Effects of the Super Bowl on the Eastern Interconnection

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Background

The Super Bowl is one of the few televised events that impact the electric grid. This has been noticed by many utilities that monitor power system frequency. An unusually large number of frequency excursions (sudden rises or drops) are observed during the game. Typically frequency excursions occur at the transition from football coverage to commercials and during game breaks such as the halftime show. Some of the authors have been monitoring the timing of the frequency excursions for many years and the behavior has been consistent. There have been many theories as to the cause of these excursions and several papers written on the phenomena.[1,2] The authors are not aware of any organized attempt to determine the cause of the frequency deviations that occur. For this paper, the authors decided to monitor the system during the game to see if the cause of the frequency variations could be determined.

Normal Frequency Behavior

On any given day, frequency excursions occur for any number of reasons, so one may ask what makes the frequency excursions during the Super Bowl so significant. In answer, we say that the authors are familiar with frequency on a normal day, and in several cases we are, or have been, responsible for reviewing records for every day of the year. With triggers set up as we normally have them, on a typical day we see very few records due to frequency change or level. Most of these can be explained, and the most common is a frequency change due to loss of a large generating unit. These loss-of-generation incidents show a frequency response that is obvious. This type of frequency event and response are different than what typically occurs during the Super Bowl. Against this background of a few triggers on a normal day, we have been observing on the order of 20 to 30 triggers during every Super Bowl since the 1990s. Others have also reported a similar number of events.[1,2] That is, we have been seeing this radically different frequency behavior during the Super Bowl since we have had frequency triggers in use. System dispatchers are familiar with this, and the word they generally use to describe it is “rocky” frequency. We do see unexplainable frequency movements occasionally, but they are isolated incidents, and they certainly do not go on for a four hour period.

There are many other cases of frequency effects due to television programming. One of the authors recognized Super Bowl type frequency movements in the data from March 3, 1999. He asked others in the office what had been televised the evening before and it turned out to be Barbara Walters’ interview of Monica Lewinsky. One of the authors remembers a frequency depression after the last episode of MASH and frequency impacts during the O. J. Simpson “white Bronco chase.” Speaking of our own experience in the U.S. Eastern Interconnection, there have not been any television programs which have produced the strong and prolonged impacts which we have been observing every year during the Super Bowl.

Frequency Regulation Process

The Eastern Interconnection is divided into “Control Areas” which each are responsible to control themselves in two respects. First, they are responsible to control their generation so as to maintain tie line flows on schedule. Second, they are responsible to participate in controlling frequency. They are assigned a “frequency bias” for each calendar year, and this bias is calculated so that each area does a fair part of the work, according to their size. System frequency is normally scheduled at 60.000 Hz. When frequency is off schedule, each area will act to increase or decrease their generation so as to return to schedule. This is a continuous control process. When there is a suddenly occurring unbalance such as a change in load or generation, the system quickly arrives at equilibrium with a new system frequency, and it takes time before the appropriate generation schedule changes are transmitted and applied. It can take several minutes after a large resource unbalance before the system fully recovers to 60.000 Hz.

Observation of Frequency

Power system frequency is observable anywhere on an interconnection. A concentrated local event such as loss of a generating unit will initially appear to nearby observers as a much larger frequency drop then it appears to distant observers. After the initial drop, the recovery looks much the same to all. There are system oscillations, particularly near the edges of an interconnection, which lead to differences in observed frequency transients. Typically, Control Areas monitor frequency directly at substation busses. In this investigation we have used frequency monitoring equipment in our homes. We have seen instances where large load changes have affected local frequency, but such effects are rare. We believe that the effects of the Super Bowl are of a distributed nature and relatively slow, so they can be observed anywhere in the interconnection. We have compared the records from two widely separate home monitoring locations (VA and NY) and we find that the frequency movements that we are reporting are essentially identical. See Figure 1.

