Restoring confidence

Control-center- and field-based feeder restoration

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Severe – and not so severe – weather conditions have the potential to wreak havoc with electric utility transmission and distribution systems. The speed and efficiency at which these repairs can be carried out depends largely on the type of decision support systems or tools available to the distribution utility.

The traditional procedure for restoring power, ie, a trouble call system and crew dispatches, may take several hours to complete. In recent years, utilities have deployed automated feeder switching devices with communications, such as reclosers and circuit breakers with intelligent electronic devices (IEDs) for protection and control applications, and as a result, the power outage duration and system reliability have been significantly improved. The information provided by IEDs has made automated fault location identification and fault isolation relatively easy to achieve. Automated power restoration, however, is another story altogether.

ABB has developed two complementary power restoration control schemes that are in essence self-sensing and self-healing distribution network solutions.

Traditionally, electric utilities use the trouble call system to detect power outages, ie, customers report when they experience a power outage. The distribution system control center then dispatches a maintenance crew to the field where they investigate the fault location before implementing various switching schemes to conduct fault isolation and power restoration. This procedure may take several hours to complete, depending on how quickly customers report the power outage and the maintenance crew locates the fault point.

Over the years demands on utilities have continued to increase, causing many distribution networks to become less (traditionally) passive and more active or dynamically adapting.

Identifying and isolating a fault is now considered relatively easy. Automatically restoring power, however, remains a challenging task.

Grids that can think for themselves

Smart grid, for some electric utilities, refers to electric power systems that enhance grid reliability and efficiency by automatically anticipating and responding to system disturbances. To achieve smart grid at the power distribution system level, various automation technologies have been attempted in the areas of system metering, protection, and control. Within these technologies, automated power restoration is an important part of the smart grid puzzle.

In moving closer to the smart grid concept, utilities have, in recent years, deployed feeder switching devices, such as reclosers and circuit breakers with intelligent electronic devices (IEDs) for protection and control applications. The automated capabilities of IEDs, such as measurement, monitoring, control and communications functions, make it practical to implement automated fault identification, fault isolation, and power restoration.

The IED data is transmitted back to a substation computer or a control center, and based on the information automated fault location identification and fault isolation are relatively easy to achieve. As a result, power outage duration and system reliability have improved significantly.

While identifying and isolating the fault may now be relatively easy, automatically restoring power remains a challenging task. Many research efforts have been dedicated to tackling this task, including consideration of the operating constraints, load balancing, and any other practical concerns.

As a result of its own research effort, ABB has developed two complementary power restoration control schemes: field-based and control-center-based. Both schemes conduct a restoration switching analysis (RSA) to achieve back-feed power restoration, ie, healthy load zones that have lost power will be restored through their boundary tie switching devices from neighboring sources. However, the field-based scheme uses a substation computer, the COM600, to run the RSA while the control-center-based scheme uses the Network Manager-DMS outage management system.

ABB has developed two complementary power restoration control schemes, field-based and control-center-based, which conduct a restoration switching analysis to achieve back-feed power restoration.

The field-based scheme

In the field-based scheme, the substation computer, the COM600, hosts the RSA engine and is used to communicate with feeder IEDs. It also acts as a soft programmable logic controller (SoftPLC) which issues control commands to the IEDs based on the restoration switching sequence produced from the RSA engine.

The RSA engine in the COM600 has a simple distribution network model that includes major feeder components: sources such as distribution substation transformers; switching devices, ie, "switches" that act to sectionalize parts of the network, load switches, circuit breakers and reclosers; and loads. It uses a network-tracing-based algorithm to reach a valid post-restoration network that satisfies the following requirements:

- The network is radial.
- There is no current violation on any network component.
- There is no voltage violation at any network node.

Therefore, the restoration switching sequence is generated online according to the pre-fault network condition instead of pre-programmed rules that are usually generated offline.

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The capacity of a potential back-feeding source may be limited, and in some cases multiple back-feeding sources may be required to reach a feasible restoration solution. In the context of this article, if a source can provide the restoration power over a single path to an out-of-service load zone, the restoration is called "single-path restoration." Otherwise, the out-of-service load zone may have to be split into two or more load zones to be back-fed, and the scenario is then called "multi-path restoration." Both single-path and multi-path restorations may have to shed load in case the back-feed source capacity or feeder components' loading capability is not sufficient.

