Information, not data

Real-time automated distribution event detection and notification for grid control

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Knowledge is power, or so an old dictum teaches us. Certainly, to be able to direct or control any system, accurate and up-to-date knowledge of its current status is invaluable. The plenitude of data that is necessary to control a complex system is well illustrated by the vast quantity of measurements that are available in the control room of an electric grid.

But how does one improve such a control system in view of rising demands and expectations? Common wisdom would suggest that this requires even more data, ie, more measurement devices collecting more measurements (including distribution feeders and the “last mile” to the customer) and transmitting them to the control room. Much of the effort that is being put into preparing the smart grid that will assure the power supply of tomorrow is consequently focused on such smart measurement devices.

This, however, is only part of the story. Without a proper strategy for handling and evaluating such input, this approach will lead to a “data tsunami”: The control room will be inundated with measurements, making it difficult to distinguish the relevant from the irrelevant. The answer lies in pursuing information, not data. Quality information involves delivering the right facts to the right place at the right time. Only by achieving this can knowledge truly assure and secure the flow of reliable power.

The protection, control, and monitoring of power systems involve making numerous decisions. These occur over a broad period and on time scales ranging from the split-second decision to trip a line or feeder for protection reasons, to issuing an alert after months of monitoring an incipient failure. System operators are often the ultimate human decision makers who still benefit from some form of information from multiple sources across a utility system. Their involvement in direct decision making decreases in situations where there is an advanced penetration of automation technologies, as occurs in substation automation systems. The industry-wide move toward smart grids is demanding more automation down to the last mile and involving distribution feeders and end customers. The ultimate goal is to enable power system protection, control, and monitoring to operate in a closed-loop mode, so becoming an enabler for a self-healing grid: a frequently sought attribute of a smart grid. This article looks at an enabling technology to help achieve such an ambitious goal. It looks at the provision of real-time and automated response to distribution feeder events and anomalies.

The grid of the future

Smart grids require three fundamental elements: data, information/intelligence, and communications. The data element is supplied by sensors and sensor systems including intelligent electronic devices (IEDs) in feeders and switch controllers. The intelligence element is provided by digital processors that are instructed to perform certain operations on data through algorithms. Finally, the communications element is required to deliver the derived intelligence to the right person/device, in the right format, and at the right time. These three elements are indeed the building blocks of current control and automation systems. They do, however, require a dramatic boost in functionality, performance, and coverage (down to the last mile and including end customers). More importantly, they require an infusion of intelligence into every system and device, ranging from a local human-machine interface to a broadband IP or fiber-optic network [1].

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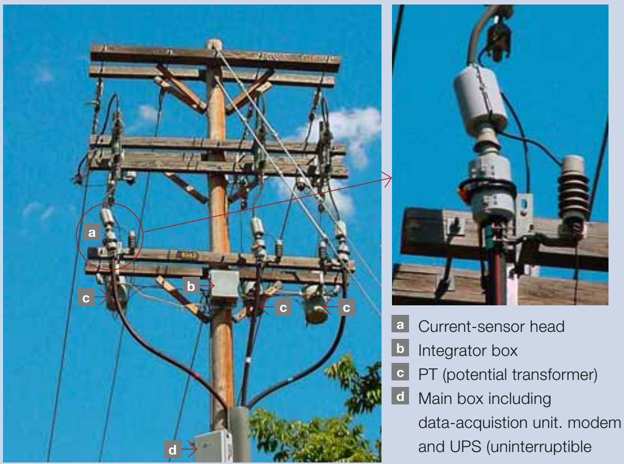
Automation technologies and the proliferation of IEDs across the transmission and distribution systems pave the way for the availability of more data and hence the improvement of the decision making process. However, the lack of application tools and automated data analyzers (ie, intelligence algorithms) hinders the effective use of data.

The promise of a smart grid cannot be fulfilled purely by continuing the digitization of the power system or expanding the communications infrastructure. At the core of any intelligent system there must be a "brain" for the processing of the data it receives. Additional sensing and measurement points alone do not address this problem but rather contribute to the overflow of data. What is needed is an extraction of the information that is embedded in the raw measurements. The decisions based on this information do not have to be made exclusively in a central location or by human agents. However, for decisions to be made, quality information needs to be collected across the system. This means that as many tasks as possible need to be automated to free up human resources to perform the tasks that cannot and should not be automated. Overloading human operators with unnecessary data can lead to the most relevant information being lost and result in suboptimal decision making.

