20 Years and Counting: Deploying a System for Automated Analysis of Transmission Line Faults

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Abstract-- **This paper describes the evolution of a system for automated analysis of transmission line faults. The analysis is based on the substation data primarily collected from digital fault recorders. The paper provides a historical overview of the implementation steps and illustrates requirements changes throughout the process.**

In addition, the paper shares some interesting experiences related to the usage of the system that illustrate the value and benefits of having the automated fault analysis solution in place. The encounters include events developed during hurricanes Rita and Ike, as well as events during dry weather in 2011. The solution for automated fault analysis played important role in diagnostics and system restoration process.

Index terms – **substation automation, intelligent electronic device, fault analysis, substation data analytics, fault location calculation**

I. Introduction

Automated analysis of transmission line faults assumes data integration and processing of waveform transients recorded in substations close to the fault. The analysis includes signal processing and feature extraction, fault detection, and fault location calculation. This paper illustrates gradual deployment of a system for automated analysis of transmission line faults used in CenterPoint Energy (CNP) during last 20 years.

Initial analysis started using Electromagnetic Transient Program (EMTP) simulations, Matlab scripts, and about a dozen field records from a selected substation digital fault recorder (DFR) [1,2]. Initial requirements and setup were based on discussion with fault analysis experts, defining the heuristics and fault behavioral patterns, and lots of experimenting in the lab [3]. The first field implementation was based on C programming language and CLIPS (C Language Integrated Production System) tool for building expert systems [4]. The field setup used a substation computer to analyze the DFR data relevant to transmission lines in a selected substation [5,6]. The analysis reports were automatically sent from the substation to the fault analysts using fax modem transmittal software. The solution was gradually expanded to cover DFR's at additional substations [7]. The expansion of the initial solution into a system solution faced many challenges: communication with recorders, file format conversion, configuration settings, data integration, configurability of the analytics tools, data viewing, substation computer performance, time required to travel to/from substations for trouble shooting, etc.

The implementation grew into an autonomous software system that is universal, more robust, and configurable with respect to data sources and deployment options. The latest version of the system used at CNP is configured to process event data from close to a hundred DFR units and about a dozen digital protective relays [8,9]. The substation computer was eliminated and communications with the DFR's utilizes the manufactures proprietary software rather than custom written software. DFR records are polled continuously and retrieved to the dedicated central file servers. Automated retrieval of digital relay data at CNP is still under development. Once transferred, fault records are moved to the central process computer which automatically converts, integrates, and analyzes fault data. The system implements a universal approach to fault data regardless of the type, model, and vintage of Intelligent Electronic Devices (IEDs). Integrated data and analysis results are disseminated using broadcasting services such as email, Short Message Service (SMS), or pager. Various improvements over the years resulted in powerful and interactive user interfaces, better maintainability, and flexible configurability. Users can access the data using the web application and universal report viewer.

This paper first discusses the automated analysis background and system growth where the user experiences that affected requirements specifications over the years. Encounters described include field events that took place during hurricane Rita in 2005, hurricane Ike in 2008 and extreme dry weather conditions in 2011. These types of events place a strain on manpower resources available to analyze events due to the increased number of faults that occur in short period of time while personnel are supporting restoration and response efforts. How the system for automated analysis of transmission line faults provided timely information that supported the fault diagnostics, helped the power system restoration process, and was used as a tool for training newer engineers is described at the end.

II. Background

CNP has come a long way from its first days of magnetic tape fault recorders that were used prior to the 1980's. The magnetic tape recorders required travel to the substation to retrieve the tape, return to a location to replay selected channels from the tape on to light sensitive paper, get the printout to the individual responsible for analysis and the individual used measuring tools and magnifying glasses to interpret the information. Many times the printing and analysis had to be repeated to gain the information needed from certain channels or because the paper became unreadable. In one case that involved a particularly significant event many print outs were studied over several months. However, when it was needed to revisit the data after a couple of years it was discovered that the magnetic tape had been returned to service and the important data had been over written. The only data that remained were the few light sensitive paper print outs that had already been handled extensively. In order to preserve the fading information, a draftsman was hired to go over the traces in pencil. In another case in the late 1970's one large substation was equipped with a "direct print on light sensitive paper" fault recorder because of the substation's remote location. Because of the size and importance of this particular interconnection substation, this substation was "manned" during normal business hour. Any paper fault record could be quickly browsed and the paper sent to the central office. However, fault records could not be replayed.