The RSA engine's algorithm starts with a back-feeding isolation switch search, which is carried out on the pre-fault network's tree structure with the tripped breaker/recloser as the root. The search is conducted down the tree to find the most downstream switch that passed the fault current. This switch is then named the "forward-feed isolation" switch. The search then moves further down to the first layer of downstream switches, which are named the "back-feed isolation" switches. The algorithm then applies numerous recursive steps, including:

- Identifying any multi-connected load nodes (also known as "T-nodes") via tracing.
- Determining if single-path restoration can be achieved via a single source. If single-path restoration cannot be achieved, the algorithm then continues to search for other switches in the network in order to achieve multi-path restoration.

In the case of multi-path restoration, the algorithm tries to determine the best reconfiguration. In some cases, the network must be divided into two sub-networks to restore all the possible unaffected loads, moving one or more normally open tie switches to other switching device locations. In other cases, all the unaffected loads cannot be completely restored, even if the tie switch locations are moved.

Typical RSA engine outcomes are illustrated in 1 and 2. In 1a, single-path full restoration is used where a fault at T-node, L3, must be isolated by opening the forward-feed isolation switch (R3) and two back-feed isolation switches (R6 and R10).[1] Back-feed sources (S3 and S4) both have sufficient capacity to pick up the out-of-service load on their corresponding restoration path, and each tie switch (R9 and R12) can be closed to achieve the restoration. The post-restoration circuit topology in 1b. 2a shows a multi-path full restoration example, where a fault at load node, L1, must be isolated by a forward-feed isolation switch (R1) and a back-feed isolation switch (R2).[2] In this example, none of the back-feed sources (S2 to S5) can completely pick up all the unaffected loads after fault isolation. Hence the algorithm splits the network into two parts by opening R13, and the out-of-service load is restored by closing both R8 and R11 (from both S3 and S4). The post-restoration circuit topology is shown in 2b.

Operation of the field-based scheme was validated using an example of a demo distribution system that has three sources, five switches and three loads 3. By implementing the algorithm in a COM600 to control five IEDs, the demo shows how single- and multi-path restoration scenarios are achieved. For example, since neither of the given source capacities at sources S2 and S3 is enough to restore the sum of the loads L2 and L3, a fault

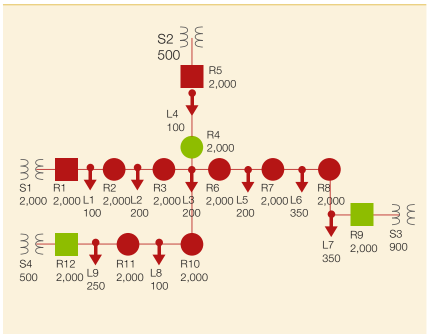
Footnotes

[1] Normally a feeder circuit breaker will not act as a tie switch. In this example, they are used as tie switches only to illustrate the concept.

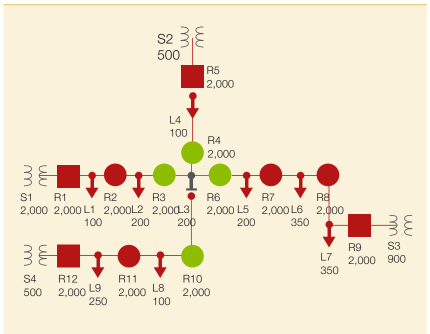
[2] In this case no forward restoration is required.