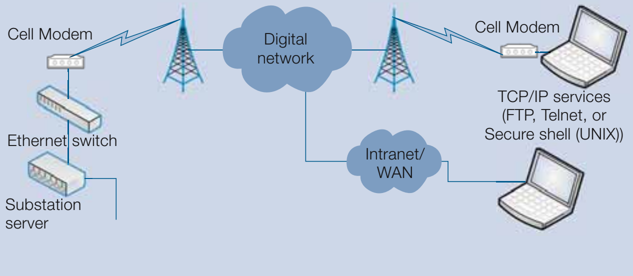
The move toward smart grids will nevertheless mean more sensors and measurement points to bring visibility to every component and down to the last mile [2]. As a result, more and more data must be collected and processed. The utility environment of today is overflowing with the mass of data already being harvested by existing systems. If the addition of new data points [3] is not to lead to a "data tsunami," the data-to-information conversion process must be optimized at every step of its path. This means that a conversion that can be performed at a lower level should not have to be performed at a higher level. The last thing that system operators want is additional data requiring avoidable manual processing.

1 Sensors and communications must be extended into the feeder lines for information on the system status to be made accessible.



a Current-sensor head
b Integrator box
c PT (potential transformer)
d Main box including data-acquistion unit. modem and UPS (uninterruptible power supply)

2 Communications infrastructure is an enabler for smart control.



Focusing on distribution operations, there is a substantial need for simpler and better optimized operations and maintenance, which should be based on data received from various IEDs installed throughout the grid. It is also desirable to be able to automate the analysis tasks and transform raw data into actionable information, upon the basis of which utility dispatchers and crews can make decisions. Conventionally, the records from these IEDs are often analyzed manually by trained experts on limited occasions. The overwhelming nature of the manual analysis of data and the issues of an aging workforce connected to today's utility environment highlight the importance of being able to perform these tasks via computer with little or no human intervention. More importantly, providing this information in real time creates an enormous added value for the utilities by improving reliability and reducing the duration of customer outages.

Levels of intelligence

Smart grids demand solutions and analysis tools to enable electric utilities to receive the right information and distribute it to the right people at the right time. As the utilities face shrinking budgets and reduced workforces, the integration of automatic event analysis into utility systems becomes imperative.

The overall theme of these changes is "data transformation into actionable information.. With reference to 4, this process can be executed in multiple levels across a utility system.

- Level 0 is at the feeder level, which includes "box" intelligence only. The transformation is typically done by embedding the intelligence into feeder IEDs such as switch controllers and stand-alone monitors.
- Level 1 is at the substation-box level. It includes applications/algorithms applicable to each individual substation IED.
- Level 2 is at the substation-system level, it includes applications/algorithms for extracting information from multiple IEDs via a substation computer or a master workstation.
- Level 3 is at the enterprise level. It includes the data warehouse/historian along with the control room applications/algorithms applicable at the aggregate utility level.

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Of course, one could add a level 4 in which data/information from multiple utilities are aggregated and processed for greater intelligence and applications on a regional or national level.

As the flow of data/information moves away from field devices and to the right in 4, the ratio of raw data to information is reduced. In other words, more and more information is made available by utilizing embedded intelligence at every step to avoid data proliferation in the next upper level.

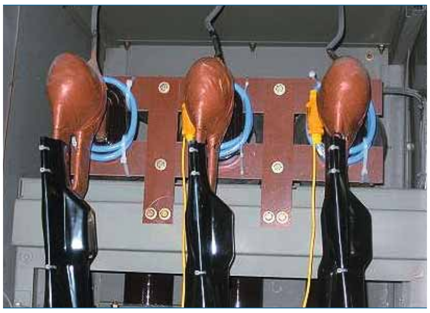
Distribution issues

Due to the historical lag in the adoption of automation technologies, the need for automation and embedded intelligence is more pronounced in distribution operations than anywhere else on the electric grid. Distribution utilities are more than ever expected to do more with less, and system automation is a practical way of achieving this. Existing architecture and systems provide a great quantity of data from a subset of key components through protective relays and IEDs. The movement toward traditional substation and feeder automation by utilities has resulted in large volumes of data, but the corresponding information capability has not received due attention. Specifically, analytical data, eg, digital fault records, target records, trends, load profile, power quality, sequence of events and event data, eg, lateral faults, equipment failures, have not received the necessary focus, especially because substation automation was considered the domain of protection engineers. Moreover, the majority of events on feeder laterals is not reported to operations groups, as the current protection and monitoring practices are limited to events on the main line. In many cases, utilities must rely on customer calls to identify and locate trouble areas down the feeder main and its laterals. Practical tools are needed to analyze feeder event data from these areas. Some utilities have migrated from traditional substation automation to a more integrated collection of operational, equipment-failure, and event data. With this additional data comes the need for specialized analysis tools for automation to enable smart grids.