Recorders and Placement

Since sudden load changes are known to cause frequency variations, it was determined that the best way to gather relevant data was to strategically place Digital Fault Recorders (DFRs) to monitor different types of load. At a minimum, these recorders continuously record RMS magnitude and phase angle data at rate of 15 samples per second. Some recorders record RMS data at 30 samples per second and some of them store several days of oscillography at a sample rate of 960 Hz. The authors felt that the RMS data would be sufficient to capture any significant load changes.

Some theories that have been presented as possible causes include water pumping facilities, water treatment, and synchronized residential power usage.[1,2] Using these as a starting point, it was decided that we should monitor certain load classes. The specific load classes we monitored were:

- Residential
- Water pumping
- Water treatment
- Sports Bar
- Single TV load

The sports bar load class was one that we weren't sure would provide useful data. They had many TVs, but other factors such as facility heating and cooking equipment could possibly dilute load associated with synchronized activity that leads to the sudden frequency changes. Although we didn't feel that this load class was a significant part of overall system load, we thought that there was a chance that this data may provide some insight since activity there would certainly be related to the game.

We placed digital fault recorders (DFRs) to monitor these load classes. In addition to these recorders, we also monitored the game and logged the times of significant events, such as television commercial breaks. We also had a fault recorder monitoring the television and sound system load at the home of one of the authors.

Several substations were identified as good places to monitor the individual load types. For example, we chose circuits that have purely residential load in order to gather data for the residential load class. In this case we already had permanently installed DFRs in two locations that monitored distribution busses. One location was in Central Virginia that monitored approximately 30,000 homes. The other location was in Northern Virginia that monitored 9,000 homes.

In order to monitor a water pumping facility, we had to find a substation with a feed to a water facility that had no, or very little, load that was not associated with water pumping. A facility was found in the Hampton Roads area and a portable DFR was installed. In this case there was a control house in which we could place the recorder. A phone line was also available. In this case we were not able to synchronize the recorder with a satellite clock. Manual methods of synchronization were available using the phone line, so we were able to dial into the device and keep the clock within a few seconds of the correct time.

Several locations were found that could be used to monitor the water treatment load class. However these locations were not conducive to DFR installations. These are small substations with no control house, no phone line, and no station batteries to power the DFR. It was decided to purchase a small outdoor enclosure from a home improvement store that was large enough to house the recorder. An uninterruptible power supply was obtained to power the recorder. Here we chose a location close to the office so that we could easily drive to the station to check on the DFR, download records, and synchronize the time as needed.

To monitor the "Sports Bar" load class we needed to find a local facility that had management that was open to allowing us to install the DFR. A local place was found near the office with a manager that cooperated with us and allowed us to install the DFR. In return, management of the restaurant was interested in seeing trends of their electrical usage. We were able to gather that data as well.

In the days leading up to the game we contacted all the monitored locations to ensure that the recorders were working and that the time on the devices was as accurate as possible.

Monitoring the Game

Several of the authors monitored the frequency of the grid during the game. The frequency was monitored and recorded using a homemade frequency monitoring device - the Power System Frequency Monitor, or PSFM. The PSFM records system frequency using the voltage in the household wall receptacle. Frequency is measured with a resolution of 1 milliHertz (mHz) and the data is continuously recorded at a rate of 6 samples per second. The PSFM also has the ability to trigger when frequency events occur. There are two trigger types. The delta trigger measures the difference in frequency of two moving averages separated by 5 seconds. If the difference exceeds 20 mHz, the trigger will activate. There is also a rate of change trigger that activates when the rate of change of frequency is 3.5 mHz or greater and lasts for a minimum of 5 seconds. The frequency data used in this paper came from several PSFM devices.

While watching the game, times of commercial breaks and important events, such as touchdowns, were entered into a log file. Large frequency excursions were also noted. This data entry was accomplished manually, so the timing was not exact, but was usually within a few seconds. It should be noted that the images displayed on different television sets across the interconnection may not be precisely synchronized owing to differences in cable and satellite boxes (or lack of either), digital video recorders, etc. At least one author has observed a time skew between the standard definition broadcast and the high definition broadcast of the same channel on a local cable system.

