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A Fully-Automated Disturbance Analysis Vision for the Smart Grid Based on Smart Switch Data

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***Abstract*—**The deployment of smart grid devices such as smart meters and smart switches (SS) supported by a reliable and fast communications system makes automated distribution possible, and thus, provides great benefits to electric power consumers and providers alike. However, more research is needed before the full utility of smart switch data is realized. This paper presents new automated switching techniques using SS within the electric power grid. A concise background of the SS is provided, and operational examples are shown. Organization and presentation of data obtained from SS are shown in the context of the future goal of total automation of the distribution network. The description of application techniques, the examples of success with SS, and the vision outlined in this paper serve to motivate future research pertinent to disturbance analysis automation.

***Keywords*—**Disturbance automation, electric power grid, smart grid, smart switch.

I. INTRODUCTION

THE Electric Power Board (EPB) of Chattanooga's approach to Smart Grid deployment is unique compared to most electric utilities. Recognizing that the success of smart devices deployed across any electric system requires a reliable and fast communications system, EPB installed a fiber passive optical network and began offering voice, Internet and video services to all customers. Once the fiber was in place, it was then possible to deploy smart grid devices. The fiber offered low latency (10 milliseconds), high bandwidth, and fast speeds. This is exactly what is needed for a smart grid infrastructure that automatically re-routes power. Upon deployment of 170,000 smart meters and 1,200 S&C SS, EPB's database needs expanded several orders of magnitude over an 18-month period. Although this was no surprise, standard business tools were quickly overwhelmed, rendering desktop applications inadequate to process the data.

The remainder of this paper is organized as follows: Section II highlights the benefit of distribution automation (DA) and uses a hypothetical scenario for emphasis. Section III outlines a vision for DA. Sections IV-VI present a concise background of the SS with operational examples for their use, followed by, the organization of data obtained from the switches and the future automation of those data. Finally, Section VII concludes the paper.

II. SMART GRID DISTRIBUTION AUTOMATION BENEFIT

DA has achieved intelligent, interactive, and self-healing objectives. Implementing DA at EPB [1] has benefitted their customers by cutting outages in half (System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAFI) improved by 50%). Software packages [2] for fault and disturbance data analysis are instrumental. To achieve further benefits, it is necessary to expand our understanding of what the data are (what patterns within the data are) telling us. Experience shows that, prior to their occurrence, some outages are preceded by an increasing disturbance rate over periods of weeks, days or hours. For example, vegetation slowly growing into a line may have a disturbance signature, while a tree falling into a line clearly cannot be foreseen. The implications are clear of the ability to automate the recognition of such signature and act on it.

A. The Need for Data Analytics Tools

Disturbance analysis is one example where the application of data analytics may result in operational intelligence in the form of actionable alerts. EPB is pursuing new methods to process unstructured data using big data analytics tools. In the short term, this process is conducted by hand. One of the authors of this paper spent time reviewing and characterizing electrical disturbances. The goal of the exercise was to propose a standard method of recording oscillography magnitudes before, during, and after a disturbance. Manually processing the data confirmed that the rate at which data are being generated has exceeded what is practical to do by hand. In addition to disturbance analysis, this paper also shares insights on many of the long-term goals of EPB's Smart Grid DA.

B. Utility Hypothetical Incident Investigation Scenario to Highlight the Benefit of Automation

In order to drive home, the need for automating electrical disturbance analytics as well as highlighting the enormous potential benefit of such automation, a hypothetical incident investigation scenario that some electric utilities may be experiencing today is presented; because of time and space constraints, the scenario is presented without detailed 'actual utility' example data. Assume that, on average, there is one electrical disturbance per year on every 2.5 miles of an electric system. For a utility with 20,000 miles of distribution lines, there may be 667 electrical disturbances per month (20,000mi per 2.5mi per year per 12 months). Assume that 35% of the disturbances result in loss of power. This yields an average of 233 outages per month. With a staff of 10 engineers responsible for designing and maintaining the electric system,