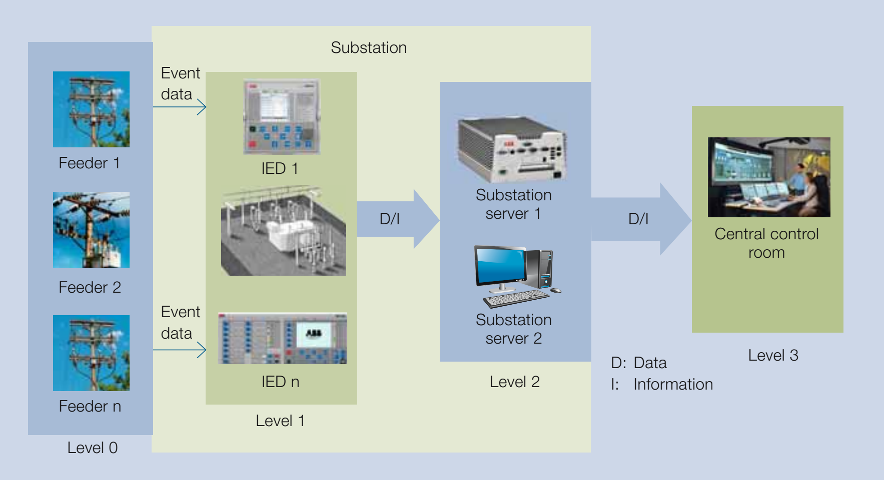
ABB's solutions

Distribution feeders, whether overhead or underground, experience faults, in-

3 Retrofit Rogowski-coil sensors



4 The four levels of intelligence in data handling



cipient failures, temporary events and transients. Objective analysis and correlation of these various types of events - some of them catastrophic - enable utilities to proactively address feeder events rather than merely being able to react to them. The logical initial step to achieve this is to enhance the IEDs and substation server to include the most valuable event analysis applications. The solution offered is therefore to address the need for transforming event data into actionable information upon which system operators and dispatch crews can act proactively.

Areas that can benefit significantly from feeder-level real-time intelligence include outage detection, confirmation, notification, and crew dispatch.

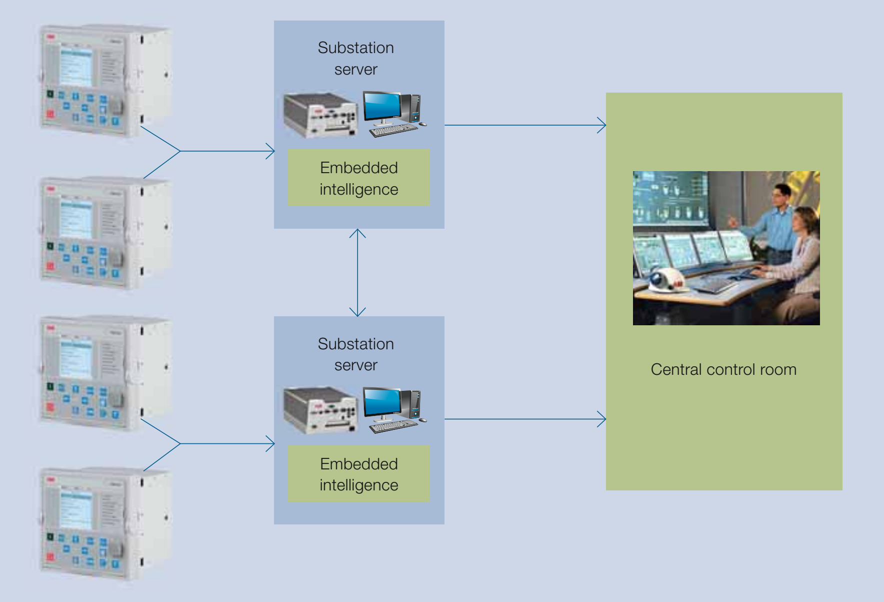
The ability to proactively address feeder problems and respond as quickly as possible to outages and feeder failures, along with the tendency toward predictive maintenance, will be a significant contributor to the adoption of smart grids. Today, maintenance schedules for assets are performed on a pre-programmed basis and do not take into account specific intelligence on feeder events or health. Thanks to such additional analysis, the operations and maintenance departments of a smart grid will have the ability to respond more quickly, send the right crew, assess the risks and proactively address feeder problems. The planning departments in turn will achieve better information for feeder upgrades and enhancement projects.