1 A single-path restoration example

a Normal topology

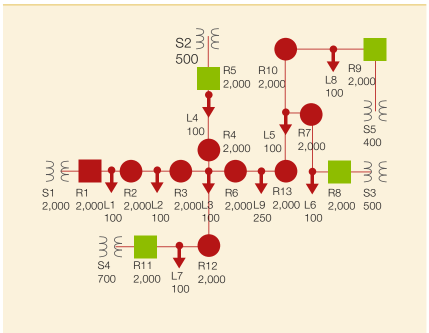


b Post-restoration topology

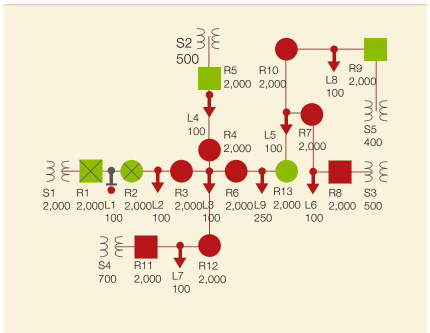


2 A multi-path full restoration example

a Normal topology

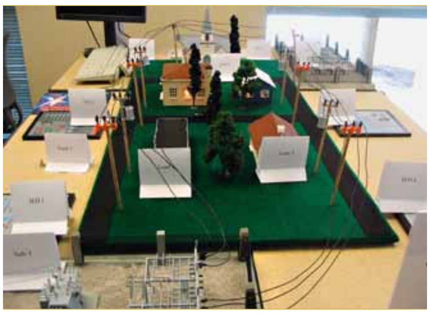


b Post-restoration topology

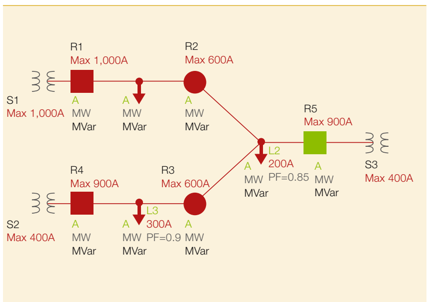


3 The demo circuit

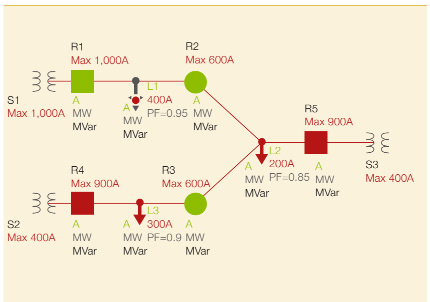
a Physical circuit



b Normal operation



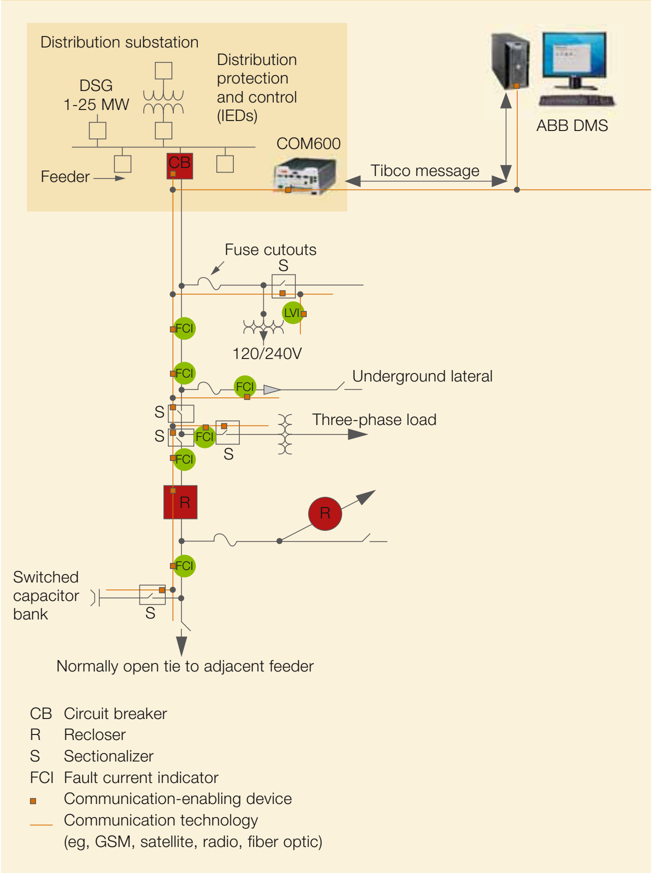
c Post-restoration operation



at load L1 causes R3 to open, which in turn splits the out-of-service network composed of L2, R3 and L3 3b. Both tie switches R4 and R5 close to restore power to the out-of-service loads 3c.

Network Manager-DMS is ABB's outage management and trouble call system that contains the network model for an entire utility distribution system.