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their workload may allow two days of outage investigations per month. This creates a resource dilemma: with 233 incidents/month and an average investigation requiring 12 hours, 2,796 hours of monthly effort would be needed to investigate all of these incidents. The available labor, however, is 160 hours per month, leaving a shortfall of 2,636 hours. Managers must prioritize which outages get a detailed investigation: of the 233 incidents, only 13.3 would have a detailed report generated. The opportunity for improvement is overwhelming. Utilities could hire more people, but that is cost prohibitive. The other approach is to develop automated data analytics tools so that all disturbances can be investigated. In the previous assumptions, the shortfall is applied only to outages, but the number of disturbances is two times the number of outages. Ideally, all 667 electrical disturbances can be analyzed and characterized automatically. Possible benefits of 100% disturbance analysis include: detecting impending insulator failure, detecting vegetation growth and contact and detecting spans where conductors are slapping. Full disturbance analysis would allow us to see all of the data and find out what the data are telling us. The technology to enable automation is available, but more work needs to be done to apply it towards 100% automation.

Scenario footnote: most utilities dispatch crews to all outage incidents for a physical review of damage or problems. The point of the scenario is to motivate a vision of a future world where 100% disturbance analysis at an engineering level may result in learning how to mitigate or avoid imminent failures.

III. AUTOMATED DISTURBANCE ANALYSIS VISION

This section outlines a vision for automated disturbance analysis (ADAVision) in six phases.

A. Phase One

Phase one of the ADAVision is to automatically alert engineers and dispatchers each time a SS senses an electrical disturbance – complete with an educated guess and probability of certainty of the category under which the disturbance falls (specifically those that do not result in loss of power to customers). Disturbances that do result in loss of power already have notification through Supervisory Control and Data Acquisition (SCADA) and outage management systems – the enhancement would be to record the events prior to the outage.

B. Phase Two

Phase two of the ADAVision is to automatically generate a sequence of events (SOE) when multiple devices sense disturbances and where fault isolation and re-routing of power has happened. The benefit is to eliminate an estimated 12 hours of engineering labor per SOE – and someday all SOEs can be analyzed and categorized in minutes, resulting in a review of all unclassified disturbances in the past 24 hours that requires only 30 minutes of an engineer's day.

C. Phase Three

Phase three of the ADAVision is to develop a system of adaptive filtering with logical rules to identify SOE patterns that lead to outage incidents. A motivating parallel example comes from a former railroad employee (currently with EPB) about a project where mechanical and chemical engineers learned how to analyze oil chemistry to predict impending engine failure. The authors do not yet have a successful adaptive filtering system for prediction of outages, but research is ongoing towards achieving this goal.

D. Phase Four

Phase four of the ADAVision is the utility adoption of the standards set by the National Institute of Standards and Technology, NIST, and other Smart Grid standards. It will benefit everyone who invests in smart grid technology to endorse a set of standards for interoperability, sequence of event summaries, and electrical disturbance analytics [3]. To use an example from the computer networks industry, it was very difficult to write interoperable software when these networks were first introduced in the 1980's. The solution was the development of the OSI model Software companies that embraced this standardized model flourished, while companies that maintained their proprietary models had very limited market success. What is currently missing is an industry standard to generate event logs and correlate events with oscillography automatically. Presently, waveform captures and event logs usually need to be manually matched up in time, and a standardized date and time format across all equipment would be a first great step. One currently has to write formulas to translate date and time formats from different equipment into a common format. Sometimes another conversion is necessary to sync up with SCADA events. This current process is very inefficient – it is time to use computers to automate the merging of SOEs from multiple devices and multiple vendors.

E. Phase Five

Disturbance analysis and SOE processing results will be available for dispatcher review within minutes after any electrical disturbance or loss of power incident occurs on the electric system. For this to happen, standards across all equipment and device management systems and standards for defining logical rules and adaptive filters need to be in place. Then it will be possible to create SOEs quickly. It may be argued that these requirements can be met with data that is available from SCADA. However, because the amount of information available from smart grid devices is recorded at 1 millionth of a second precision, relying on SCADA presents challenges. For a SCADA system polling devices at a two second rate, the authors have found SS to have more than 2,000 event log records between consecutive SCADA polls. SCADA is important and is not expected to be obsolete, but the explosion of available telemetry data is making it abundantly clear that new tools are necessary in order to process unstructured data in seconds. The value of data diminishes very quickly over time. In order to achieve operational intelligence and make data valuable, it is necessary to develop systems that can glean useful events from the gigabytes of data that are being generated daily. The days where electrical engineering and other professionals read through long event logs to piece together what happened will be noted in history books as an archaic, inefficient method of event analysis.

