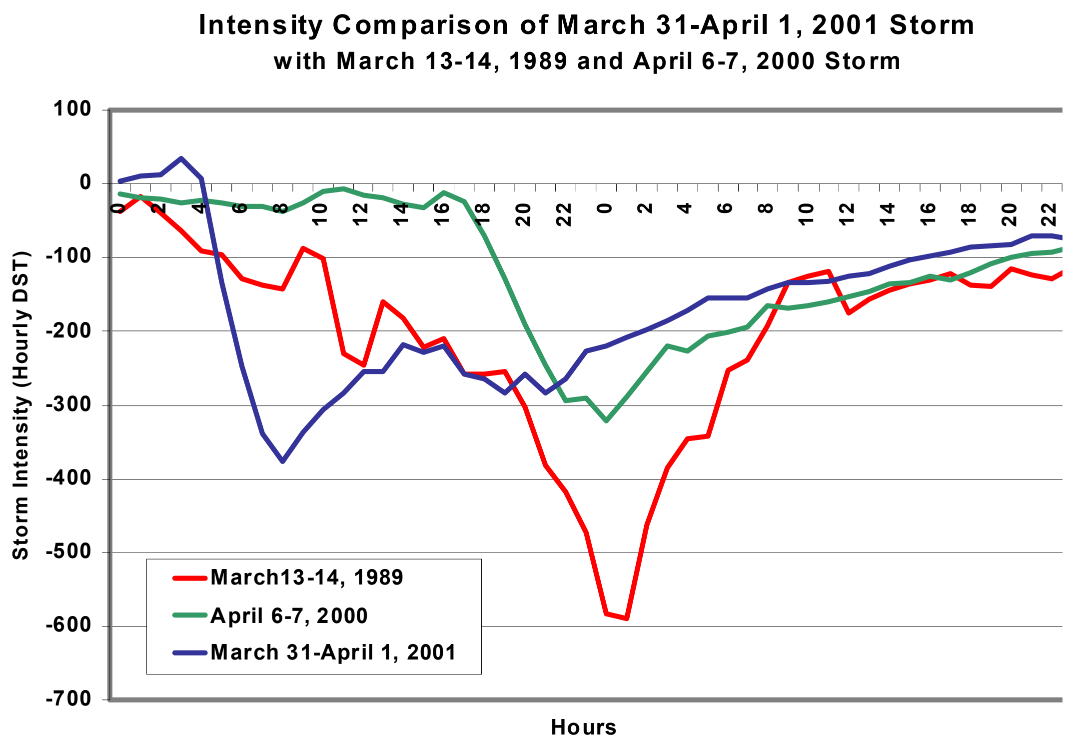

Figure 1– A comparison of the March 31, 2001 storm indicates that this storm was (as projected) at a level of intensity between the storms in April 6-7, 2000 and the March 13-14, 1989 Superstorm. The storm built rapidly in the early hours but deteriorated over the rest of the two-day period.

Region and Time Specific Review of Storm Activity and Impacts

The storm conditions exhibited several important phases that would have the possibility for impacts on power system operations. The times and locations of these impacts can be summarized as follows:

Sudden Storm Commencement (SSC) – 00:53 UT

At 00:23UT, the solar wind monitoring satellite detected the arrival of a large high-speed solar wind shock front. This large shock pushed in the dayside magnetosphere four or more earth radii and produced a wide spread, but short-duration geomagnetic field disturbance which was observed at approximately 00:53 UT around the world. The region of highest-intensity would have been centered over the Pacific and at low-latitudes. Figure 2 provides an illustration of the highest intensity regions that would have experienced the disturbance.