It was shown in 4 how intelligent event detection and analysis algorithms may reside at different levels in the supervision and control hierarchy. The feeder IEDs can host algorithms that use local data to detect anomalies in the power system behavior and identify an abnormal situation (such as a fault). Based on their local analysis, they can take an appropriate action (such as tripping appropriate circuit breakers or switches) or forward the fault/event information to the next higher level of the hierarchy (which can be a substation computer) 5. This essentially minimizes the amount of data that must be sent up to the substation or DMS at the control center and has the additional positive impact of reducing the communications bandwidth required.

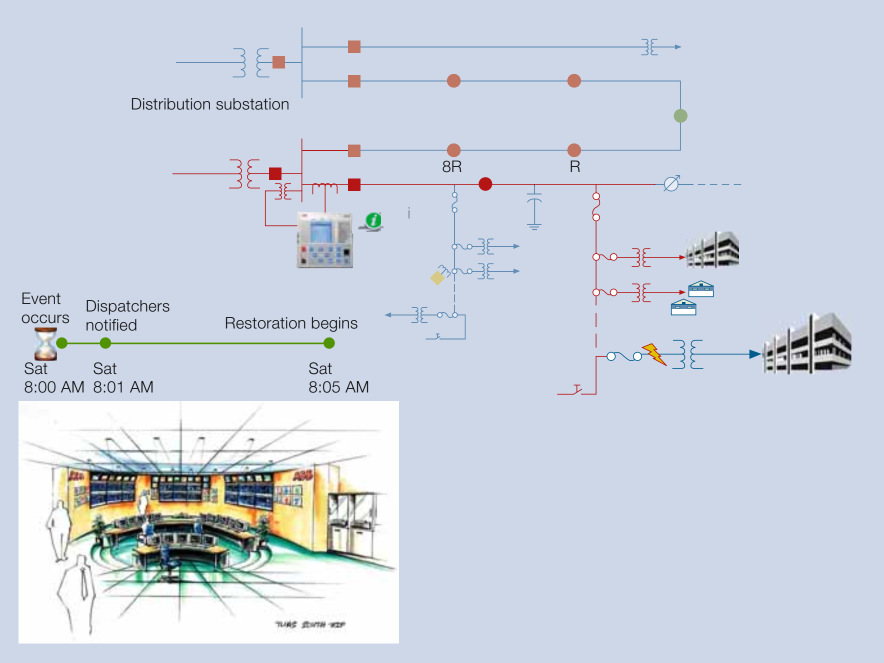
One way to achieve this is to host the fault/event detection functionality on the substation computer. The benefit is that it provides more visibility of system activity at the feeder level (information that is unavailable with conventional protection and control IEDs). This information can be utilized to take actions that address the issue at hand more precisely.

Along the same lines, the event-detection functions can be hosted at the DMS level. Each of these solutions comes with its own benefits and limitations. These need to be carefully evaluated by the user to achieve optimal net benefit from the chosen design. The solution selected can be tailored

5 Embedded intelligence can take actions locally or foreward the notification to the next higher level.



6 Reduction of outage duration through real-time event detection and notification



on the basis of complexity, scalability, cost, communications options and customer preference.

Benefits

Areas that can benefit significantly from feeder-level real-time intelligence include outage detection, confirmation, notification, and crew dispatch. Electrical faults and the resulting outages on distribution feeders result in loss of revenues and adversely affect customer satisfaction and reliability. Such events contribute significantly to customer-minutes-out and ultimately impact the utility's performance. For example, a certain class of feeder faults does not cause the substation breaker to operate and therefore does not generate a reportable SCADA (Supervisory Control and Data Acquisition) event. As a result, the utility has to rely on customer calls to notify it of sustained outages impacting the customer's premises. This type of reactive response can become a thing of the past if appropriate technologies are deployed 6.

The technology can help detect incipient faults that are on the verge of escalating into full-grown failures.