Benchmark Frequency Event during Super Bowl XLVII

A number of significant changes in interconnection frequency occurred throughout the duration of the Super Bowl. Perhaps the most notable such event occurred shortly after the Superdome power outage. The outage occurred while announcers Jim Nantz and Phil Simms were analyzing a replay of the most recent play (a sack of Kaepernick). At about 20:37:03 EST (01:37:03 UTC), the announcers' voices suddenly cut out because of the power outage. The replay of the previous play continued for about 12 more seconds, after which a live shot of the field was shown at about 20:37:15 EST. This live shot was a slightly darker image than the replay because of the reduced lighting in the stadium. As shown in Figure 1, frequency at this point was 59.986 Hz; its slope changed from a very slow decline to a very slow rise. Five seconds later (20:37:20 EST), the image changed to a view of the Ravens' sideline, which was noticeably darker. Three seconds later (20:37:23 EST), the image switched to a view of the blacked-out stadium lights, which was a very dark image. From 20:37:20 to 20:37:22, as the television image darkened, the rate of the frequency rise increased quickly to approximately 5 mHz/s, suggesting a load reduction of approximately 1300 MW on the Eastern Interconnection. Frequency reached a peak of about 60.047 Hz at about 20:37:33.

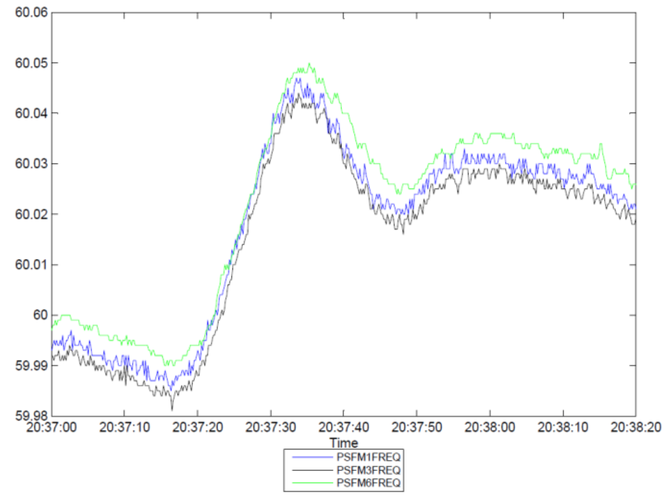

Figure 1 – Frequency Recordings in Albany, NY and Richmond, VA during the Superdome power outage.

Frequency remained at the peak of 60.047 Hz for about 2 seconds before starting to drop again. Notably, the television image partially brightened again at 20:37:37 EST as the camera started showing some of the stadium lights that were still on. Frequency declined at a rate of about 3 mHz/s for about 10 seconds, then rose again slightly, and finally settled at about 60.025 Hz for at least 15 seconds starting at 20:37:52. The next block of commercials started at 20:38:16.

The times of the benchmark frequency event are estimated to be accurate to ±1 second. A clock synchronized to the atomic clock and a review of a recording of the television broadcast were used to make these time records.

Data Analysis

Once we had gathered the data from the various DFRs, we looked at the times where there were large frequency excursions. The most notable one occurred at the same time as the Super dome power outage. We then focused on the load data from that time. The load data from one recorder was significant, while the others showed virtually no load changes at all. Figure 2 shows the load of a single TV at the time of the power outage during the game.