4 High-level architecture for integrated feeder automation and DMS



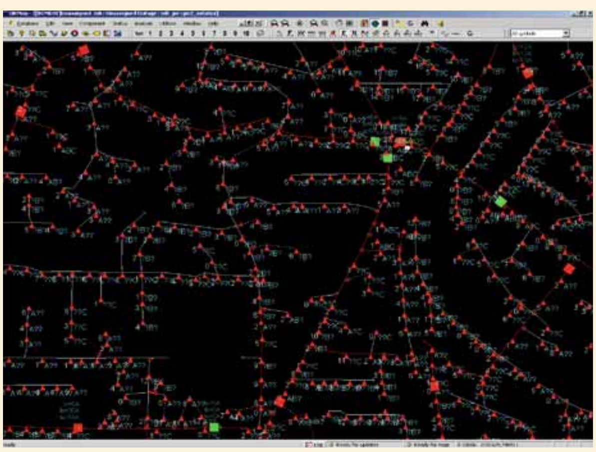
The control-center-based scheme

In a control-center-based scheme, the substation computer COM600 is used as a gateway to transmit field IED data back to the outage management system at the control center, and conversely control commands from the control center to the field IEDs. The COM600 first uses industry-accepted protocols, such as IEC 61850, DNP3 and Modbus, to obtain the necessary data from each of the feeder IEDs, and then analyzes this data to detect if a fault has occurred in the system. In the event of a fault, the COM600 sends this information upstream to the Network Manager-DMS via proprietary methods using a real-time messaging system. When the Network Manager-DMS receives the data, it analyzes it, determines the location of the fault, and subsequently runs the RSA to determine the proper isolation and restoration switching actions that should be taken. The Network Manager-DMS then sends the switching control commands to the COM600 either automatically or after an operator authorization action, whichever is preset in the control center DMS application. The high-level system architecture of this scheme is shown in 4.

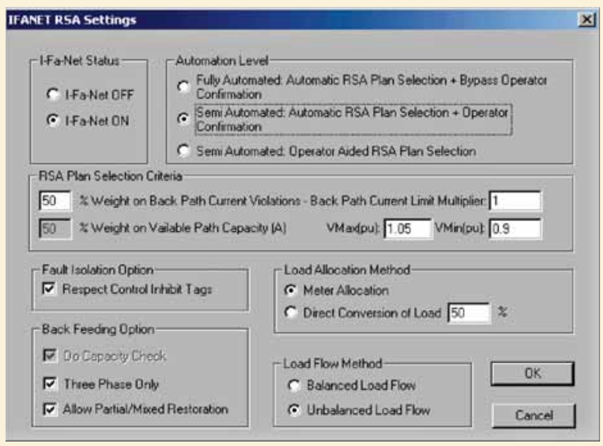
Network Manager-DMS is ABB's outage management and trouble call system. It contains the network model – which is typically stored in an Oracle database - for an entire utility distribution system, from substation components all the way down to residential service transformers. The control-center operator interface for a typical residential distribution system, modeled in Network Manager-DMS, is illustrated in 5. The solid lines represent overhead distribution lines and the dotted lines represent underground distribution lines. The boxes represent reclosers or switches, with the red boxes indicating normally closed devices and the green boxes indicating normally open devices (ie, potential restoration paths). The red triangles represent service transformers.

Historically, when customers lose power, they call the utility's automated answering system, which enters the outage data into Network Manag-

