Mapping the weakest link

New tools for visualizing the state of the power system

Mats Larsson, Reynaldo Nuqui, Linda-Maria Johansson, Stefan Bengtzing

Recent major blackouts have exposed the vulnerability of power transmission networks. Often such blackouts are caused or aggravated by the overloading of equipment. The resulting tripping shifts the overload to other lines. A rolling blackout can ensue with its negative consequences on the productivity of companies and the safety and comfort of people.

In most cases, the scope of the damage can be limited by operators taking the right decisions at the right time. This in turn requires information to be available in an easily accessible form.

ABB is bringing innovations to the control room. Graphical displays show the load on all lines and help identify the weakest links. Network topology is also matched with geographical and environmental data – operators can identify lines that are at risk of failing due to the weather or vegetation.

In most parts of the world, the demand for energy is increasing. However, the expansion rate of power networks is slowing, mostly due to environmental but also due to economical concerns. As a result, power grids all over the globe are more heavily loaded and are working harder than ever before. This means that margins with respect to equipment failure are shrinking.

Large power outages are usually the result of multiple component failures occurring within a timeframe of minutes, if not within seconds. Monitoring and control systems installed at utilities gather information from sensors within their own grid. They then evaluate this information to determine whether their network is operating in a state that ensures secure operation and delivers the power to meet demand conditions.

Most power system applications in use today report problems only on an individual component basis, such as line overloads, under/over voltage at specific points. Simultaneously, when things go wrong, power utilities are often dependent on operators taking the correct action to prevent an everyday event turning into a wide-spread blackout. Such an event can start with the outage of a single component, for example, a line or a transformer, and develop into a cascading series of failures, resulting in a severe outage.

A typical transmission grid may have thousands of lines and substations; a vast quantity of measurement data is collected during operation. Since it is impossible for an unassisted operator to grasp the information content of all this data in a timely manner, security assessment and visualization tools that distil the data into useful information are becoming increasingly important.

Large power outages are usually the result of multiple component failures occurring within a timeframe of minutes, if not within seconds.

These needs are underlined by the excerpts from the August 2003 North American Blackout Report [1] presented in the Factbox.

One part of the solution that is presented in this article, lies in achieving better situational awareness for power system operators. This can be achieved through tools that process power system measurements using advanced stability assessment and visualization techniques.

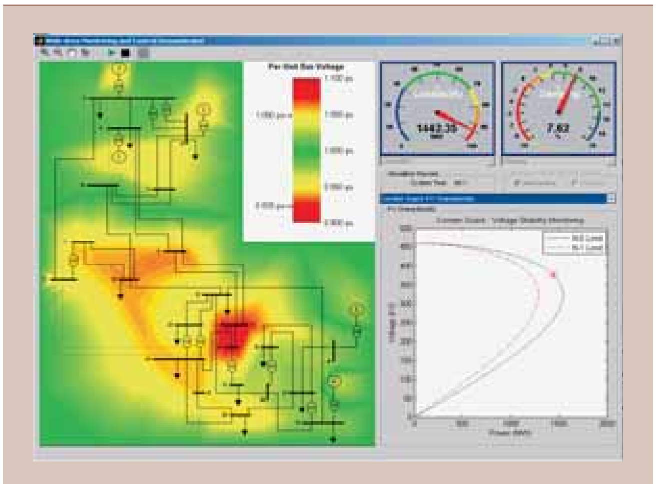
Visualization of static power system data

ABB has a range of network management software based around SCADA (Supervisory Control and Data Acquisition) and state-estimation packages. These provide a detailed and accurate picture of the network with a time-resolution of seconds to minutes. This is sufficient for the analysis of all static aspects of power system operation such as reactive power balance and margins, component or transfer path loadability limits and voltage profiles.

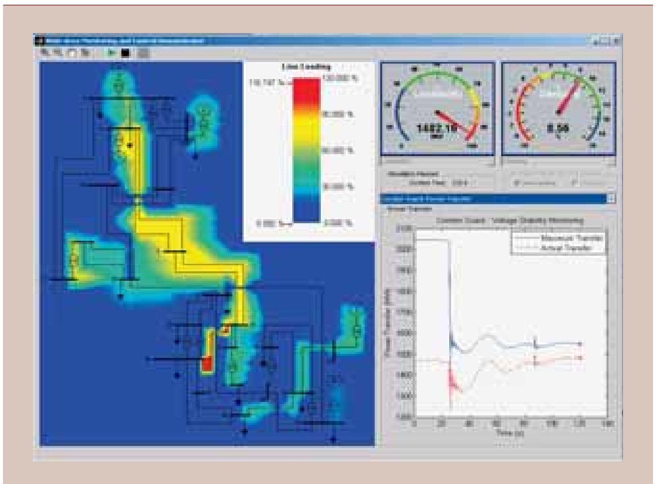
Factbox Excerpts from the August 2003 North American Blackout Report [1]

