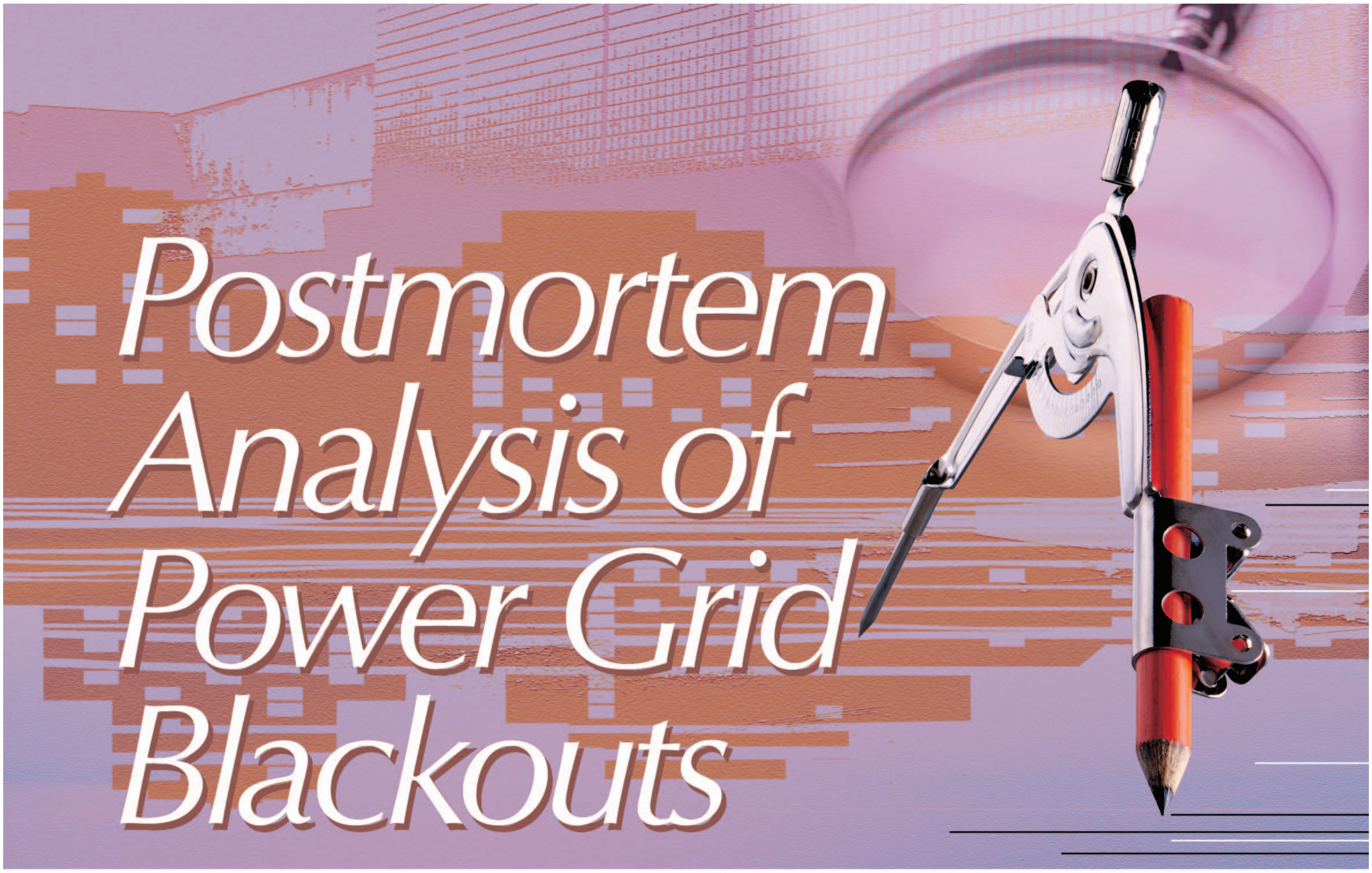

Postmortem Analysis of Power Grid Blackouts

PROMPTLY FOLLOWING ANY BLACKOUT, AN INVESTIGATION IS CONDUCTED to determine the who, what, where, when, why, and how. For system operators, it is important to quickly grasp the scale and magnitude of the event and rapidly restore service. Then, a broader set of stakeholders gets involved to assess system performance, determine root causes, compile lessons learned, and develop recommendations. At the heart of the postmortem investigation is the detailed sequence of events. As accurately as possible, investigators need to know what happened and when. Especially during a cascading failure where events occur rapidly, accurate timing is crucial to understanding how the event unfolded so that the root causes can be determined. The sequence of events is based on vast amounts of data collected from multiple points in the system from myriad data collection instruments, some devoted to the purpose of supporting system disturbance postmortem analysis, others providing useful additional context or filling in missing gaps. The more that the investigators know about their available sources of data, and the inherent limitations of each, the better (and quicker) will be the analysis. This is especially important when a large blackout has occurred; there is pressure to find answers quickly, but because of the size and complexity of the event, a deliberate and methodical investigation is necessary. This article discusses the role that system monitoring plays in supporting the investigation of large-scale system disruptions and blackouts.