In 1985 CNP began replacing the magnetic tape fault recorders with digital fault recorders and remote communication. Also, the number of recorders grew. The amount of data available to be analyzed began to expand exponentially. Since that time, all first generation digital fault recorders have been replaced and CNP is now in the process of replacing second generation DFRs. Shortly after CNP installed the first digital fault recorders it became apparent that there was a need for automated analysis of the overwhelming amount of data. The development began as an expert system R&D project in a university lab as a demonstration [3].

III. Growing the System for Automated Analysis

A. Developing a prototype

Development of the concept for automated analysis of started in cooperation with Texas A&M University in early 90s. The prototype architecture for the computer-based analysis of transmission line faults is depicted in Fig. 1. The development was based on utilization of test data coming from the EMTP simulation of transmission line faults, as well as from a few field examples captured by early DFRs [1]. The solution for data import and the raw data samples processing was done by Matlab routines [2]. The extracted features were then passed to the event diagnostics implemented using expert system rules in CLIPS [4]. The setup was used as a proof of concept and set stage for field trials [5].

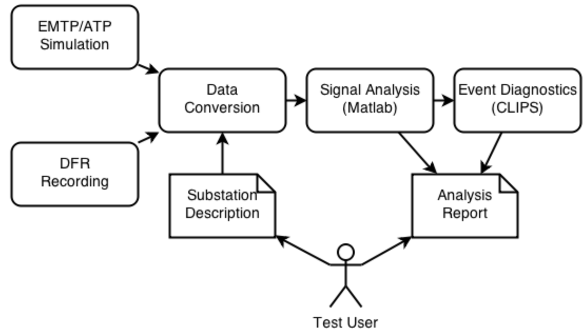

Fig. 1. In-house proof of concept

B. Field trials

The successful demonstration in the lab was followed by a field trial in a substation. Because the original direct print fault recorder at a large interconnection substation had been replaced with a first generation digital fault recorder it was decided to demonstrate the benefits if the new automated analysis system at this remotely located substation which had many long transmission lines. The setup is illustrated in Fig. 2.

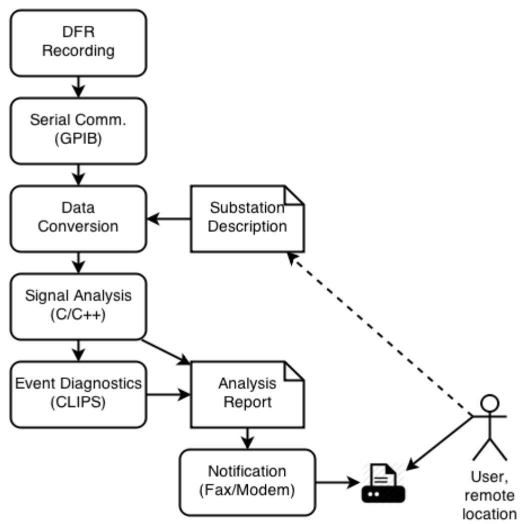

Fig. 2. Single substation field implementation (1 DFR)

The implementation took place in mid-90s. This particular DFR created multiple data files for each event. The data was retrieved from the DFR using GIPB serial link and DFR specific protocol. The data files were then merged and converted into signal samples corresponding to a single event. The samples were processed in order to extract signal features needed for the event diagnostics. The event analysis report were sent our using fax/modem and received by a fax machine at remote location. The setup was configured and limited only to one substation and the transmission lines that were monitored by that DFR. For each operation of the DFR there was a 1-2 pages fax analysis report received [6]. This field installation was in place for a couple of years and the solution went through some improvement and tuning iterations.

This system performed reasonable well but if the automated analysis failed to identify the correct transmission line of interest, the fax contained information that was of limited use.

C. Commercial deployment

With the success of the field trials, it was decided to develop a decentralized solution with additional capabilities. In the late 90s CNP started the implementation of the automated analysis of DFR data in multiple substations. The initial focus was on the same type and vintage of DFR recorders. There were about 30 substations equipped with early generation DFRs. The targeted architecture is depicted in Fig. 3. The plan was to install a PC in each substation and on each PC to install the analysis client software. The analysis was a new, Windows NT based, generation of the fault analysis software [7]. All of the components including the communication, signal processing, and expert system, were implemented from scratch using the experience with the initial field trial, but also with the aim to migrate the solution to a new platform. The analysis reports were combined with converted event data, zipped, and sent to a server using dial-up communications.