- **Observation** – "A principal cause of the August 14 blackout was a lack of situational awareness, which was in turn the result of inadequate reliability tools and backup capabilities."
- **Needed Action** – "Improved visibility of the status of the grid beyond an operator's own area of control would aid the operator in making adjustments in its operations to mitigate potential problems"
- **Observation** – "This resulted in an inability to detect, assess, respond to, and recover from IT system-related cyber failures (failed hardware/software, malicious code, faulty configurations, etc.)."
- **Needed Action** – "IT and EMS support personnel implement technical controls to detect, respond to, and recover from system and network problems."

1 Visualizing voltage magnitudes through color contours – the red colored section in the center of the system identifies areas with an abnormally low voltage



2 Visualization of line loading through a contour display – the color corresponds to the loading of each line relative to its capacity



Capital productivity

Experience has shown that humans can absorb and analyze visual information much more quickly they can absorb numerical information [2]. Contour mapping of voltage, load or generation profiles can be used to visualize the system-wide operating conditions and help operators pinpoint trouble spots in the grid with just a glance at the screen. One example is depicted in 1, where voltage magnitudes are shown by color contouring. The red sections in the center of the system identify areas with an abnormally low voltage. Following a quick localization, more detailed numerical displays can be opened to further investigate the source and possible solution to an abnormal network situation. In a contour plot, the color indicates the severity of the threat and the locations in the contour maps correspond to the geographic location of the problem area. Compared to a conventional alarm or warning log which typically shows only the location as a text string, it is much easier for an operator to find a solution to the problem. More importantly, when there are deviations from the normal voltage profile in several locations at the same time, the color display can be used to rank the severity of the different threats to power system security and quickly select the best area to focus corrective actions on first.

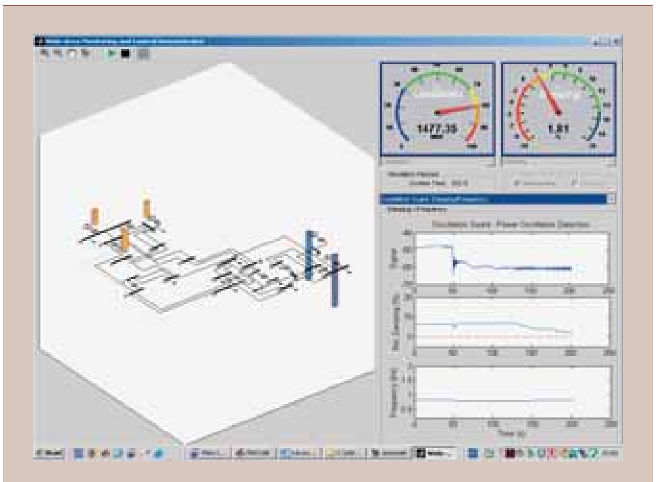
Once a trouble spot has been located on the contour map, an operator can take preventive action to ensure an abnormal situation does not progress into a system-wide outage. In the example of 1, the operator can disconnect load or insert additional capacitor banks or FACTS (Flexible AC Transmission System) devices to regulate reactive power and improve the voltage profile.

Contour mapping can also be effectively used to pinpoint overloaded components in the network. If such overloads are allowed to persist, most equipment must be fitted with local protection devices that will disconnect it with a time delay of tens of minutes. Thus, given the right information, operators can observe overloads in time and take corrective actions such as disconnecting load or reconfiguring the network before lines are automatically disconnected by overload protection, thereby preventing cascading failures and blackouts. 2 shows an example display where the color contour corresponds to the loading of each line relative to its capacity. The red colored section can be used to quickly pinpoint lines that are overloaded.

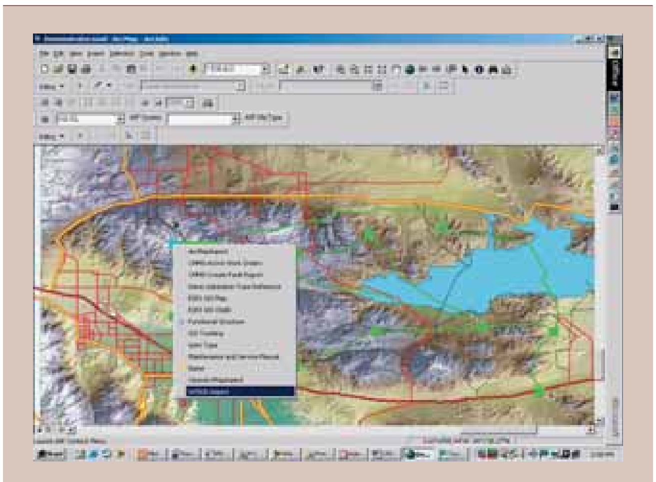
Visualization of power system dynamics

New phasor measurement and wide-area monitoring system (WAMS) technology is able to provide data at a rate of 10-20 values per second. This ensures a response of the measuring system that is fast enough for the monitoring, not only of slow phenomena such as voltage and load evolution dynamics, but also of faster phenomena such as oscillatory, transient and frequency dynamics that are im-