The North American interconnected power system has been called the largest and most complex machine ever devised by man. This machine must be continuously engineered and managed over multiple timescales. Examples of these timescales include: continuous closed-loop feedback control; protective relays calculating whether or not a fault has occurred every few milliseconds; an operator contemplating which capacitor banks are needed to support voltage over the next few hours; decisions regarding which plants should be brought online to meet today's peak demand; scheduling power plant maintenance outages; deciding when and where to build additional generation, transmission, or

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The Role of Measurement Systems

distribution; engineering settings and design requirements for these assets; and determining what investments are needed to research future technologies. And the stakes are high: consequences include well-known and highly visible concepts such as stranded assets and blackouts. Our modern civilization and economy has become inexorably intertwined with a reliable and efficient power system.

Fortunately (thanks to the investment of money and effort) the reliability of this "machine" is quite good. The system is designed to tolerate a failure in any critical component at any time without causing disruption to the system (the so-called N-1 criterion). And if multiple events occur that overwhelm this design requirement, backup and emergency controls are installed to mitigate the consequences to the smallest extent possible. Multiple layers of controls for in-depth defense are the hallmark of modern power engineering design. However, on rare occasions, events do conspire to create widespread blackouts. A prime example of this occurred on 14 August 2003 when the eastern North American interconnected power grid suffered its largest blackout in history. Other major blackouts are shown in Table 1.

Fundamentally, managing this complex machine requires good information; a necessary but insufficient ingredient of good information is good data. Also important are the decision processes supporting power system planning and operations, as shown in Figure 1. As it relates to supporting a large-scale blackout investigation, good data are of paramount importance. A good investigation process will first establish the facts. Then the investigators will follow these facts to find the root causes, lessons learned, and recommendations. It is important to avoid the temptation to formulate early theories and conduct analysis to support these theories; doing so may lead the investigation to a different conclusion than if a more thorough

Table 1. Major North American blackouts.

Date	Location	Load Interrupted
9 November 1965	Northeast	20,000 MW
13 July 1977	New York	6,000 MW
22 December 1982	West Coast	12,350 MW
17 January 1994	California	7,500 MW
14 December 1994	Wyoming, Idaho	9,336 MW
2 July 1996	Wyoming, Idaho	11,743 MW
10 August 1996	Western Interconnection	30,489 MW
25 June 1998	Midwest	950 MW
14 August 2003	Northeast	61,800 MW

and deliberate process had been followed. This is called *cognitive lock*. It occurs when an early theory seems to be supported by the details, and as more information becomes available, the tendency is to either use it as supporting evidence or discount its veracity if it doesn't match the working theory. A good investigation team will avoid this temptation, avoid jumping to conclusions, and follow a deliberate process that is driven by facts.

The early emphasis on pinpointing the cause of a large-scale system disturbance requires the reconstruction of a detailed and accurate sequence of events. A variety of sources is needed to compile the sequence of events, such as logs from supervisory control and data acquisition (SCADA) and energy management systems (EMS), digital fault recorders, digital protective relays, and synchronized phasor measurement units. The remainder of the article describes these measurement technologies in the context of supporting postmortem investigations of large-scale system disturbances and blackouts.

Supervisory Control and Data Acquisition

Throughout the early development of the interconnected power grid, obtaining data about the condition of the grid and being able to remotely control it pushed the limits of contemporary communication and computing technology. As SCADA systems evolved, operators were empowered with more information and the ability to better manage the power grid. And as communications technology and computers have become more capable, these systems have also increased in complexity and capability. Specialized protocols were developed to more efficiently communicate telemetry and control signals. The number of remote sites increased while polling times were reduced. In addition to presenting information to the operators, SCADA data is used to support a wide variety of automated control functions, such as automatic generation control or online contingency analysis. And the reliability and availability of the system continues to be very high. However, these SCADA systems have fundamental limitations. The data collection rates are relatively slow, typically 2–4 s between data points.