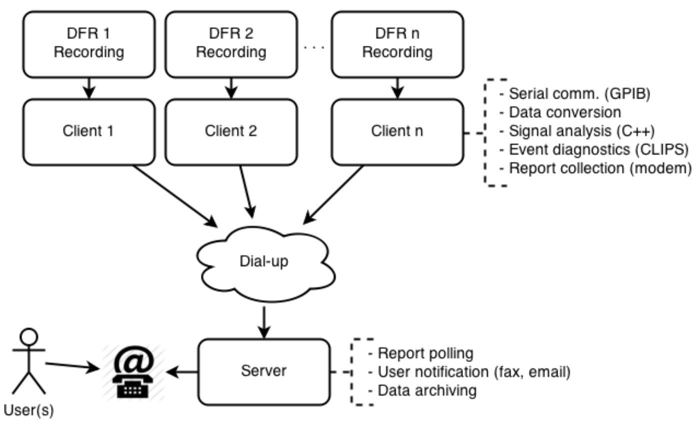

Fig. 3. Decentralized system solution using dial-up (~10 DFRs)

The field commercial deployment of the solution started in early 2000s with involvement of Test Laboratories International, Inc. At the time, this was not a project with CNP IT department support. DFR system at CNP was on its own Ethernet LAN, separate from the corporate LAN, therefore those in CNP implementing the system were able to do pretty much whatever was needed. The downside is that there was a lack of support within CNP from IT staff that was the most knowledgeable of computer hardware and software systems. It was just a couple of basically computer illiterate relay engineers that had to learn computers down to the bios level, and operating systems that were new to them. The substation client computers that were purchased were non-hardened, consumer grade computers running "off the shelf" Windows NT operating system. As a result, soon after installation, only a few of the computers were able to continue to function. Most were continuously crashing, and requiring multiple trips to re-boot the computers. There were approximately 35 computers at remote substation sites; some were over one hour drive from the central office. While parameter updates and periodic maintenance is possible using remote communications software, re-booting from a crash and diagnosing the cause of the crash must be performed locally. To get this system even marginally functioning was a major challenge. It quickly became evident that this solution would require field personnel that were computer competent, computers that were hardened for a substation environment and, periodic replacement of all computers. Another solution was needed. The main challenges throughout the above deployment can be summarized as follows:

- Slow deployment as each substation required installation of a PC, configuring, and commissioning,
- Reliability issues with installed PCs (some would work great, some would frequently crash),
- Release of new generation of DFRs introduced mixture of different device vintages and types,
- Issues with phone lines and possibly fax/modem cards.

There were up to 10 DFRs configured following the architecture depicted in Fig. 3 when CNP decided to use the DFR vendor's proprietary communications software to retrieve events to the Master Station located at the central office. While this solution would increase reliability by avoiding the complexity of multiple remote client computers, event retrieval would only be as fast as could be accomplished over the single phone line connected to the Master Station. Another advantage of this solution is that the client computers would no longer need to communicate directly with the fault recorders. At this time CNP had multiple vintages of fault recorders from the same vendor, requiring multiple Master Station computers. It was decided to keep the Master Station computers separate from Data Analysis Server. No commercial software could be located that could create an image of the Master Station event directories on the Data Analysis Server on a near continuous basis and this routine was custom written.

The architecture of the solution was modified according to the diagram in Fig. 4. DFR vendor's Master Station software is now utilized to communicate with the DFRs using auto-polling feature. The fact that all of the DFRs were coming from the same vendor made it little bit easier when the vendor provided a version of Master Station software capable of dealing with various types and vintages of the DFR devices. The collected DFR event files were passed on to the application server PC that hosted both the processing client (fault analysis) and server (data manager). This centralized architecture was fully deployed and utilized throughout mid-2000s. The solution was configured for DFRs in over 30 substations and utilized different vintages of DFRs. User notification was done primarily through emails and pager messages. In addition, the solution provided for a web access to the event data and analysis reports archived at the server [8,10].

During this period some new requirements came in to the picture [11,12]:

- Need for improved configuration management.
- NERC requirements.
- New generation of DFRs.

- Considerations to include digital protective relay (DPRs).
- Data analysis that enables interactions with users.
- Improved data management tools.