3 Real-time visualization of frequency dynamics in 3-D with the generator speeds and results of oscillatory stability monitoring illustrated by bars animated in real-time.



4 Real-time visualization of electrical network overlaid with GIS shaded relief map and road network map layers



portant for the stability of the power system. However, because of the high time-resolution of the measurements, a WAMS will deliver huge amounts of data that needs to be properly processed for specific applications before being presented to the operator.

The phasor measurement data can also be analyzed automatically in a number of ways. Voltage stability monitoring uses measurements from both ends of a line or corridor that is known to be critical as far as voltage stability is concerned. It creates an equivalent model of the corridor and assesses the voltage stability of the system as often as 10–20 times per second. The output is visualized using the power-voltage characteristic shown in the bottom right portion of 1, with the current operating point illustrated by the red asterisk and the maximum loadability illustrated by the rightmost point of the blue curve (bottom right). The meter display marked "Loadability" also shows that the current loading is 92 percent of the theoretical maximum.

The monitoring of oscillation damping uses on-line estimation of an equivalent dynamic system model based on phasor measurement data. The model can be used to assess the stability of so-called inter-area oscillations that are becoming more and more common as networks are interconnected to span large areas. The damping is illustrated by the meter in the top right of 2. 3 shows a situation in which there is 1.8 percent damping of the dominant oscillatory mode. A negative damping would imply that the oscillation is unstable and could lead to a power system collapse. Typically, at least 6-7 percent damping is desired. When such a low damping as that shown here is detected, the operator must be alerted so that corrective actions can be taken.

Furthermore, 3 shows a 3-D visualization of frequency dynamics. The bars shown below the schematic in cool color tones (from violet to green) represent busses or generators where the estimated or measured frequency is below the weighted system average. The bars rendered above the schematic in warm color tones (from green to red) represent areas where the frequency is observed to be above the weighted system average. The figure clearly shows that the two generators at one end of the system oscillate as one group against the group of three generators at the other end. In this case the oscillation is close to being unstable – this is illustrated by the low damping shown on the damping meter at the top right.

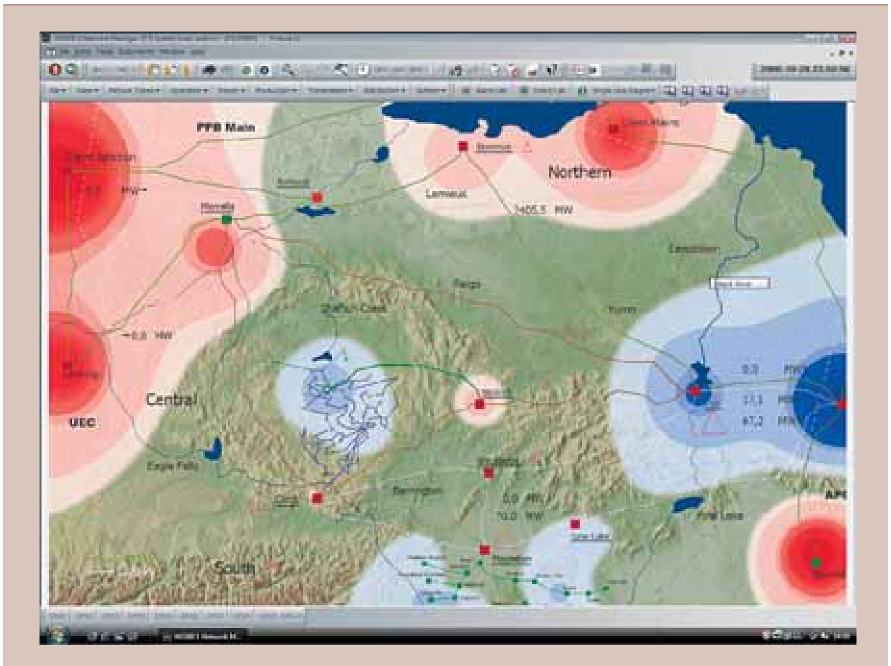
Contour mapping can be effectively used to pinpoint overloaded components in the network.