Real-time and automated event analysis/detection and notification reduce the time required to respond to an outage and provide an advance notification of a sustained outage before customer calls start overflowing the call centers. By enabling the utility to address the problem before an outage report is received, or by avoiding the outage altogether, this smart grid functionality has the potential to reduce customer-minutes-out that negatively affect both the utility's performance metrics and customer productivity. Furthermore, it improves the utility's preparedness for outage calls and provides an effective tool to confirm the reported nature of the incident. In particular, the technology applied to underground feeders notifies the utility of the cable faults that are cleared by the protection device – typically a fuse – along the feeder. More importantly, it can help detect incipient faults that are on the verge of escalating into full-blown failures, thereby optimizing the annual maintenance expenditures on cable replacements. This can be done using direct evidence of feeders with high activity of temporary underground faults.

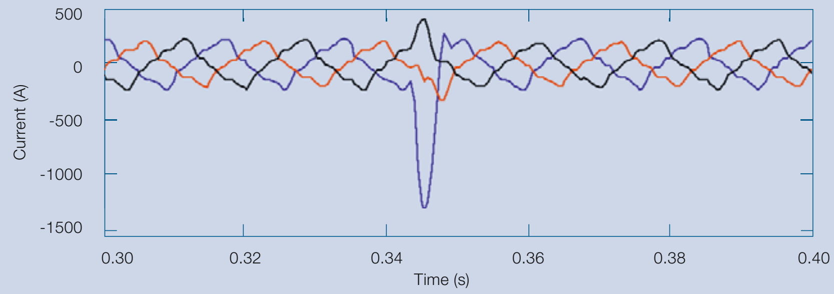
It is advantageous from the economic perspective to position this intelligence in the same location as the traditional intelligence, eg, in a substation or intelligent switch rather than placing it specially on feeder lines. Being able to learn of events to the "last mile" at the substation presents a very cost-effective moinitoring solution

Feeder event examples

A certain class of incipient faults in underground cables results from moisture/water intrusion and subsequent intermittent self-clearing arcing in splices [1]. The fault clears itself quickly due to vapor pressure, with the result that protection devices do not come into operation – hence the description of these events as self-clearing. Since underground cables very often form a major part of a utility's assets, monitoring and recognition of these failures is essential for the proactive management of faults and predictive maintenance. Continuous monitoring and automated data analysis with embedded intelligence is vital for achieving this smart grid functionality.

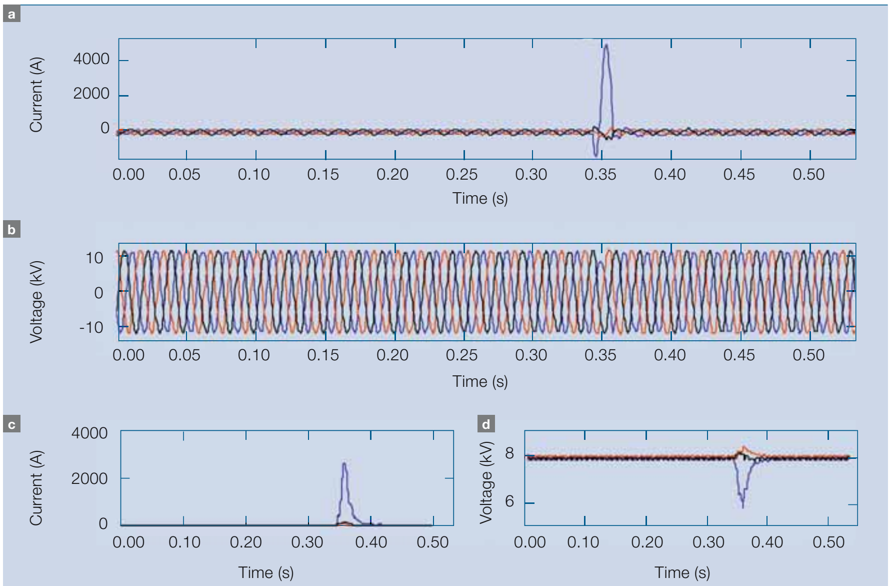
An example of an incipient failure that occurred in a utility feeder is shown in 7. The fault peaked at 1,287 A and

7 Example recording of an incipient failure. This was a self-clearing fault that did not result in any immediate outage.



Subsequent monitoring recorded 140 additional cases of similar incipient failures until the catastrophic failure nine months later that blew a 65A fuse 8.