5 Operator interface (OrMap) for Network Manager-DMS



6 Operator-setting interface for control-center-based restoration

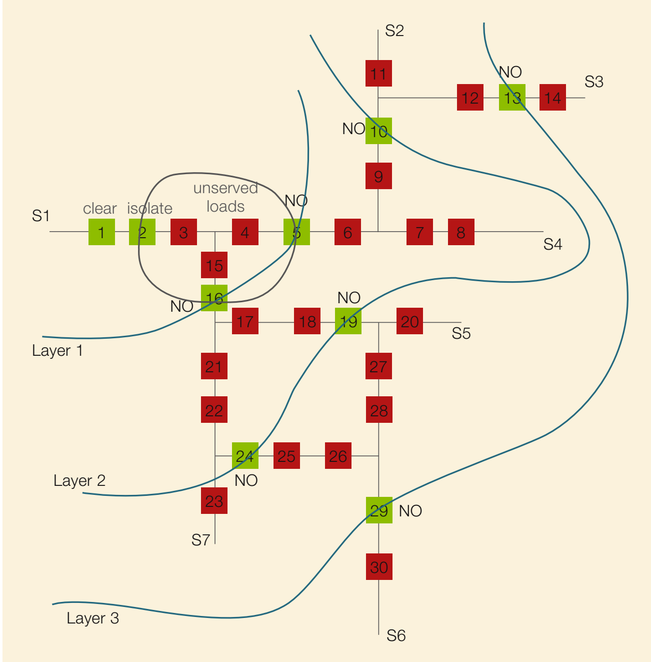


er-DMS. This data is then displayed on the operator interface. As more phone calls come in, Network Manager-DMS tries to determine the cause of the outage, for example if a switching device or fuse in the field operated to clear a fault or if a transformer or other component failed. The operator then uses the interface and output of the RSA feature of Network Manger-DMS to coordinate isolation and restoration of the feeder by dispatching crews to conduct switching operations.

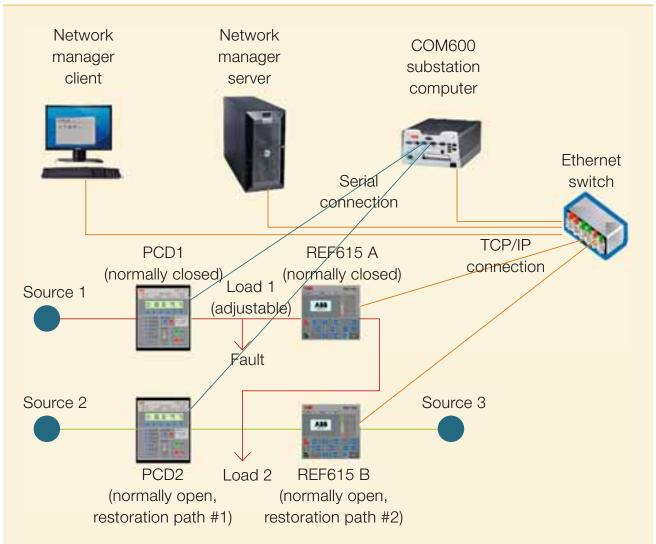
With the integrated control-center-based restoration scheme, the COM600 will detect the outage based on the IED-sensed network events, and inform the Network Manager-DMS automatically. When the Network Manager-DMS receives this notice, it will run the RSA with respect to the outage area and generate power restoration schemes, which are otherwise known as restoration switching plans (RSP). Whether an RSP is sent to the COM600 for execution immediately after the RSA run is based on the operator's preferences. The operator interface application allows three types of restoration control 6:

- Fully automated control where the operator is not involved in the RSP execution process
- The operator one-click confirmation-based RSP execution
- The operator-aided RSP selection and execution

7 The multi-layer restoration switching analysis (RSA) concept



8 Connection diagram for the control-center-based restoration demonstrator



The RSA is based on the detailed network model and unbalanced load-flow analysis of this model to make sure the post-restoration network does not have current and voltage violations. The RSA combines a network-topology tree-tracing and genetic algorithm, thereby enabling it to take care of both lightly and heavily loaded network conditions. If the loading of the network is light, then single-path restoration is sufficient. If the network is heavily loaded, either a multi-path restoration is required, or a multi-layer RSA has to be used.

