Distribution Automation Case Study: Rapid Fault Detection, Isolation, and Power Restoration for a Reliable Underground Distribution System

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***Abstract*—Electric utilities continue to deploy innovative technologies in power distribution systems to reduce outage time and provide more reliable delivery of electric power. Fault location and fast service restoration are challenging in underground looped distribution feeder systems electrically separated by normally open switches. Traditional fault location detection methods are time-consuming, labor intensive, costly, and detrimental to field equipment. This paper describes the objectives and operating principles of a centralized and automated underground distribution automation system (UDAS) that was developed and applied for rapid fault detection, isolation, and service restoration. The UDAS significantly reduced outage time and maintenance costs by executing tasks that were previously done manually by a field crew, therefore improving the performance of the distribution system.**

I. Introduction

CenterPoint Energy is a major electric transmission and distribution utility serving the Houston metropolitan area. CenterPoint wanted to improve the reliability of the underground distribution system serving a master-planned community, which is spread across 11,400 acres in the northwest Houston suburb of Cypress, Texas. This community presently serves 800 single-family homes and will serve more than 21,000 single-family homes and 65,000 residents. The underground distribution system is a 34.5 kV looped power system with two radial feeders fed from different sources and electrically separated by two normally open (NO) switches. The distribution system reliability objectives are to reduce outage frequency, reduce outage duration, and reduce costs associated with outage management [1].

A centralized underground distribution automation system (UDAS) was developed and successfully implemented for rapid fault detection, faulted section isolation, and automatic network reconfiguration to restore service to nonfaulted feeder sections, therefore minimizing the number of affected customers. The UDAS uses a high-speed fiber-optic communications network to dramatically increase its operating speed and fault isolation capabilities as well as decrease the power restoration time. Making use of modern communications technologies allows the UDAS to acquire data from distributed intelligent electronic devices (IEDs), process data, and analyze the most recent state of the distribution system. The UDAS makes well-informed decisions and takes corrective actions by sending control signals to operate equipment.

II. The UDAS Overview

The UDAS constantly monitors the distribution system for electric fault conditions based on information from microprocessor-based IEDs interconnected on a fiber-optic communications network. Integrated with modern recloser controls and motor-operated switches, the UDAS automatically reconfigures the distribution system topology to isolate the permanently faulted section. It evaluates the system and determines the best possible solution for service restoration based on the criteria of energizing the maximum loads possible and restoring power to the nonfaulted feeder sections with minimal delay. For multiple simultaneous faults occurring at different locations in the distribution system, the UDAS responds to address every fault situation and satisfies the criteria described.

Abnormal conditions, such as communications failures, device diagnostic failures, and command failures, are monitored by the UDAS to avoid any undesired operations. The system reliability is further improved by implementing an automatic source transfer scheme (ASTS) with open transition rollover and closed transition rollback features. A human-machine interface (HMI) provided at the control center monitors the UDAS status and IED data, displays fault locations, and sends control signals to the field equipment. The UDAS initiates an automated return-to-normal (RTN) sequence of operation after an operator command from the HMI. The RTN function is useful when returning the distribution network back to its normal arrangement after temporary reconfiguration due to a feeder section outage or maintenance. The UDAS provides instant event alarm notification to personnel via email and telephone voice annunciation. The UDAS also automatically retrieves oscillographic data captured by the IEDs, stores the event files, and send copies to designated personnel via email.

III. Distribution System Architecture

The electric power distribution system includes two 34.5 kV line sources feeding two electrically separated radial feeders. Each source is equipped with a recloser and a recloser control. The two radial feeders comprise twenty-two 600 A pad-mounted switches. Each pad-mounted switch is equipped with a dual-feeder protection relay for two line-side switches and two overcurrent controllers for two load-side fault interrupters. The reclosers and line-side switches have remote control capabilities and offer significant improvements in service reliability.

In the figures in this paper, the pad-mounted switch, which comprises two line-side switches and two load-side fault interrupters, is simplified as a single switch. Also, a motor-operated symbol is shown with some of the pad-mounted switches and represents that one of their line-side switches is motor-operated and can be controlled remotely by the UDAS.

The field equipment (reclosers, recloser controls, pad-mounted switches, current transformers (CTs), protective relays, communications switches, and fiber-optic cable) was already installed and operational before the UDAS was deployed. Protection and automation engineers worked together to create settings for the IEDs to include both the protection and automation aspects of the system.