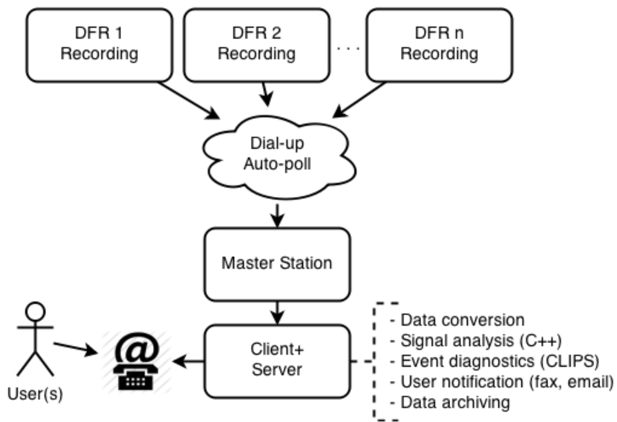

Fig. 4. Centralized system solution using dial-up (~30 DFRs)

D. Second generation

The latest generation of the solution has been completely migrated into platform-independent environment. It is implemented using Java and open source technologies [13-15]. The development and deployment of the second generation solution was iterative and an incremental process [16]. The solution setup is illustrated in Fig. 5.

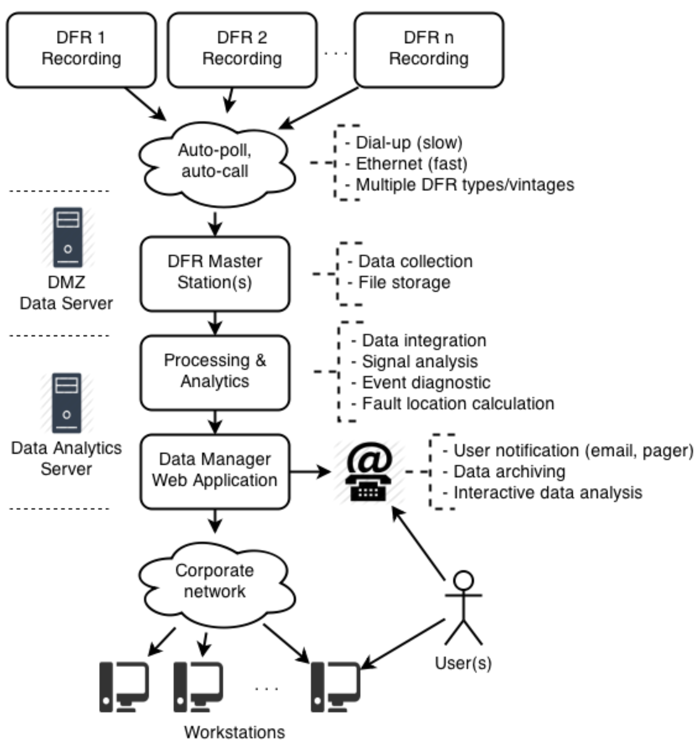

Fig. 5. Full-blown centralized system solution (~ 100 IEDs)

The latest setup was installed and commissioned in 2013 by Xpert Power Associates [17]. It is configured to support various types and vintages of DFRs (~80) and distance DPRs (~12). The configuration includes settings for replaced DFRs (~20) so that historical data can be analyzed as well. The latest generation allows for mixture of IED types and vintages and it is open for interfacing with new IEDs and third-party systems [9].

Additional improvements to the solution included:

1) Interactive fault location calculation

The automatic fault location capability of fault analysis system is only as accurate as the input information for the algorithm [18]. The capability of the system to perform accurate automated fault location assessments can be severely limited when:

- The analog input measurement channels (Line currents and voltages) are not accurately configured in the system. This can be, for example, the result of system reconfigurations or topology changes.
- Line positive and zero sequence impedance parameters and line mileage, also crucial for accuracy, are susceptible to ongoing alterations as a result of power system changes.

The option to manually adjust these parameters when viewing the automatic fault calculation within the solution's report viewer module was crucial to the speed of delivery and accuracy of fault location results during times of power system configuration changes [19]. Optimally all changes to power system design are updated within the solution's configuration tool (separate module), which serves as a repository for the configurations data and source that information to the fault location algorithm. However, multiple stage projects and busy project schedules are a few examples of forces acting against the need to timely update the configuration of the fault analysis system.