8 View of the catastrophic failure following on from 7, showing three-phase currents a, voltages b, current-phasor analysis c and voltage-phasor analysis d.



lasted 0.22 cycles without causing any outage or fuse operation. Therefore, no corresponding record was registered in the outage management data. Subsequent monitoring recorded 140 additional cases of similar incipient failures until the catastrophic failure nine months later that blew a 65 A fuse. The current and voltage views for this final event can be observed in 8, showing a peak fault current of approximately 5,000 A. Between the first incident and the catastrophic failure, there were similar cases of incipient faults with current spikes varying between 1,000 A and 3,000 A in magnitude and with both positive and negative polarity. None of these events left a trace in the outage data nor led to any customer interruption.

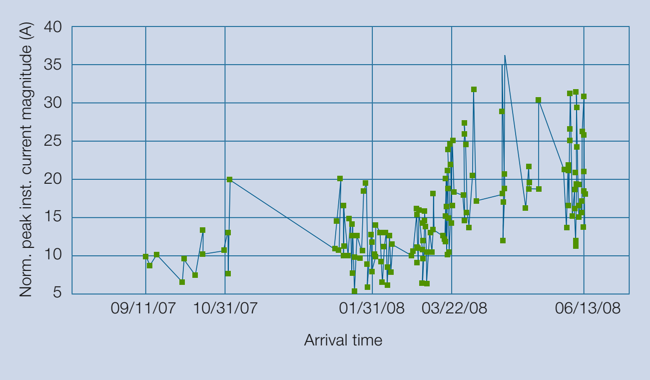
Subsequent trend analysis and quantization revealed a progressive development in normalized peak faults toward the eventual fault time 9. The normalized peak increased to almost three times its initial value by the end of the monitoring period. This observation indicates that the cable splice integrity was being degraded further with every instance of a reoccurring incipient fault and arcing.

This real-time feeder intelligence can raise the value of existing sensor installations and is easy to retrofit. It unleashes the potential of substation data that is already being recorded by digital protection systems but remains underutilized. In this way, it provides an "always-on" monitoring capability. Additionally, it also demonstrates that it is feasible to pick up the signature of, and predict a unique class of feeder faults that develop over time from a reoccurring incipient stage to a full-blown failure.

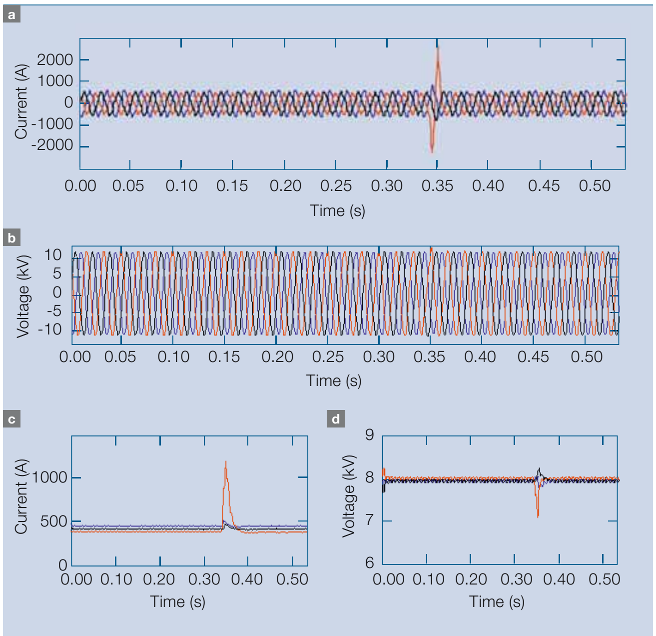
Similar analysis can be performed on other types of feeder events, most notably permanent underground cable failures.