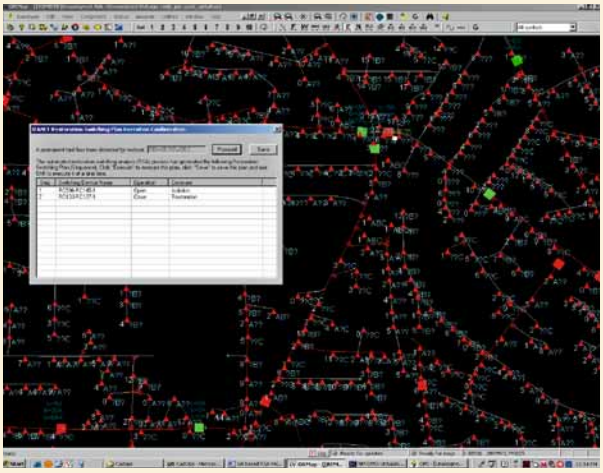
The concept of the multi-layer RSA is explained in 7, where the green squares represent tie switches or fault clearance/isolation switches. The tie switches that bound the unserved load area are called the first layer of tie switches for restoration. Subsequent layers are named sequentially (eg, second layer, third layer). Under heavy load conditions, only closing the first layer restoration switches may not be suitable to meet the power requirement of the unserved loads. Thus, load transfers from the zone between the first and second layers to the zone between the second and the third layers may be necessary. ABB has implemented a genetic algorithm-based method to resolve this problem.

A control-center-based scheme has been developed and validated by ABB in the lab and a demonstrator built to show the concept 8. A Network Manager-DMS server was configured to store an example network model, and a Network Manager-DMS client laptop was configured to be able to access and display this model. These computers, together with the COM600 substation computer and two REF615 distribution IEDs, communicated with each other via TCP/IP through an Ethernet switch. The two PCD recloser controllers communicated with the Modbus protocol through serial connections to the COM600.

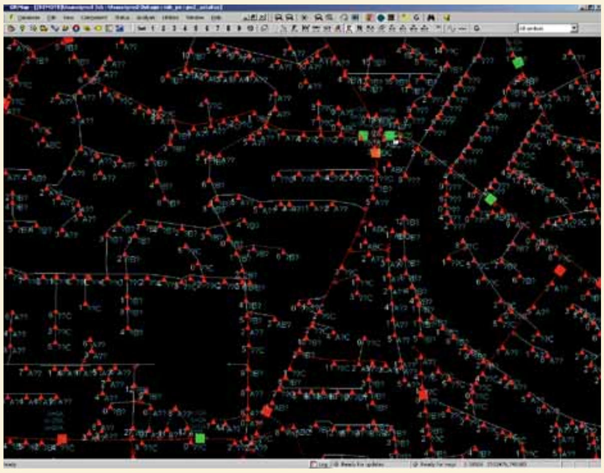
In 8, Load 1, the adjustable load, is a light bulb controlled by a dimmer switch, which is set via a remote control. Load 2 is fixed, ie, a light bulb with no dimmer switch. A fault is simulated at Load 1 by pressing a button on the dimmer switch remote control, thereby increasing the load (light-bulb illumination) level from the half-load to the full-load setting of the switch. This action causes a fault, forcing PCD1 to go through a reclosing sequence to lockout: its over-current pickup setting lies between the pre-fault load level (half load setting) and the fault load level (full load setting).

When PCD1 locks out, this action triggers the fault detection in the

9 NM-DMS operator interface (OrMap) screen for semi-automated RSA



10 NM-DMS operator interface (OrMap) screen after restoration



COM600. When the fault has been detected, the Network Manager-DMS is notified and the RSA is automatically run to determine all the restoration paths. The RSA setting will determine if the isolation and restoration actions are fully automated, semi-automated with one-click operator confirmation, or semi-automated with operator confirmation where the operator selects the restoration path. In the first two cases, the best restoration is automatically determined by the RSA. In the last case, the operator "manually" selects the best path by analyzing the output data of the RSA, such as allowable capacity, loading levels, and load-flow violation data. The Network Manager-DMS operator interfaces for semi-automated isolation and restoration with one-click operator confirmation are shown in 9 and 10.

This demonstrator was shown at several conferences in 2009, including DistribuTech, ABB Automation & Power World 11, and the FERC Expo Day.

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Self-healing distribution networks

ABB is actively developing new grid technologies, especially in the distribution automation, feeder automation and distribution control application areas. The field-based and control-center-based power restoration control schemes are just two examples of these developments. These technologies provide a self-sensing and self-healing distribution network solution, greatly reducing the customer outage time and increasing service reliability.

11 The demonstrator at the 2009 ABB Automation & Power World in Orlando

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[1] **Wang, Z., et al.** (July 2009). A deterministic analysis method for back-feed power restoration of distribution networks. IEEE General Meeting, Calgary, Alberta.