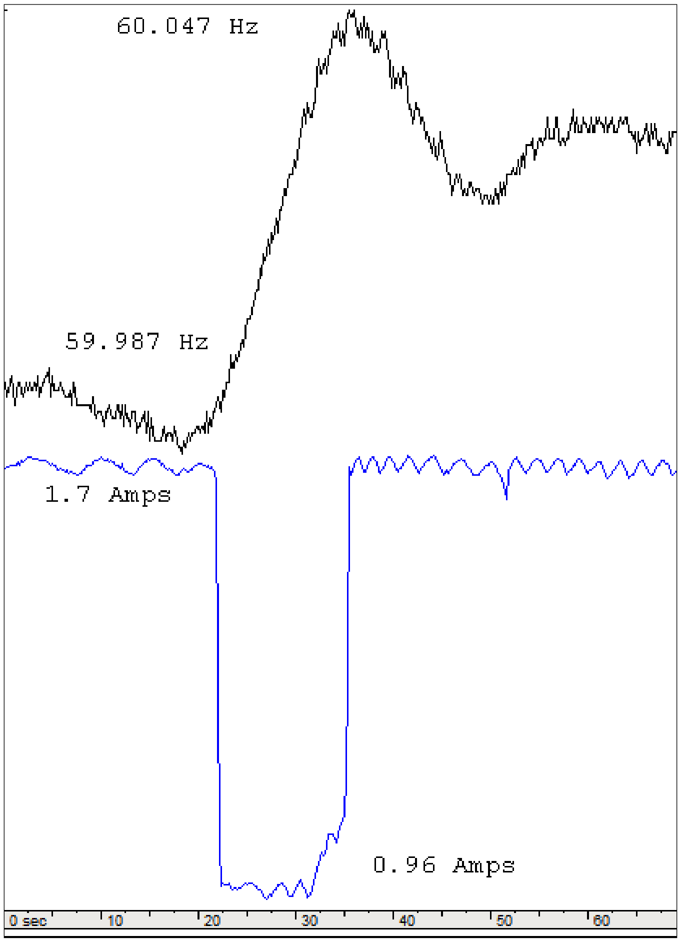

Figure 2 - Single TV load and system frequency during the power outage

This clearly shows a correlation between TV load and system frequency. The next question was "why did the TV load change?" We reviewed the recording of the game, and at the time the load dropped on the TV, the screen went dark. When the screen got brighter, the load went up. The total duration of the frequency rise, load drop-off on the TV, and the dark screen on the TV was 14 seconds.

We then reviewed the data during the entire game and noted that whenever the TV load dropped, the frequency went up. These load drops (frequency rises) were frequently associated with a dark screen on the TV during the transition to and from commercial breaks. This explains the rapid frequency change triggers that the authors have observed during past Super Bowl games.

Another question that we had was why these load changes did not show up in the residential load recorded by the DFR. We ran calculations assuming a 60 Watt drop in load per TV. The residential load we monitored consisted of about 9,000 homes. This load, when converted to three phase primary, was only about 9 A per phase. The nominal load we were measuring was around 900 A. A 3 A change is not noticeable given that amount of base load.

Figure 3 shows the voltage and current from one of the DFRs measuring residential load. There is no perceptible change in load current for the reason cited above. However there is a perceptible rise in voltage that lasts for approximately 14 seconds. This voltage rise is a result of the combined load loss across the grid.

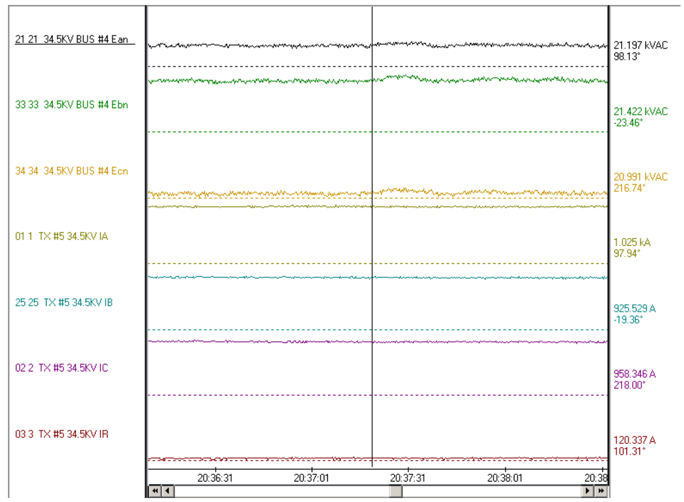

Figure 3 - Residential load at the time of the power outage

There is also the matter of deferred load, which is load resulting from human activities that are postponed until a suitable break in the action. This effect leads to slower frequency movements compared to the effect of television load. When most viewers remain watching, they are not doing any of the many possible activities that they would do if they left their televisions, activities which generally lead to load. Conversely when they engage in those activities, load increases, and frequency falls.