F. Phase Six

The last phase of the ADAV utilizes all the tools mentioned above in order to complete the development of automatic electrical disturbance analytics in the next five to ten years and make it available to the next generation of electrical engineers and managers to help them to better protect our electrical system from future natural disasters and hostile human threats.

G. Sharing the Vision

EPB is sharing these objectives and vision in this paper as it has shared them verbally with the Distribution Modernization Demonstration project and the S&C development team at the Electric Power Research Institute, EPRI.

IV. DISTURBANCE ANALYSIS

This section presents a concise background of the SS and gives operational examples for their use. The following section discusses the organization of data obtained from the switches and the future automation of that data.

A. Smart Switches (SS)

The SS used is a unitized package for overhead distribution systems, comprising the fault interruption components capable of fault isolation and circuit restoration. The package features standalone fault interruption and integration into SCADA and/or Automatic Restoration systems [4], [5]. Key features of the SS are PulseClosing, Conventional Closing, Closing Profiles, Intelligent Fuse Saving (IFS) and Communication Enhanced Coordination (CEC).

1) PulseClosing

PulseClosing Technology^{TM} is engaged prior to the start of a closing operation to ensure first that no distribution line segment is faulty. This technology is also good for reclosing. As opposed to conventional closing, it produces less stress on system components and reduced voltage sags experienced by customers upstream of the fault. The relative let-through energy, in I^2t, of a PulseClosing operation is typically less than 2% of a conventional reclosing operation [3]. There is a provision for hard switch closing following the first trip. This is a fuse saving option allowing resumption of operation after a very fast trip [5].

2) Closing Profiles

A ‘Closing Profile’ refers to a setting that is different from the ‘General Profile’ for closing a SS that has been open and locked out. The closing profiles provide for several parameters to be set such as one that allows a “Synchronization Check” prior to closing and one that specifies use of the ‘PulseClosing’ described above. Overcurrent, voltage, and frequency protection are set for one trip to lockout. Upon successful switch closing, the switch setting reverts to the General Profile assigned to it [5].

3) Intelligent Fuse Saving (IFS)

When the IFS element (phase and/or ground) picks up and starts timing for a minimum of two cycles, and the current goes below both the Phase and Ground minimum trips for at least two cycles, then the IFS elements are turned off for the duration of the O/C and IFS Sequence Reset time. If another fault occurs within the Sequence Reset time window, then only the Base curve is active, so it will time and potentially trip the SS, which then enters the test sequence as usual. The SS will stay in its Initial Trip state unless it trips on the Base curve. After the Sequence Reset time expires and no elements have been picked up, IFS is re-instantiated and the SS is reset to the Initial Trip state. IFS is only active in the Initial Trip state, and this feature only applies when IFS is active [6].

4) Communication Enhanced Coordination (CEC)

When a CEC-configured SS senses a fault current, it sends a curve-shift message to its source-side neighbor asking the device to change to a slower protection curve. All the CEC-configured SS sense faults at the same time and send a curve-shift request to their source-side neighbor. Only the SS at the faulted line segment will not receive a curve-shift message because it does not have a load-side neighbor sensing the fault current. It will not change to the slow protection curve and will trip before the other SS [6].

B. Implementation and Operation

It is a fact that the majority of recorded faults occur within the distribution section of the Utility Grid. For this purpose, much emphasis will be placed on distribution instead of transmission circuits. In order to illustrate key advantages of a DA network that utilizes the SS, three operational examples are discussed below.

1) Example 1: 12 kV Automation

In Fig. 1, circuit breaker BKR1 sources a circuit serving 1643 customers under normal configuration and ties to circuit breakers BKR2, BKR3 and BKR4. In this configuration, there are no SS components so that a fault anywhere between BKR1 and any of the other three downstream breakers will render the entire circuit devoid of power. This is the condition of the majority of the national utility grids. EPB, however, has been at the forefront of smart grid network technologies that are aimed at not only shorter outage durations, but also smarter switching techniques so that faults can be isolated and locked out and that power outside of faulted regions can be rerouted and restored within seconds. A network installed with EBP’s Smart Grid Technology will allow for such.