Fig. 1 shows the UDAS architecture. The loads at the distribution voltage levels are supplied by two sources: one preferred source, which is the normal supply of power to the load, and one alternate source that can supply power to the load in the event that the normal source fails. The two radial feeders are separated by two NO switches (S8 and S21). The dual-source configuration enables the UDAS to monitor the line voltages from both sources and automatically transfer loads to an alternate source if the normal source is interrupted for more than 3 seconds.

Each switching device is identified as normally closed (NC) or NO during system configuration. The distribution network comprises zones. A zone is defined as a section that can be disconnected from the distribution system using switching devices. Based on the location of the switching devices in the distribution system, the network has the following zones: Source 1-R1, R1-S3, S3-S6, S6-S8-S14, S14-S18, S18-S21, S21-S8-S10, S10-S9, S9-R2, and R2-Source 2. Each zone in the distribution system can be energized from only one source at any given time.

The UDAS can be enabled or disabled from the control button on the HMI. Regardless of whether the UDAS is enabled or disabled, it collects information from IEDs and displays it on the HMI for monitoring purposes. When the UDAS is disabled, all automation on the feeders in its control area is disarmed. When the UDAS is enabled, the feeders in its control area can be included or excluded from the UDAS by an operator using the HMI. If a feeder has been excluded, the circuit is disarmed. The UDAS will not operate on an unarmed feeder.