Even though North America and Europe where located quite distant from the highest impact regions, sizable shocks would have resulted in these regions, capable of producing large but brief GIC's. Some

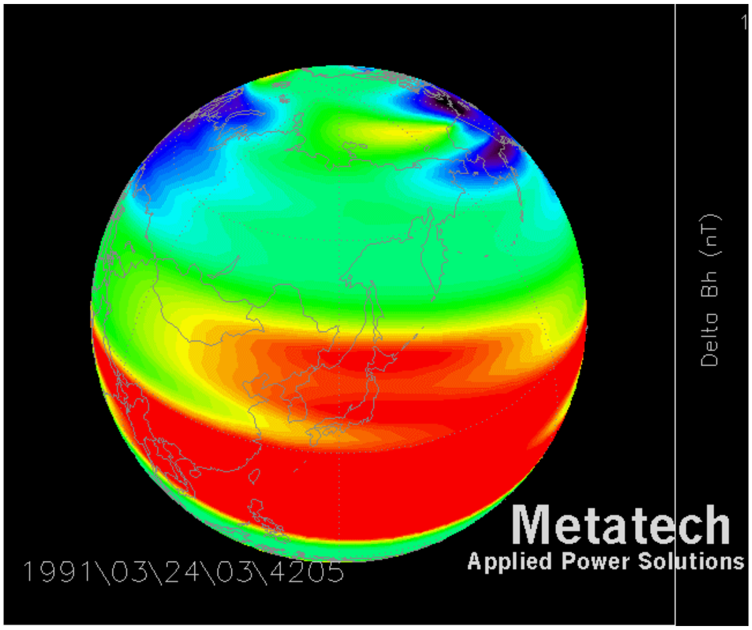

Figure 2 – Regions of highest intensity magnetic field disturbance due to SSC event at time 00:52-00:55 UT. Large GICs could result across broad regions across Japan, Korea, China, India, etc.

power system disturbances were observed in New York due to this event, as an example of the widespread footprint of these shocks.

Preliminary data indicates that this particular SSC was not a particularly large event relative to events that have been previously observed. Sizes that are a factor 5 times larger can be expected to occur in the future. Other times of the SSC onset would have placed the most intense portions of the storm geographically at different regions of the planet. A SSC shock at time 12 UT would have been centered over Western Europe and Africa. Time 18 UT would have placed the disturbance over the middle of North America. These type of disturbances have caused numerous power system operational problems. They are particularly problematic due to the broad geographic exposure, and they occur mid-day locally (during system load peaks).

Electrojet Activity Storm Intensifications 02-08 UT

Beginning around time 02 UT, the solar wind magnetic field turned strongly southward beginning the growth of the main phase of the geomagnetic storm. These solar wind conditions persisted until approximately 08 UT. The coupling caused by the solar wind began a process of building unstable magnetosphere structure that produced substorms and electrojet activity at high-latitude regions and the build up of the equatorial ring-current. The electrojet activity particularly energetic from times 05-08 UT throughout North America and Western Europe. In North America, magnetic field disturbance activity was particularly intense along the US-Canada border. In Northern Minnesota magnetic field disturbances reached approximately 600 nT/min (this is a proxy for level of GIC in a region). Other observations indicate levels from 200 to 300 nT/min along the US-Canada border. For perspective, a larger storm has the potential to produce intensities up to 2000-3000 nT/min in these same regions. Similar intensity disturbances were observed at similar times across Europe, with observatories as far south as Germany recording geomagnetic field disturbances. In the southern