In Fig. 2, nine SS have been added to the network between breaker BKR1 and tie breakers BKR2, BKR3, and BKR4 for the purpose of automation. All tie breakers are closed to provide multiple power sources should rapid switching be required. SS 1, 4, and 9 are open under normal configuration to prevent power flow from multiple directions.

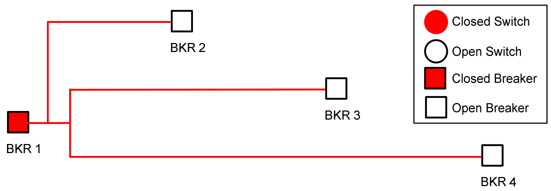


Fig. 1 Example 1 Network before SS were Incorporated. SS Indicates SS and BKR Indicates Breaker

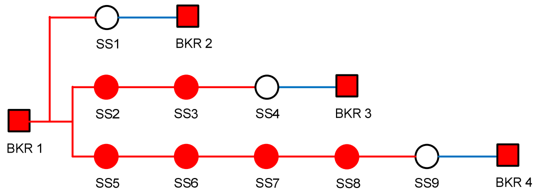


Fig. 2 Example 1 Network with SS Incorporated

In Fig. 3, a fault is experienced downstream of switch SS7. The aforementioned switch opens to isolate the fault, then attempts to close by performing three pulse-tests, each at a specified time interval, but eventually locks-out since the fault remains. As a result, 451 customers between switch SS7 and SS9 lose power. 1192 of the 1643 customers between the breaker BKR1 and switch SS7 experience approximately a 1/3 of a second interruption (flicker) of service. Recalling Fig. 1, a fault anywhere on the circuit without the installed SS renders the entire circuit without power.

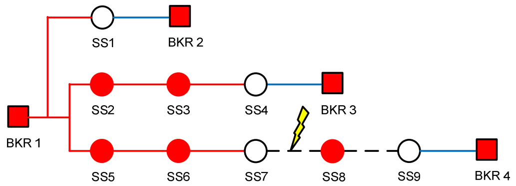


Fig. 3 Example 1 Automation - Starts

In Fig. 4, switch SS8 also senses the fault, which is between SS8 and SS7, and opens to allow the restoration of power from tie breaker BKR4.

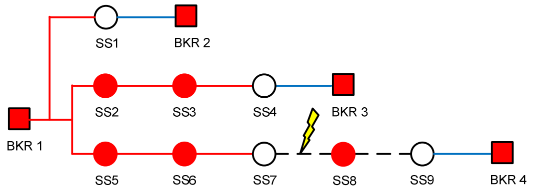


Fig. 4 Example 1 Automation - In-Progress

Once the fault has been isolated between switches SS7 and SS8, alternate configuration switch SS9 closes to restore power to 197 customers located between switches SS8 and SS9 (Fig. 5). Because this is an intelligent and self-healing smart grid, all switching actions take place within 1-2 seconds. Finally, 254 of the 1643 customers within the faulted zone are left without power until manually restored.

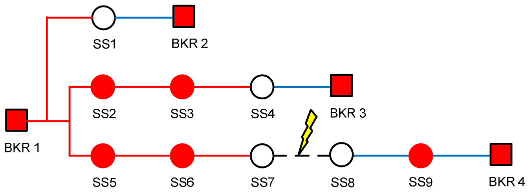


Fig. 5 Example 1 Automation – Finished

2) Example 2: 46kV Automation – Regional Map

This example (explained with the help of Figs. 5-11) is similar to Example 1 in that SS are used for fault isolation, pulse testing and automated power restoration. However, instead of depicting the 5-step operation using one-line form, regional area maps are employed for illustration. A one-line diagram is still provided (Fig. 8). In this example, a timestamp for all affected zones is contained within EPB's Smart Grid. In this example, a system sourced from breaker CB-111 in the normal configuration with ties to other 46 kV circuits (BBB & CCC) through normally open breakers CB-999 and CB-1010. This circuit (AAA) is the source to 12kV distribution substations 12 kV-1, 12 kV-2 and 12 kV-3. Each substation is monitored by SS. Elements 222 – 888 are 46 kV motor operated switches. In five steps, the system in Example 2 shows transitions from total blackout from a fault caused by a tree to total restoration of power due to the automation process of EPB's Smart Grid.