As a secondary benefit of the "on-the-fly" manual configuration capability, single ended fault locations can be improved upon depending on circumstances surrounding the topology of the system. A single ended fault location is inherently incapable of accounting for the apparent impedance changes created when the bus at the remote end of a line has three or more sources connected. However, under the conditions that it has only two sources (i.e. the line from the substation with a fault data measurement and another line that could potentially have a fault) the adept user of the system can leverage that information. By knowing the system topology and knowing there is not a source of in-feed at the remote substation, the single end fault location can be extended beyond the end of the line and still calculate an accurate fault location, to the extent inherent in-accuracies will allow.

The manual control options are not limited to just configuration parameters. Furthermore, the user of the system is allowed to select the portion of an event waveform, by way of directing a cursor-line, the fault location algorithm is utilizing for its calculation. This benefits the user, particularly when fault events produce measured quantities that may not represent a textbook example. A related development came when the cursor-line was developed into the form of a line with a displayed range of 1 power system cycle centered at the cursor-line. The range indicates the data-window being used to calculate RMS value that is presented to the user within the GUI.

2) Data management tools within the GUI

Technical issues in data recovery and accuracy are an ever-present reality for power system engineers. The GUI within fault analysis system has been updated with tools that provide quick data checks and improve the ability of users to filter and sift the data, enhancing the process of drilling down to the required data-set.

The “event preview window” was born from a desire to see relevant information from an event data-set without having to fully load all of the data-points. The window provides a preview of waveforms and digital status points. The information is selected by the GUI algorithm to be data that has the characteristics of a fault event and will leave out data that does not meet the profile. This step then saving the computing time of displaying the information in total and necessitating a user define the narrowing in of informational focus.

The data files, received by the fault analysis system, contain GPS clock accuracy time data that synchronizes the sequence of the event data. The time relative order of the events is then useful in finding the particular file of interest. Challenges with the accuracy of time-stamp information contained within the data files (unreliable GPS clock synchronized Disturbance Monitoring Equipment) resulted in a method of time-stamping the data upon arrival and processing by the automated fault analysis solution.

IV. Encounters and Testimonials

A. Events during hurricane Rita

Early morning of September 24, 2005, even as Hurricane Rita was still passing through the east side of the CNP service area, engineering personnel were at the CNP Energy Control and Data Center (ECDC) and also at their homes assisting system dispatchers is assessing the damage to the power system, almost exclusively from the reports produced by the automated fault analysis system. This level of support would not have been possible without the availability of the automated analysis software package and the access to the output via CNP’s corporate network. This also speaks well of the integrity of CNP’s network infrastructure, that even though a strong hurricane passed over part of its service area, data was still able to be collected, processed, and analyzed from far opposing ends of the service territory. Data was being collected at a facility in the southern portion of the CNP service area, it was then transferred to the data analytics server processing the data which was located near the center of the CNP service area, and results were being viewed at the ECDC and by VPN by an engineer at home in the northern portion of the CNP service area with the wind still blowing and power out (battery powered laptop) [20].

B. Events in March 2006

On March 28, 2006 a major event occurred in the 138 kV electrical system of a large industrial plant which is connected directly to the CNP transmission network. A total of 11 records were captured by 3 different DFRs. The event involved multiple contingencies and delayed fault clearing. The automated analysis provided a quick snapshot overview of the pertinent information from each of the 11 records and greatly reduced the time necessary to assess which records were most important to creating a summary sequence of events. In addition, the automated analysis output provided an assessment of the performance of the protection system components connected to transmission lines of interest, which contributed to the overall detailed event analysis [20]. Systems for automated fault data retrieval and analytics have critical role in reducing the time needed to process increasingly overwhelming amounts of data captured by various IEDs during power system events.

C. Events during hurricane Ike

Hurricane Ike, September 2008, made landfall as a Category 2 with 110 mph winds and carried a 550-mile wide wind field (Fig. 6). Over 90% of the more than two million customers lost power and it took 18 days to complete restoration. In CNP’s emergency operations plan all employees take on critical emergency response roles and postpone non-essential business tasks. This means there are fewer people available to analyze fault and disturbance data. CNP experienced 99 transmission circuit lockouts. Every transmission circuit that locked out was patrolled, debris removed and repairs made as needed. When it came time to attempt to re-energize each transmission circuit it was important to have timely information regarding faulted phase, distance to fault and circuit breaker & protective relay performance if the transmission circuit faulted again. The automated DFR data retrieval and analysis of transmission line faults played an important role in the restoration process.