Immediately after the first half of play ended, there was a sharp frequency drop. Frequency remained low for about 4 minutes. In a similar way, a period of many minutes of very low frequency was seen following the game. That is, loads which had been deferred during the entire period of the game were applied after the game was over. This sort of frequency behavior has commonly been seen over many Super Bowls and has led to prolonged depressions of frequency more than 50 mHz below nominal. However, during Super Bowl XLVII, this behavior was not nearly as severe as it had been in years past. There was also a drop off in the number of frequency triggers that occurred after the blackout. These two pieces of data lead us to believe that many people stopped watching the game, either changing the channel or turning off the TV, during the prolonged game delay caused by the power outage.

In a previous FDAC paper[3] one of the authors reported on frequency effects of the Super Bowl. The load shifting mechanism was covered, and there was discussion of rapid frequency changes at the time of scene changes and programming transitions, however this was not understood. The role of the television receiver was not known, and nothing in that area was mentioned.

Lab Testing

Testing was performed in an attempt to reproduce the results measured during Super Bowl XLVII during the benchmark frequency event. Five different displays were used in a laboratory environment to test the conclusions from the data collected during the event.

The displays used were:

- 70 inch LED television
- Two 56 inch LCD televisions
- 42 inch LCD television
- 19 inch CRT monitor

These displays were connected to a central replay computer which was used to replay the recorded event as well as a preprogrammed transition from light to dark through all the displays. All four televisions' displays were connected to a PC through an RGB connection to enable all 4 devices to display the video files. The resolution of all displays was 1200 x 1600. A portable DFR with continuous recording was set up and connected to all four displays by using clamp-on CTs to measure the current draw of each individual device. The portable DFR was recording at a sample rate of 4800 Hz, using 16 of those samples per cycle to calculate RMS, which was written to a file at 1 sample per cycle (60 Hz). The CTs were clamped around the hot leg of the 120V power supply cable to each display as shown in Figure 4.

The single 19 inch CRT was connected to the same central PC through and RGB connection to display the same video images as the above televisions. The resolution of the monitor was 600 x 800. The same continuous recorder was set up and connected to measure the current draw of the display using the same clamp-on CTs.

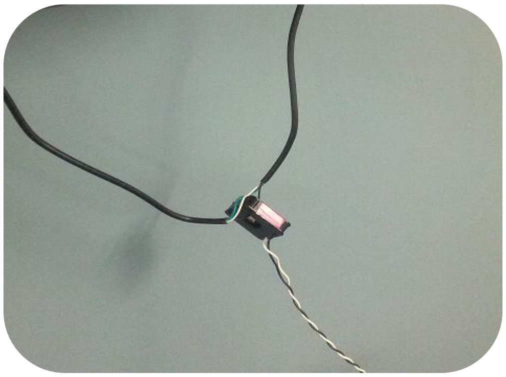

Figure 4 - Photo of CT connected to TV power supply.

There were two parts to this experiment. The first sequence involved replaying a 10 minute session of the recorded game back through all 5 devices. A segment from 20:31 EST to 20:41 EST was replayed through all five devices to measure the current draw of each device during the game. The video replayed included commercial breaks and the Superdome power outage.

Figure 5 - Photograph showing the replay of the Super Bowl on the 70 inch LED and two 56 inch LCD displays.

The data collected during testing is displayed in *Table **1***. When the screens went from bright to dark , the 42 inch LCD screen dropped 60 mA, the first 56 inch LCD screen dropped 40 mA, the second 56 inch LCD screen dropped 40 mA, the 70 inch LED screen dropped 810 mA, and the 19 inch CRT screen dropped 14 mA.