1. Fig. 6 - 6:51:09 PM – 11,258 customers lose power.
2. Fig. 7 – Service restored to 10,000 customers

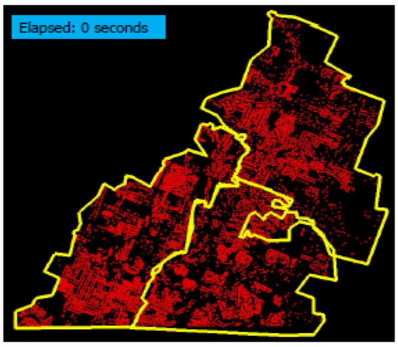


Fig. 6 Example 2 Automation: Blackout (All Areas Shown as Red)

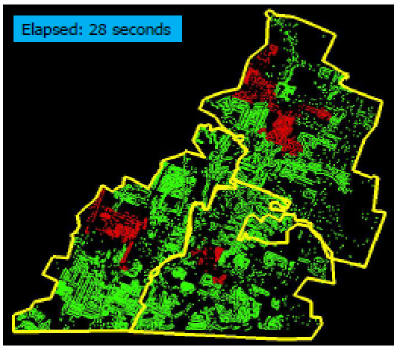


Fig. 7 Example 2 Automation – Start (Areas Off-Grid in Red)

Before the 46 kV breaker completes the reclose cycle, the DA senses the loss of voltage and automatically opens and closes switches to reroute power from adjacent 12 kV lines. Fig. 8 is the one-line illustration.

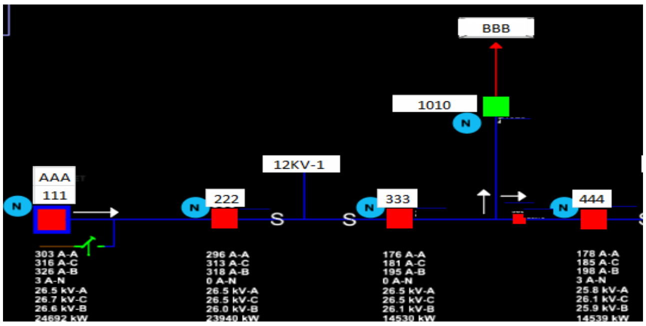


Fig. 8 Example 2, One-line illustration of area map. Shown is a system sourced from breaker 111 with ties to circuits AAA, BBB, CCC through breakers 999 and 1010. Motor Operated SS are shown numbered 222 to 888

3. Fig. 9 - 6:51:52 PM – Service restored to another 800 customers: as the 46 kV breaker completes the reclose cycle and locks out, the 46 kV automation identifies the fault location, then opens and closes switches to energize two of the three substations.

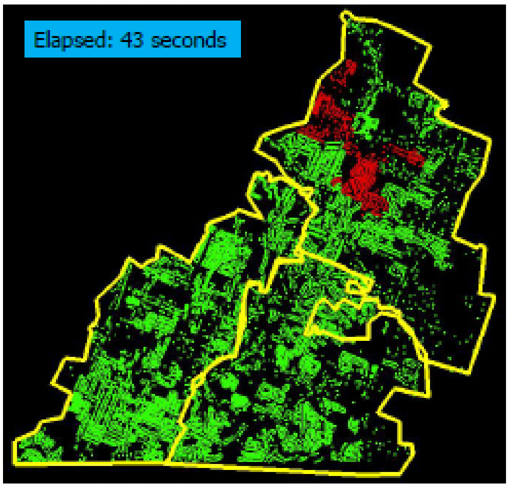


Fig. 9 Example 2 Automation - In-Progress

4. Fig. 10 - 6:55:04 PM – Service restored to 289 customers: a dispatcher opens the 12 kV-3 201 breaker and closes the first PCR on the 12 kV-3 201 circuit. The 289 customers between these two points now have electric power service.
5. Fig. 11 - 6:57:47 PM – All service restored: a dispatcher now opens the 12 kV-3 202 breaker and closes the first PCR on the 202 circuit. The remaining customers between these two points now have electric power service. Smart meters confirm that all electric services are restored.