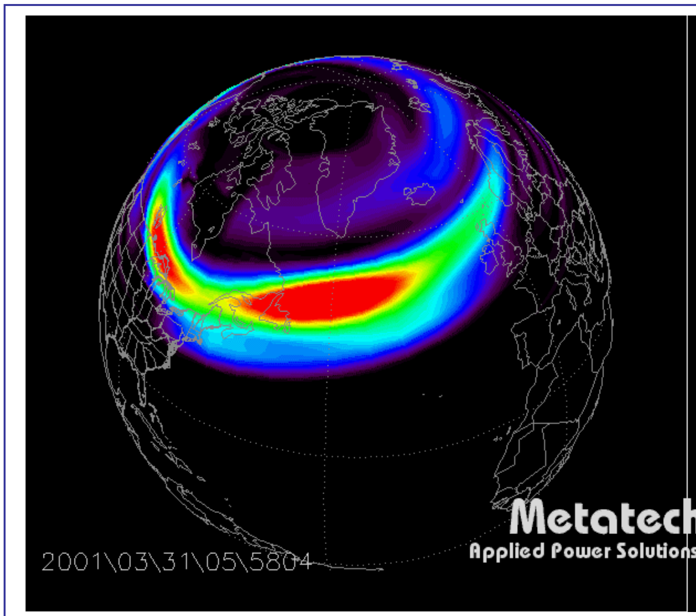

Figure 3 – Forecast Electrojet conditions 06 UT on March 31, 2001

hemisphere, activity likely extended as far north as New Zealand and southern Australia.

At lower latitudes, the intensification of the equatorial ring-current is likely to have caused low-level GIC's but for very long-durations. This storm process would cause GIC sufficient to half-cycle saturate exposed transformers and lead to possible internal heating concerns.

Electrojet Activity Storm Intensifications 14-24 UT

At 08UT, the solar wind polarity turned sharply northward and remained this way until 14UT, at which it turned southward once again until 22 UT. This prolonged southward orientation re-started the growth phase of the geomagnetic storm. This began a process of substorm activity and development and intensification of electrojet activity over broad regions. The timing of this activity meant that regions of Europe would experience the most intense activity caused by the storm. Substantial geomagnetic field disturbances were observed over this entire time interval. Particularly large impulses were observed at around times 16 UT and 18UT from Sweden through the United Kingdom, and as far south as the northern portions of mainland Europe. Similar intensifications could have been occurring over the southern hemisphere as far north as South Africa. North America experienced lower levels of activity during these times (northern Minnesota observed 400 nT/min impulses around 23 UT).

Long-duration GICs would have again been observed at low-latitudes during this period of storm interval as well, due to continual build-up of the equatorial ring current located broadly over these regions.

At time 22UT, a second solar wind shock arrived, which would have again produced a small SSC. More importantly, its arrival heralded solar wind conditions that lead to the rapid decline of the storm, as interplanetary magnetic field strengths in the solar wind fell almost immediately to near zero.

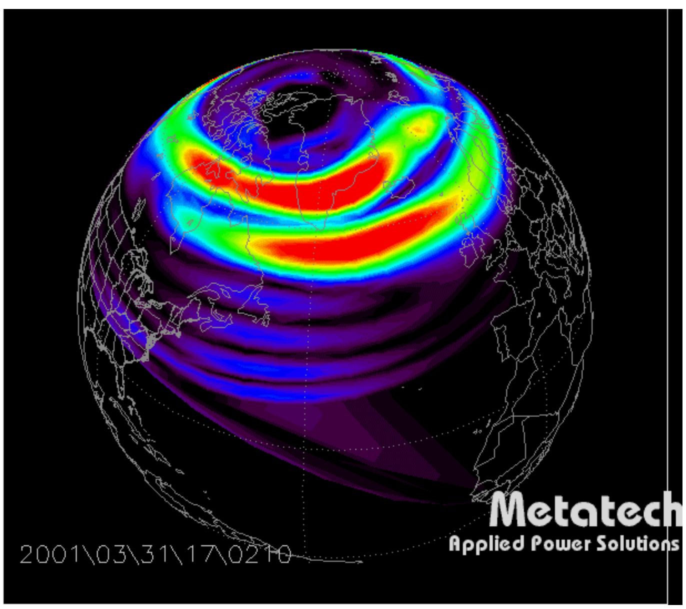

Figure 6 – Forecast Electrojet conditions 18UT on March 31, 2001 over eastern North America and Western Europe.