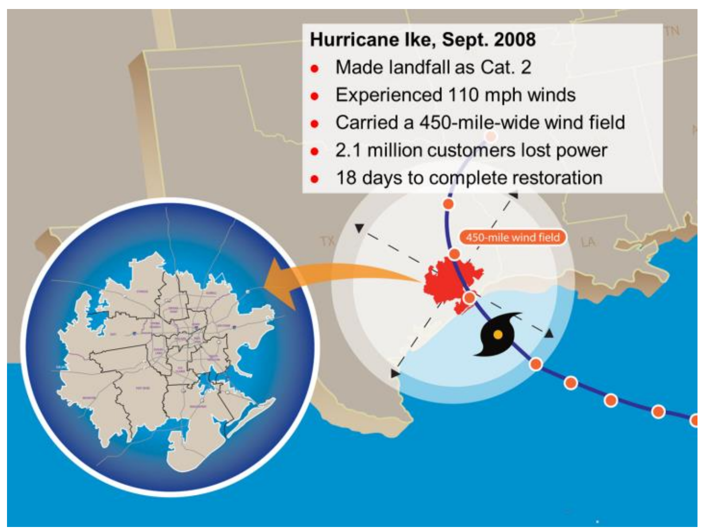

Fig. 6. Hurricane Ike September 13, 2008

D. Dry weather in 2011

In late 2010 and early 2011 CNP experienced a period of very dry weather. The dry weather resulted in an excessive buildup of contaminates on electrical insulators and equipment. Electrical flashovers began occurring at an unprecedented rate in April, May and June until rainfall (see Fig. 7).

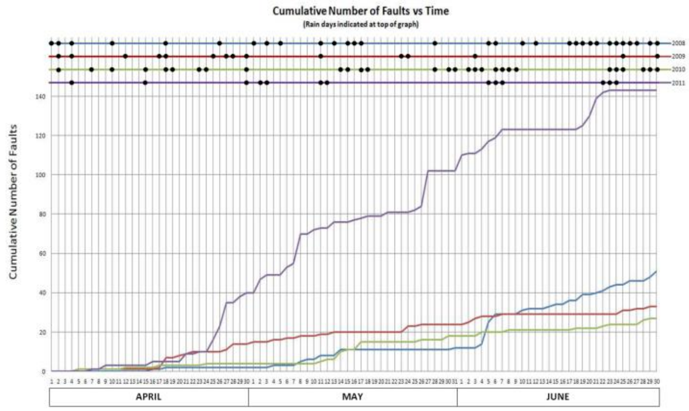

Fig. 7. Dry weather flashovers in 2011

In a three month period CNP experienced more than three times the number of transmission system faults than would typically occur in the same period in a normal year. Several methods for mitigating the faults due to contamination were used (i.e. aerial "line live" high pressure water washing, substation "dead bus" low pressure water washing, etc.). However, to make the most efficient use of these resources precise fault locations were needed in a timely fashion in order to confirm the problem area and direct crews to the appropriate locations. Most of the faults would occur in the very early hours of the day (midnight to midmorning) when air temperature and humidity conditions were most conducive to contamination flashover. Again, the automated DFR data retrieval and analysis of transmission line faults played an important role in the process to deal with this unusual situation.

V. Conclusions

The paper provides a historical overview of deployment of the system for automated analysis of transmission line faults. The paper covers a time period of over 20 years and provides insight into the evolution of the solution. The time line is illustrated with lessons learned and changes in the requirements that unfolded over time.

The latest generation of the solution, presently installed at CNP, is configured for automated retrieval and analysis for over 100 IEDs, mainly DFRs. The solution has been expanded with some custom features that enable users to perform "on the fly" configuration settings changes, interactive fault location calculation, and updating of fault event details.

The paper illustrates importance of the tools for automated IED data collection and fault analysis with their role during some major events such as hurricanes Rita and Ike, as well as the events during the dry weather in 2011. The system for automated data fault data analysis plays important role in event diagnostics and power restoration process.

The directions for further improvements include speeding up the data communication, automating retrieval and inclusion of digital protective relay data, grouping and tagging event data that correspond to same event, addition of redundancy checks, and making user interface even more flexible.

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