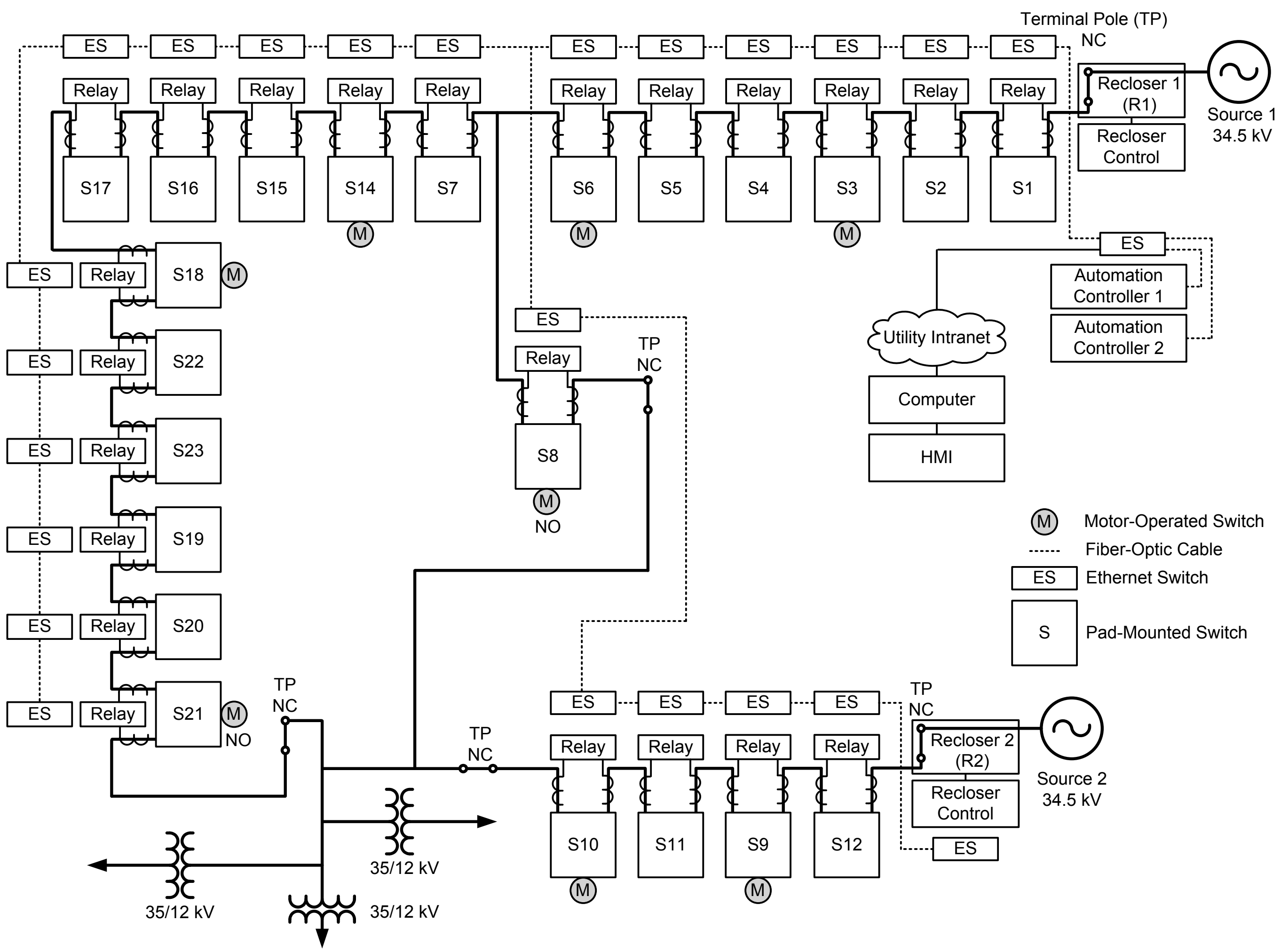

Fig. 1. The UDAS Architecture

A. UDAS Components

The UDAS integrates various system components. The basic features and functionality of the components that constitute the UDAS are as follows.

1) Protective Relays

The protective relays provide the UDAS with a communications interface to the switches and reclosers. Along with performing protection, control, and fault recording for the feeder circuits locally, the relays also communicate with the UDAS to provide analog, binary, and counter data from different points of the distribution system for complete system awareness. The two line-side CT inputs from each switch are connected to the dual-feeder protection relay. Auxiliary contacts from the line-side switches (52A and 52B contacts) are connected to the relay, which gives the UDAS the present position of the switches.

2) Automation Controllers

Two automation controllers with robust logic processing capabilities were used for the UDAS. The automation controllers have the following features:

- IEC 61131-3-compliant logic engine.
- Data concentration.
- Protocol conversion.
- Sequence of events (SOE) recording and viewing.
- Remote access services (for remote computers).
- Integrated security and data access control.

Each automation controller has a unique assigned function. The first automation controller contains the algorithm for the distribution automation (DA) logic. It collects data from and sends control signals to recloser controls and dual-feeder protection relays. When an event occurs, the first automation controller also sends email notification over the Simple Mail Transfer Protocol (SMTP) server.

The other automation controller polls data from the fault interrupter controllers. It also sends text messages for the alarm states to a serially connected event messenger unit. The event messenger then converts the received text messages into speech and delivers those messages by telephone, thus providing event alerts via voice annunciation. There is a provision to enable or disable the voice alarm notification by an operator command from the HMI.

3) Computer

The navigation of the UDAS HMI occurs via a computer located at the utility central control location. Both automation controllers communicate with the HMI system. The HMI provides screen displays for the UDAS status, system topology, recloser and switch status, fault location, fault conditions, metering, alarms, and operator-initiated control actions within the system.

The computer also runs oscillographic event collection software. The IEDs generate and store event oscillographic data when a fault occurs. The event collection software looks for the event reports and automatically collects the event data from the IEDs and stores the data on the computer. The software creates a summary database that acts as an index to the stored data and allows the searching and sorting of the collected data. It also sends email messages with a brief fault summary and an event report to specific email addresses.

4) Satellite-Synchronized Clock

The satellite-synchronized clock is a precise-time device with a high accuracy of ±100 nanoseconds. This Global Positioning System (GPS) time source provides the IRIG-B signal to the UDAS. The UDAS then retransmits the time synchronization signal to all of the compatible IEDs via Simple Network Time Protocol (SNTP) over the Ethernet network.

Communication with the GPS time-synchronized IEDs enhances the use of the IED-derived data. Having synchronized time signals to all the IEDs provides the ability to have comparable time-aligned power system fault data (disturbance event reports), sequential events records, and time-accurate reporting for state-change records. It is invaluable to be able to perform time-deterministic root-cause analysis of system events and combine the event report data from different IEDs to calculate in real time the timing between occurrences related to the same incident [2].