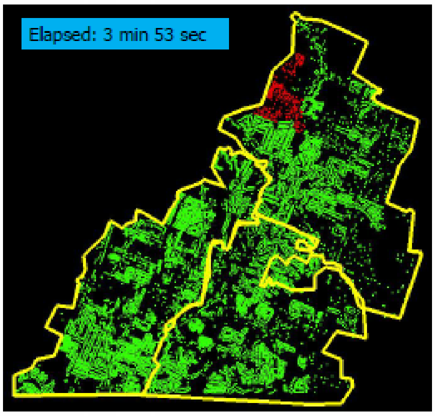


Fig. 10 Example 2 Automation - In-Progress

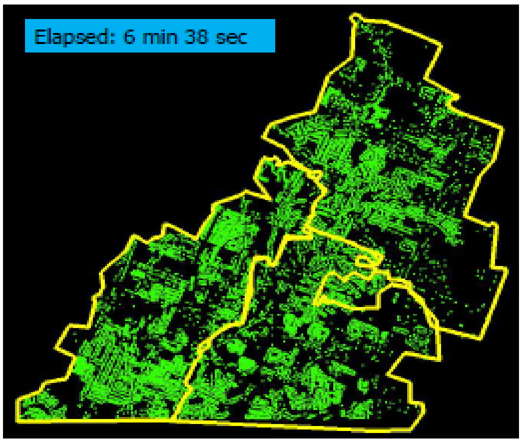


Fig. 11 Example 2 Automation – Finished (All Areas Restored, Green)

3) Example 3:12 kV Automation – Oscillography

In addition to the automation process of the SS network, as previously discussed in Examples 1 and 2, Example 3 delves deeper into engineering and component data behind this automation. This example will discuss oscillography waveforms and data captured by a single pole (SS2) during a storm on July 5, 2012. Disturbances, as captured in the aforementioned waveforms, occurred at exactly 19:49:23 hours and lasted 246.34 cycles (approximately 4.1056 seconds). The oscillography for each of the steps numbered below is shown in the appendix.

The radial network (shown in Fig. 12) is sourced by breaker BKR1 and is composed of four SS. SS1, SS2, and SS3 are closed, while SS4 functions as an open-tie.

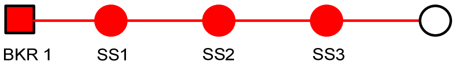


Fig. 12 Example 3 One-Line

In the following sequence of events describing the disturbances captured by SS2, each number corresponds with a timestamp or time span as shown on waveform diagrams in Attachment A.

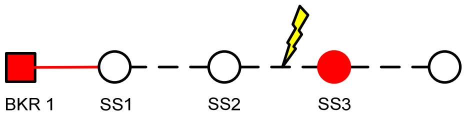


Fig. 13 Example 3 Automation - Start

1. In Fig. 13, smart switch SS2 detects a fault on pole 3 (I_3 = 2273A rms, I_1=60A, I_2=42A)
2. Both SS1 and SS2 trip, when only the latter should have. Herein is an example of miscoordination, which was corrected in June 2013 by incorporating Communication Enhanced Coordination (CEC) as a means of improvement. Recall that CEC tells the source side device to shift to a slower curve.