Circuit-breaker events (associated with transmission lines or generating units) are logged in SCADA and EMS alarm logs. But there are a variety of errors in the timing of these records, generally because the event is time-tagged when the event is logged by the computer, not when it occurs in the field. Various time errors associated with the inherent limitations of a SCADA system, including communication latency, time skew, and data buffering issues, can create significant (and variable) differences between the time of the actual event and the time of the record in the alarm log. Also, these records should be synchronized to an accurate national time standard.

Digital Fault Recorders and Protective Relays

Intelligent electronic devices (IEDs), such as digital fault recorders and microprocessor-based protective relays, provide another valuable source of data for establishing an accurate and detailed sequence of events, particularly during the cascading phase of the blackout when events are occurring rapidly.

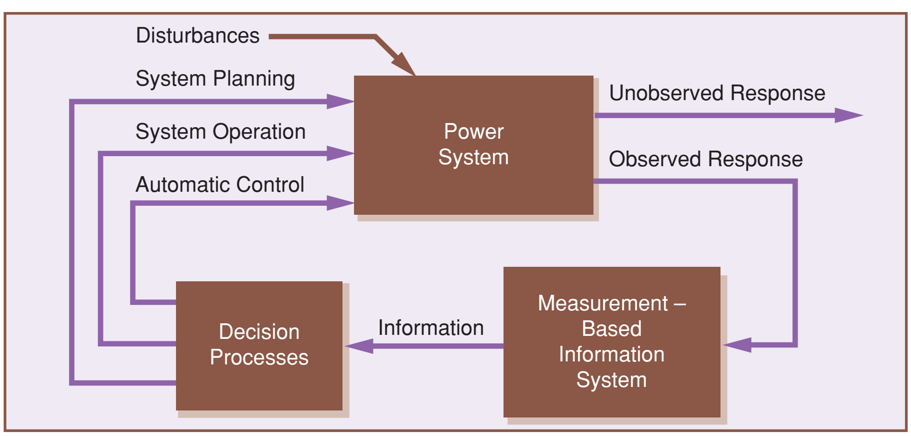

figure 1. The accuracy and completeness of measurement-based information systems are critical for managing electric power systems. (Courtesy of Dr. John F. Hauer, Pacific Northwest National Laboratory.)

Digital fault recorders and protective relays are high-speed instruments installed in substations that are designed to measure faults and, in the case of protective relays, act on that information to trip circuit breakers to protect assets from becoming damaged. By capturing the waveform of a fault, detailed information regarding the nature and location of the fault can be calculated, and the proper response of the protective relays and circuit breakers can be confirmed. These devices gather high-speed data

The more that the investigators know about their available sources of data, and the inherent limitations of each, the better (and quicker) will be the analysis.

and are (usually) synchronized to an accurate time standard. When a large-scale system disturbance occurs, they are an invaluable source of data that is used to support the investigation process, particularly in establishing the timing of events or confirming the cause of the relay action and breaker trip.

The Common Format for Transient Data Exchange (COMTRADE), IEEE Standard C37.111, is a widely used example of a digital data format for oscillography. Most classes of IEDs that capture high-speed data can export their data in the COMTRADE format. However, the investigation team's access to this data can often be cumbersome. Therefore, it is preferable to proactively consider issues such as nondisclosure agreements, information sharing agreements and protocols, and remote data access, handling, and dissemination so that delays during the investigation process can be minimized.

Wide-Area Measurement Systems

Wide-area measurement systems (WAMSs) provide a big-picture overview of the grid by collecting widely dispersed high-quality data. Leveraging ubiquitous and accurate time synchronization provided by the global positioning system (GPS) and advances in networked computing, WAMS has evolved over the past two decades to provide the following functions:

- ✔ real-time observation of system performance
- ✔ early detection of system problems
- ✔ real-time determination of transmission capacities
- ✔ analysis of system behavior, especially major disturbances
- ✔ special tests and measurements, for purposes such as
  - special investigation of system dynamic performance
  - validation and refinement of planning models
  - commissioning or recertification of major control systems
  - calibration and refinement of measurement facilities
- ✔ refinement of planning, operation, and control processes essential to the best use of transmission assets.

Information collected from WAMS is often used to support postmortem investigations of large-scale blackouts (see Figure 2). The disturbance monitoring function is characterized by large signals and relatively short event records. In addition, precursors to the actual disturbance are often only found in WAMS data, which uniquely also provide long records containing high-bandwidth small signals. With complex processing (such as correlation analysis of multiple records) and direct motioning of phase voltages and currents, early warnings of emerging trouble can be found.