An example of a cable failure on the primary feeder lateral that was cleared by a 40A fuse is shown in 10. It shows the current 10a and voltage 10b raw-data waveforms, as well as the phasor magnitude plots 10c 10d. The sub-cycle current spike can be seen in the current plots. Using embedded intelligence and automated analysis, this

9 Fault current trend leading up to the failure of 8

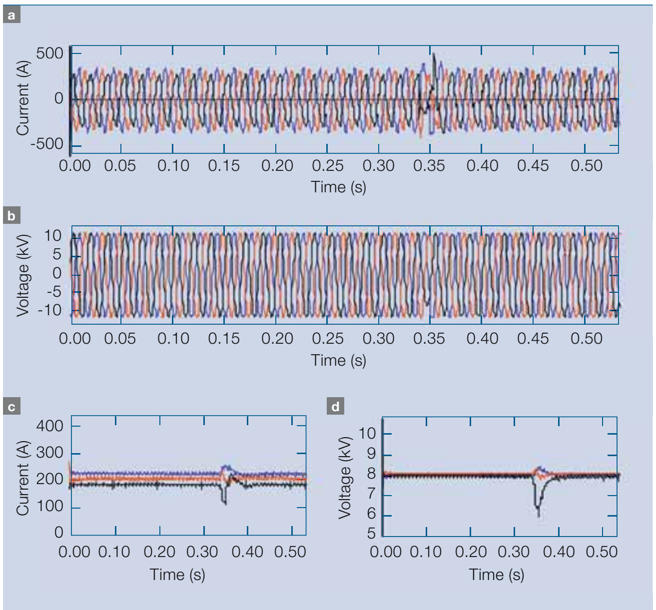


10 Waveforms a–b and phasor-magnitude c–d plots for an underground cable failure

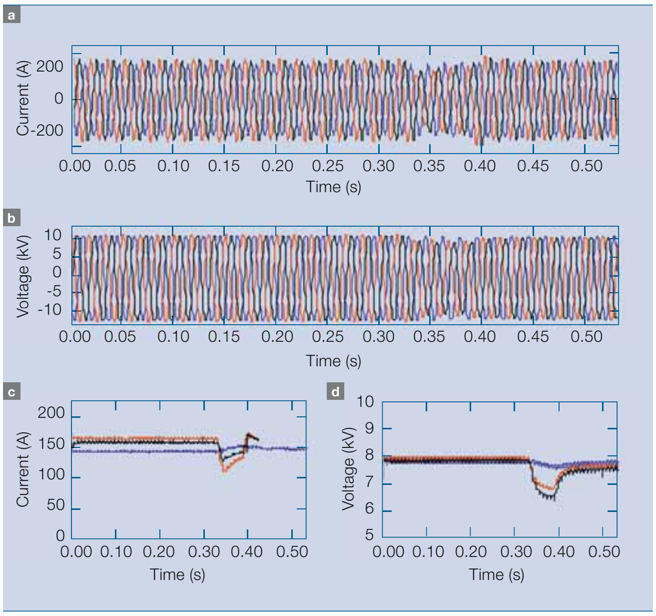


Transmission events propagate through the transmission grid and can impact the distribution grid as well.

11 Current a and voltage b waveforms and the corresponding current c and voltage d phasor-magnitude plots for an underground cable failure on an adjacent feeder



12 Current a and voltage b waveforms and the corresponding current c and voltage d phasor-magnitude plots for an upstream transmission fault



event was detected and confirmed with the utility data.

Furthermore, such processing can also detect a failure on the adjacent feeder. An example of an underground cable failure on a feeder adjacent to the monitored feeder is shown in 11. The plots show a voltage dip and its effect on the current waveform.

Finally, certain transmission and generation events can also be observed and analyzed at the distribution level. An example of an upstream fault on the transmission system is shown in 12. The plots show current and voltage dips on multiple phases.

The road to tomorrow's grid

The path toward achieving a smart grid is about modernizing the century-old electric grid to meet or exceed the needs of the digital society and promote customer participation. This is accomplished in part by providing or enhancing data acquisition, management, transport, interpretation, and automation systems across the board from end-customer premises to conventional and renewable power plants. The key area for this modernization is the distribution grid and the last mile, which are undergoing a radical change in relation to their original design and purpose. Means of communication are needed for enhanced protection, control, and automation with various levels of intelligence to process the utility data and act intelligently, confidently and timely.

Real-time and automated event detection in distribution grids, as well as near real-time notification, are prerequisites of the ultimate goal of moving to closed-loop mode in protection, control and monitoring. Such a vision of the future can be fulfilled by acquiring useful raw data and deploying flawless intelligence systems to deliver actionable information for appropriate control decisions via a reliable communication infrastructure. While numerous sensors deployed in the grid make more data available, it is crucial that the core information content be extracted in a timely and efficient manner to truly achieve the objectives of the grid of the 21st century. It is envisioned that integrating such functionalities into the operations of the distribution grid will effectively help make the grid more efficient, reliable, robust, and smarter than before.

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