The Problem with Indices and Real-time Monitoring

The rapid evolution of storm conditions on a planetary scale again illustrated the limitations of real-time monitoring and K Index notices and warnings to provide useful lead-time for operators of critical infrastructures that can be impacted by disturbances. A planetary level SSC shock occurred around 00:53-00:55 UT, this solar wind shock was first observed by our forecast system at 00:24 UT, a lead-time of approximately 30 minutes. This solar wind speed stayed relatively constant throughout the rest of the storm, which provided a consistent 30-minute lead-time throughout the storm of activity. NOAA did not issue their K6 warning until 00:54 UT. At 06:30 UT the largest North American substorm event occurred, starting with growth of a large west-ward electrojet over the continent beginning at 6UT, with the largest impulse in the magnetic field occurring around 6:28UT. NOAA issued both their Warning for A >50 and Observed A>50 storm alerts in the same minute at 06:24 UT.

Real-time observations of GIC would have been even more problematic due to the lag inherent in observing rapidly changing space weather disturbance conditions. GIC's can be at levels below threshold one minute and suddenly grow to very large level the next minute, too fast for any meaningful human situational awareness and intervention. Neither K Indices nor monitoring of GIC at a handful of locations provides the critical infrastructure operator with a detailed overview of the storm situation. The K indices are very vague as to which region or specific time the activity is expected, Figures 2, 3 and 4 illustrate that storms can be viewed in manner similar to the way ordinary weather is presented. This capability also allows GIC and GIC-impacts to be determined throughout the network.

Conditions Needed for a Superstorm

This storm event illustrated the potential of a moderate storm and the widespread impacts they may have upon operation of critical infrastructures. Even though this storm rated a K9 intensity at times, the more objective measure of the storm for GIC impacts comes from reviewing specific impulse intensities and locations, as discussed earlier. As mentioned, disturbance intensities could be a factor of 5 to 10 times higher at many locations than those caused by this storm. The primary solar wind conditions that determine the storm characteristics are intensity/direction of the interplanetary magnetic field and the speed of the solar wind. These variables determine the strength and location of SSC shocks and electrojet patterns. While speed was high for this storm, speeds can increase for more energetic storms by at least a factor of two. The strength of the interplanetary magnetic field could also increase by more than 50% compared to intensities observed in this storm. Another key factor was the duration of the storm, the longer the storm persists, the lower in latitude the electrojet boundaries can stretch. Electrojets extending down to the Gulf of Mexico have been observed in prior storms. Subsequent shock events can also act to intensify a storm. The secondary shock that occurred at 22UT March 31, extinguished the storm because it no longer contained intense magnetic fields. It could be just as likely that secondary shocks will have even more intense field intensities and because the magnetosphere is already highly disturbed, it has an effect somewhat like throwing kerosene on a fire and leading to a true Superstorm scenario.

The power industry was also fortunate in the timing of the event which fell over the weekend, when load demands on the network drop as much as 50 % from peak load conditions during the work week. Further, the equinox period usually presents a pattern of reduced seasonal power demands compared to summer air-conditioning load seasons, where substantially higher electric power demands are present on the network. The Bastille Day storm on July 15, 2000, also happened during the summer season. But again the Power Industry lucked-out, with the storm occurring on a Saturday, rather than mid-week demand period. Some very intense electrojet conditions were observed across North America from 20UT – 24 UT on July 15, this occurred during late afternoon early-evening daily peak loads, but the country was experiencing benign to mild temperatures which reduced air conditioning loads in these regions compared to those likely during a major heat-wave. The attached AVI animation illustrates the extent and dynamic behavior of the electrojet from times 21:30-22:20 UT on July 15 over North America. This is still considerably smaller than the March 13-14, 1989 events that we have also mapped. Higher resolution images are available upon request. The major X-Class flares of the past few days illustrate that Earth has also been lucking out on timing of solar activity. Sooner or later it's number will come up.

Long-term climatology indicates that we have experienced on average 1 or 2 Superstorms per solar cycle (or every 11 years). It has now been 12 years last month since the last Superstorm of March 13-14, 1989.

Best Regards, John Kappenman
Metatech

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