Display Type	**Current Draw Dark Screen (A)**	**Current Draw Bright Screen (A)**
42 in LCD	0.79	0.84
56 in LCD	1.34	1.38
56 in LCD	1.32	1.36
70 in LED	0.36	1.17
19 in CRT Monitor	0.67	0.81

Table 1 – Current draw of TVs with bright and dark images.

A graphical view of the current draw of the 70 inch LED display is shown in Figure 6. This portion shows the 14 seconds of the Superdome power outage. Before the screen went dark the screen was using 1.01 A of Current, and then dropped to 0.877 A during the dark period. The screen stayed dark for 9.33 seconds drawing 0.877 A and as the camera slowly panned into the section of the stadium where the lights were still energized the screen gradually became lit over a period of 3.66 seconds. The game then cuts away to commercial with a quick dark transition causing the current to again drop, but a bright white screen then appears increasing the current draw to 1.17 A.

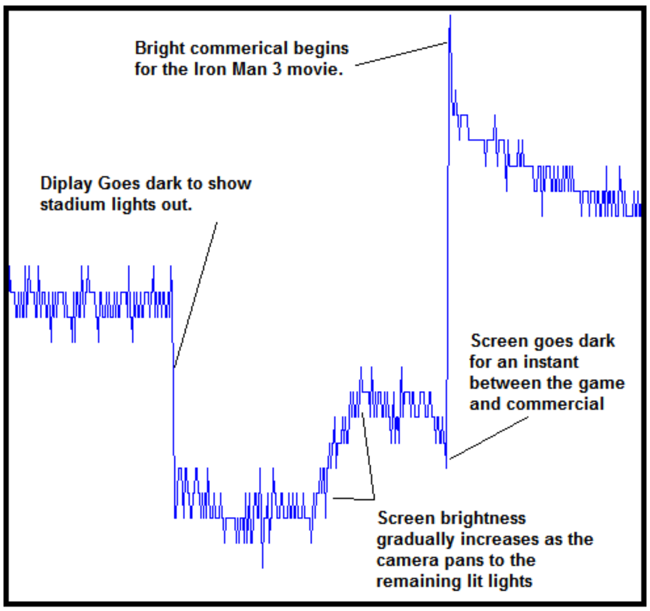

Figure 6 - Current draw of 70 inch LED display during the Superdome power outage.

The second part of this procedure involved taking the screen from dark to bright and bright back to dark. The purpose of this was to document instant transitions, shown in Figure 7. The current draw during the dark period is 0.313 A, and the current then jumps to 1.302 A when the screen instantly goes to white. The current decays to 1.190 A over a period of 3 seconds and holds for the remainder of the bright period. There is no change to the brightness of the screen during that period. When the display is instantly changed back to dark, the current draw drops back to a steady 0.313 A.

Figure 7 shows the change in current over the 20 second test. The screen starts out as dark and is drawing 0.313 A. As the screen gradually brightens the current quickly increase to 1.096 A over a period of 1.33 seconds and then a more gradual increase to 1.284 A over the remaining 3.77 seconds. The current then begins to decay to 1.19 A while the screen is fully lit. When the screen begins to dim back to back, the current rises for 2.4 seconds and then gradually decays from 1.190 A to 0.846 A over a period of 10 seconds and then rapidly drops to 0.312 A over a period of 0.518 seconds. The pattern repeated for each run of the test.