A continuing challenge to the integrated processing of WAMS information is ensuring that measurements from the various data sources are consistent. For example, different sampling rates are used by various instruments. Dissimilar filtering is also a source of inconsistent analog signals, which may require special compensation. While these instruments provide excellent opportunities for enhanced insights into system operations, they are emerging technologies that are still adapting to a wide range of situations. Issues such as dynamic response and consistency need continued attention. Sometimes these issues are not revealed until after the data are recorded, which requires extensive effort to repair the data. According to Dr. John F. Hauer, Pacific Northwest National Laboratory, "Cheap data can become very expensive if substantial engineering time is needed to repair its deficiencies."

WAMS began its deployment in the Western Interconnection of the North American grid to measure wide-area dynamic performance. Over the past several years, the U.S. Department of Energy has been supporting and facilitating the Eastern Interconnection Phasor Demonstration Project (EIPP) to investigate applications of this technology to support advanced decision support tools. Additionally, a growing community of researchers and utility experts are working on practical applications and installations of this technology around the globe. An increasing number of transmission system operators worldwide are evaluating the benefits of this technology and implementing demonstration projects. CIGRÉ (the International Council on Large Electric Systems) has recently commissioned a task force under Work Group C4.6.01 on Power System Security Assessment to develop a document titled "Wide-Area Monitoring and Control for Transmission Capability Enhancement," which summarizes WAMS installations internationally.

Lessons Learned and Recommendations

Challenges associated with developing the sequence of events following large-scale blackouts reveal numerous

> Comprehensive monitoring capabilities can facilitate and expedite the postmortem engineering analysis following a blackout.

lessons learned for improving the process of disturbance reporting. Included are the better calibration of recording instruments (especially establishing time synchronization), standardized formats, and instructions for determining what data should automatically be provided immediately following the disturbance so that the necessary pieces of the puzzle can quickly be assembled. Waiting for formal data requests tends to slow down the process. Also, necessary logistical details, such as confidentiality agreements, should be executed proactively to the extent practicable.

Another valuable lesson learned is establishing a framework for the infrastructure necessary to support the blackout investigation, such as designing a data warehouse that can be used to support the investigation team. The servers and databases to store and index the investigation data, with specific