The role of GIS

GIS (Geographic Information Systems) enhance visualization of power systems by associating spatial data with transmission assets. They support a wide range of visualization options such as contouring and animation, making them attractive platforms for displaying geographically referenced real time power system data such as the voltage and line loading contours discussed above. GIS information is stored in geographical map layers making it easy to relate transmission network conditions with other relevant information such as weather, vegetation growth, and road networks. Real-time weather data integrated in GIS increases the operator's situational awareness. For example, with the help of such a system, the identification of a weather front moving towards a given area enables operators to quickly pinpoint transmission facilities with increased risks of outage. In conjunction with SCADA/EMS[1)] data, the operator can then initiate dispatching orders to protect the system against potential cascading failures. GIS vegetation maps can be combined with real time line loading information to identify lines with increased risk of flashovers and faults due to sagging. Such lines can then be considered candidates in the EMS contingency analysis. Conversely, if the GIS vegetation map shows negligible growth, operators can push more power through a corridor with line-sag constraints.

GIS data can also enhance operator actions after disturbance conditions. Results from transmission line fault location devices can be translated into

5 The ABB Network Manager function, Dynamic Contour Coloring, monitoring deviations from nominal voltage levels – red areas signal high and blue areas low voltages



geographical coordinates to identify affected tower spans; this together with GIS data on terrain, vegetation, road networks, and weather conditions enables operators to quickly estimate the time required for repairs. The time to repair plays a critical role in deciding whether an operator should issue costly unit start-up/shutdown orders. In major storm events, GIS maps displaying the relative geographical locations of line and tree maintenance crews assist operators in deciding which parts of the power system can be quickly restored to minimize customer outage time.

GIS data can be made available to operators via cross application navigation with SCADA/EMS systems.

4 shows a GIS interface displaying an electrical single line diagram with geographical-based maps and road networks. Assuming that a GIS object representing a substation has changed color and starts flashing, indicating an alarm; the operator can then right-click on the GIS object to bring up a context menu allowing him to navigate into the ABB NM WS500 interface for that substation. In the WS500 interface, the operator finds that the alarm indicates a breaker fault and acknowledges it and then sends out a maintenance order. The operator then right-clicks on the breaker, navigates back to the GIS interface and quickly views the road network around the substation. The operator can then order a re-dispatching of generation and transmission facilities based on the new operating conditions resulting from the outage.

The geographical information from the GIS data can also be combined with the contour mapping of the electrical state as illustrated in 5 (showing a screenshot from the ABB Network Manager). Here a relief map imported from a GIS is shown together with a network diagram. The voltage profile is shown as a contour map.

Geographic information systems enhance visualization of power systems by associating spatial data with transmission assets.

From the research labs into the ABB SCADA systems

Visualization of power system dynamics is still an important research area in which new visualization techniques will emerge in order to further improve situation awareness in power system operation. But techniques are now also finding ways out of the research labs into the ABB SCADA systems used for geographically distributed processes.

The ABB Network Manager system now supports a function using the dynamic contour coloring technique. This is shown in 5 – the WS500 operator station shows a zoomable world map with a geographic process overview. The dynamic contour coloring layer is semitransparent and may, as in this figure, be superimposed on a GIS map layer retrieved from a web-based GIS map server. Real-time information is overlaid over the GIS map and the dynamic contour colored image. Aspect object navigation can be used to navigate to asset and maintenance management systems, for example.

A model of the ABB Network Manager control room

Mats Larsson
ABB Switzerland Ltd, Corporate Research
Dättwil, Switzerland
mats.larsson@ch.abb.com

Reynaldo Nuqui
ABB Inc, Corporate Research
Raleigh, USA
reynaldo.nuqui@us.abb.com

Linda-Maria Johansson
Stefan Bengtzing
ABB Power Technologies Network Management
Västerås, Sweden
linda-maria.johansson@se.abb.com
stefan.k.bengtzing@se.abb.com

Footnote

1) SCADA: Supervisory Control And Data Acquisition (a large-scale, distributed measurement and control system) EMS: Energy Management System (a system of computer-aided tools used to monitor, control, and optimize system performance)

References

[1] US-Canada Power System Outage Task Force „Interim Report: Causes of the August 14th Blackout in the United States and Canada“ November 2003.

[2] Human Factors Aspects Of Power System Voltage Visualizations, Wiegmann, D. A., A. M. Rich, T. J. Overbye, and Y. Sun. Proceedings of the 35th Hawaii International Conference on System Sciences. September 2002.

[3] M. Zima, M. Larsson, P. Korba, C. Rehtanz and G. Andersson, "Design Aspects for Wide-Area Monitoring and Control Systems," Proceedings of the IEEE, pp. 980–996, vol. 93, no. 5, May 2005.