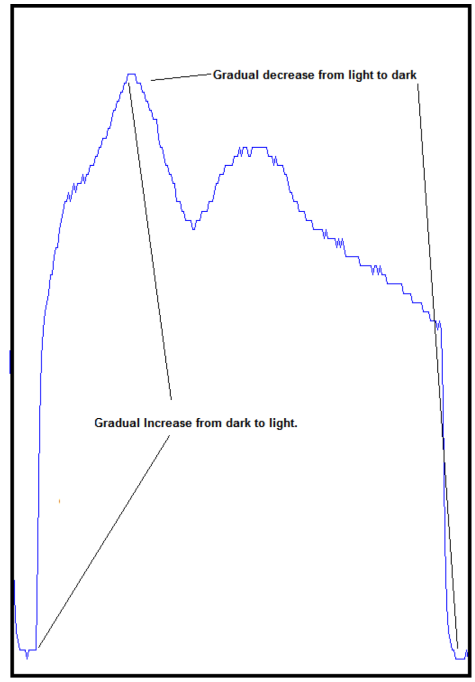

Figure 7 -Load change during gradual light to dark transitions.

The results of the laboratory testing confirm the data and testing hypothesis of the paper. All tested video display devices use more current while the screens are bright than when the screens are dark. The instantaneous change from white to dark during television programming caused a 71.9% drop in load for the 70 inch LED. The LCD displays did not display the same magnitude of change; however, they still followed the same pattern. These displays only dropped between 2.8% and 5.6% of their load during the white to dark transitions.

Conclusion

The synchronized load changes of many television sets across the grid cause the unusual rapid frequency changes. Also, load shifting causes slower frequency movements and periods of sustained high and low frequencies. Together these mechanisms explain the unusual frequency movements which are observed annually during America's most widely viewed event, the Super Bowl.

Biographies

Eric Allen (M'95, SM'07) received his B.S. degree in Electrical Engineering from Worcester Polytechnic Institute in 1993 and his S.M. degree in Electrical Engineering from the Massachusetts Institute of Technology in 1995. In 1998 he received the Ph.D. degree in Electrical Engineering from M.I.T. with the thesis titled "Stochastic Unit Commitment in a Deregulated Electric Utility Industry." Eric was employed for more than 7 years as a Senior Engineer in transmission planning at the New York Independent System Operator (NYISO), and he is now employed as a Senior Engineer in Reliability Initiatives and System Analysis at the North American Electric Reliability Council (NERC). He participated extensively in the investigation of the August 14, 2003 blackout. He is a licensed Professional Engineer in New York and participates in the IEEE Power System Dynamic Performance Committee, in the IEEE Power System Relaying Committee (PSRC), and is currently Vice-chair of PSRC H Subcommittee.

Brian Starling Graduated from Virginia Commonwealth University in 2006 with a Bachelors degree in Electrical Engineering, Minor in Physics, and Minor in Computer Science. From 2003-2006 worked in the system protection relay lab for Dominion Virginia Power testing, installing, and repairing protective relays and substation communications infrastructure. From 2007-2009 he worked in Electric Transmission Calculations group specifically line impedances and relay settings. From 2009-2013 Brian worked in Electric Transmission Reliability Operations Analysis.

Robert Orndorff has worked at Dominion since 1984. He spent 11 years as a field relay technician and in 1997 transferred to the Fault Analysis department where he now works. His current responsibilities include maintaining and configuring Dominion's Digital fault recorders, event retrieval and analysis from smart relays and DFRs. Robert is an IEEE member and has been a member of the Transient Recorder's User Council (TRUC) since 2002.

Kyle Thomas received his M.S. degree in Electrical Engineering from Virginia Tech in 2011 and is currently pursuing his Ph.D. while working for Dominion's Electric Transmission Reliability group. He has technical expertise in power system protection, automation, control, and wide-area measurements. Kyle is technical lead of Dominion's synchrophasor installations, applications, and training, and is actively involved in the North American Synchrophasor Initiative (NASPI) organization.

Jim Ingleson began his electric power engineering work for the City of Jamestown (NY) a municipal utility. He graduated from RPI in 1975 with a M. Eng. In Electric Power Engineering. He is a registered professional engineer, a Senior Member of IEEE, and has worked for General Electric Co., New York Power Pool, New York ISO, and most recently for RLC Engineering. His main areas of work have been system protection and power operations.

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