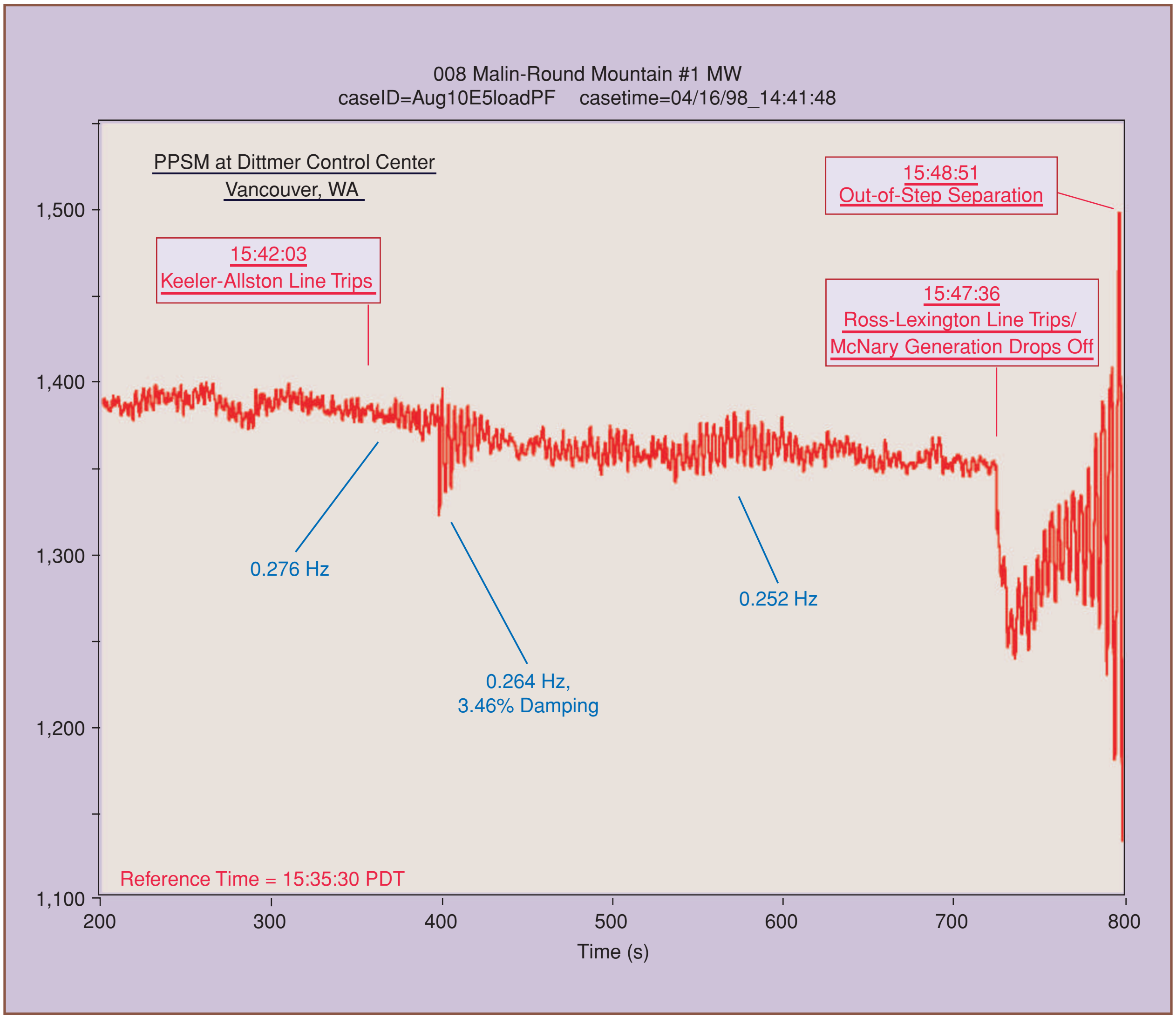

figure 2. WAMS data gathered during the 10 August 1996 blackout. (Courtesy of Hauer and Dagle, 1999; Data courtesy of Bonneville Power Administration.)

> A good investigation will follow a deliberate process that is driven by facts.

formats for various categories of data, could be prestaged before the event, which would greatly expedite the investigation process. With such an infrastructure in place (specific predefined formats for information submittals and a mechanism for accepting and logging information received), the workload and time involved in managing the data requests, submissions, and dissemination to the various teams involved in the investigation would be greatly reduced.

Automated disturbance reporting, where information is quickly gathered and collated, could also greatly facilitate analyzing large-scale disturbances that involve multiple organizations. This information could be routinely collected (for later analysis) for both transmission and generation events. Then, all of the mechanics of data formats, exchange protocols, confidentiality issues, etc., can be worked out and tested on an ongoing basis. Ultimately, with such a system, the blackout data can be collected in a matter of hours rather than a matter of weeks (or months).

It is often found after the fact that buried within the measurements at hand were clues that system behavior was abnormal and that the system itself was becoming more vulnerable. Less direct indications of a weakened system are sometimes observed by system operators, but without methods for interpreting these indicators and procedures for acting upon them, these indicators are seldom acted upon in a timely and effective manner.

Additional emphasis is needed to develop and install an advanced information network for measuring and monitoring system performance. Research and development is needed for advanced, production-grade mathematical tools for extracting useful information from system measurements that can be acted upon in a timely and effective manner. Core technology areas include centralized phasor measurements, mathematical system theory, advanced signal analysis, and secure distributed information processing. With direct examination and assessment of power system performance, systematic validation and refinement of computer models, and increased sharing of useful and actionable information, the potential for future catastrophic widespread blackouts is minimized. Additionally, comprehensive monitoring capabilities can facilitate system restoration and recovery and expedite the postmortem engineering analysis following such an event.

Nobody knows when the next big blackout will occur, but there is some certainty that it will occur. It is the duty of all who are associated with the operation and planning of the power system to be prepared so that the consequences of the blackout can be minimized. Continued vigilance is the price of a reliable and secure electric power grid.

Acknowledgments

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For Further Reading

J.E. Dagle, "Data management issues associated with the August 14, 2003 Blackout," in *Proc. Power Syst. Dynamic Performance Committee Panel Session, IEEE Power Engineering Society General Meeting*, Denver, CO, vol. 2, 2004, pp. 1680–1864.

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Biography

Jeffery E. Dagle received B.S. and M.S. degrees in electrical engineering from Washington State University in 1989 and 1994, respectively, and since 1989 has been supporting electric power reliability and security programs at the Pacific Northwest National Laboratory, operated by Battelle for the U.S. Department of Energy. He is a Senior Member of the IEEE and a licensed professional engineer in the State of Washington, and he was named 2001 Tri-City Engineer of the Year by the Washington Society of Professional Engineers. He supported the 14 August 2003 blackout investigation, leading the data requests and management team for the electric working group at NERC.