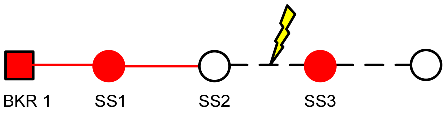


Fig. 14 Example 3 Automation – In-Progress

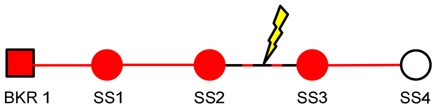


Fig. 15 Example 3 Automation – Finished

3. In Fig. 14, SS1 performs a single pulse test (Test #1) on pole 3 first, then pole 1 and lastly pole 2. As each pole test results in "unfaulted", the respective pole switch closed. SS2 remains open.
4. SS2 receives a clean source and performs a Single Pulse test (Test #1) on pole 3. As the test detects a faulted condition, it continues with a Double Pulse test to rule out startup transients such as magnetizing currents of transformers, voltage regulators, etc. The Double Pulse test results verify that conditions are indeed faulted and SS2 remains open.
5. In Fig. 15, SS2 waits for the reclose timer (duration = 3 sec) of Test #2 to expire. The system is in a mode known as Storm Latch Mode (SLM) and for this reason SS2 does not perform pulse testing, but hard closes for Test #2. Poles 1, 2 and 3 hard close in this order. SLM then employs an operating scheme called Intelligent Fuse Saving (IFS). In Test #1, IFS is permitted to open quickly, thus removing the fault energy faster than the fuse. This operation saves the fuses. However, due to limited human resources and the need to keep power on during inclement weather conditions, SLM permits the fuses to blow during Test #2, removing power from a smaller portion of the circuit than that of a SS trip.
6. SS2 detects the fault as pole 3 closes.
7. A downstream fuse blows and clears the fault on pole 3. Pole 1 and 2 remains closed and operational. The fuse had not been permitted to blow, all three poles would have opened. Test #3 would have been performed after the reclose timer (10 sec) expired. If Test #3 results in a fault, SS2 will lock out all three poles and a service crew will need to be dispatched to the site of the fault.

V. THE NEED FOR ORGANIZATION OF DATA

With the installation of approximately 1200 automated SS on EPB's distribution network, several thousand files of oscillography waveforms have been captured during 12kV fault events. The desire is to know what the data is revealing about the grid's behavior. Some potential uses for captured data are as follows:

- Classification of "fault signatures" into types and characteristics - No two faults are identical, however, often they share similar attributes that place them into a general classification. The objective here would be to see if any correlation exists between a waveform "signature" and the fault.
- Early warning correlation - Data obtained several weeks before an event could be reviewed to determine the existence of early warning signs. The pre-event disturbance data could have the same general "signature" of the event disturbance data but perhaps at lower magnitudes or for shorter durations. As a result of this effort, faults could be predicted and corrected by analyzing electrical disturbance characteristics that may indicate that a fault event is likely to occur.
- Post event - Data obtained several weeks after an event could be reviewed in order to determine whether or not a particular section of the grid remained disturbance free after all repairs were performed.

It is therefore necessary to find a standard method to describe and organize these disturbance data. The main goal is to automate the disturbance analysis process.

VI. FUTURE AUTOMATION OF DATA

In addition to fully automating a distribution network such that power-flow switching is done automatically and generally without human intervention, it is desirable to organize and present the data received from SS devices in a concise and interactive manner. Below are some key points for current and future research investment opportunities.

- Intelligent alerting – generate reports with actionable intelligence without the need for managers and engineers to retrieve and format data.
- Adaptive filtering – replace traditional queries and filters with multi-pass queries that refine search criteria based on what is learned from previous results.
- Data analytics/visualization – build dashboards that allow users to mine information they want in three mouse clicks.
- Efficient time navigation – develop visualization tools that allow users to click "Next"/"Back" buttons to navigate to the next event of interest without the need to enter date/time ranges in calendar choosers.

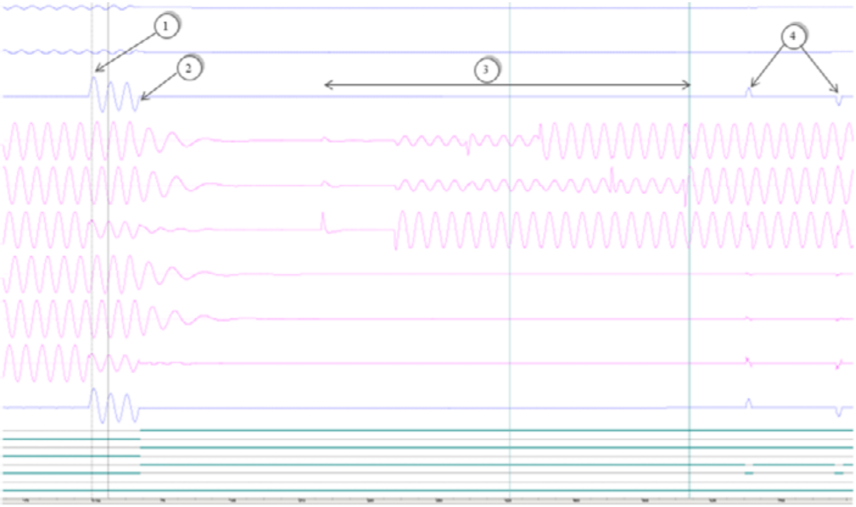
- SOE lists – create a method for Smart Grid systems to self-generate meaningful sequence-of-events (SOE) lists, saving engineers and managers hours or days of work to create useful SOE necessary to begin event analysis.
- Situational awareness – develop a method that allows smart grid systems to modify their behavior or respond to events for different situations.

VII. CONCLUSION

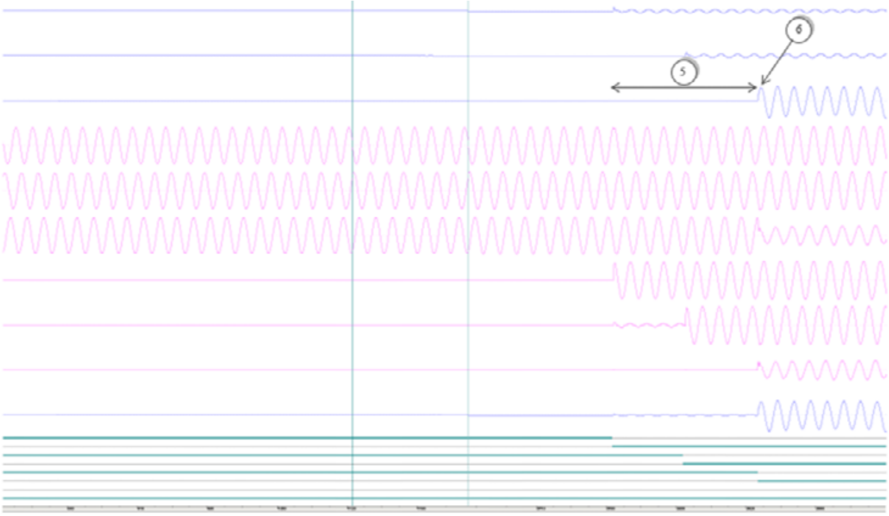
This paper described, with examples, the application of automated switching techniques using SS within the electric power grid. The presentation highlights the availability of useful data and the great utility of switching techniques in order to generate more interest and motivate future research to realize visions such as the disturbance analysis automation vision shared in this paper.

APPENDIX A

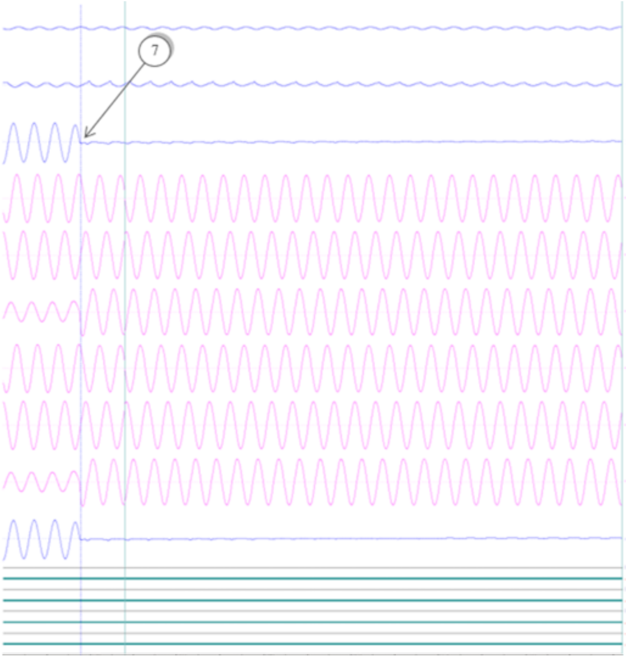
As mentioned in Section IV, B, oscillography waveforms for the steps enumerated in Example 3 are given in Fig. 16. For clarity, the waveforms are split into three subfigures (a), (b) and (c).



(a)



(b)



(c)

Fig. 16. Oscillography waveform for the steps enumerated in Example 3 of Section IV, B. For space considerations, the waveforms for steps 1 through 7 are shown spread over three parts (a), (b) and (c)

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