B. Device Data Communications

The fiber-optic communications network between IEDs forms the backbone of the UDAS. Reliable communication is required by the UDAS to monitor the present state of the power system and make well-informed decisions. The UDAS is dependent on device communication to operate properly. Loss of communication to a device disables automation for a particular feeder because the status of that device is no longer available to the UDAS.

Predefined sets of data and control points from each IED are configured in the UDAS. The UDAS collects analog and digital data and sends control signals to the IEDs using DNP3 over serial or Ethernet connections. All DNP3 devices are configured with a custom DNP3 map. Using this technique greatly reduces data traffic on the communications link and minimizes the bandwidth requirement. The unsolicited-report-by-exception technique of DNP3 is used for data collection from the IEDs. In other words, data are transmitted from the IEDs as conditions change, which reduces the time between an event occurring in the power system and the event being reported to the UDAS. The UDAS also sends an integrity poll to each IED every 30 seconds to ensure that the IED is communicating and healthy [3].

For each pad-mounted switch, one dual-feeder protection relay and two fault interrupter controllers are connected to a managed Ethernet switch. The dual-feeder protection relay communicates with the UDAS via DNP3. The two fault interrupter controllers are connected to two individual EIA-485 serial ports and communicate using Modbus® RTU protocol. The managed Ethernet switch converts Modbus RTU to Modbus TCP.

The recloser control for each line source communicates DNP3 over Ethernet via a tunneled serial connection. The managed Ethernet switch encapsulates each DNP3 serial data packet within an Ethernet frame for transmission over the fiber Ethernet network. All Ethernet switches are interconnected via single-mode fiber-optic cables and connected back to the centralized UDAS. Fig. 2 illustrates the system information flow diagram.

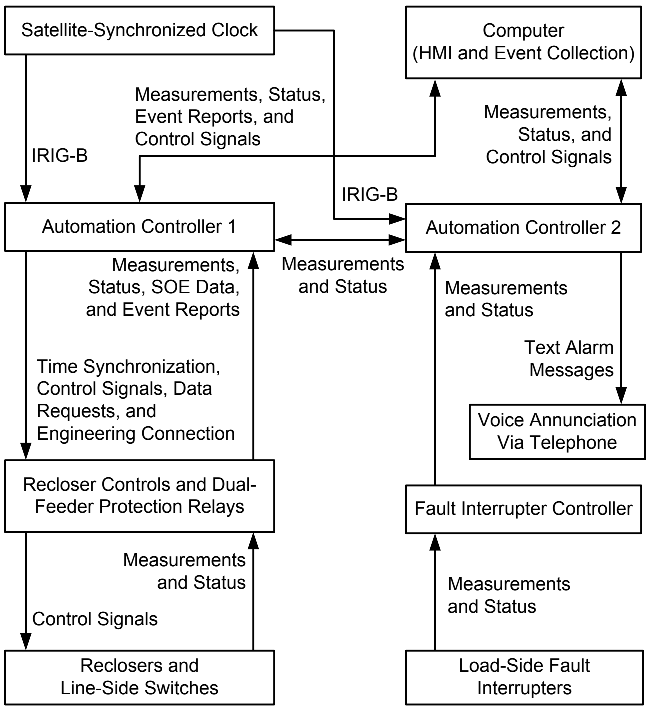

Fig. 2. System Information Flow Diagram

C. Motorized Switch Flag

Of the 44 line-side switches, 8 are motor-operated and are issued control signals by the UDAS. The UDAS indicates through a flag whether the line-side switch is motor-operated or not. A motor-operated switch can be controlled by the UDAS via the IED for sectionalizing the faulted section so that more unaffected sections can be restored after a fault has been cleared. During the sectionalizing of a faulted section, if the UDAS determines that a particular switch is not motor-operated or the IED has an active hold tag, it will look for the next available motor-operated switch that can be controlled to isolate the faulted section.

D. Local and Remote Control

An IED can be set to local control by pressing the front-panel pushbutton. Once in local control, the IED cannot be changed to remote control from the HMI for personnel safety. Local control is typically applied when a field crew plans to be working on the circuit associated with the equipment controlled by the IED. Enabling local control in the IED disables any remote closing or opening of the recloser or switch by the UDAS and allows only local operations. The logic that blocks the remote commands when in local control resides in the IED.

E. Automatic and Manual Modes

An IED can be set to automatic mode or manual mode either locally via a pushbutton or remotely via the HMI. When a pad-mounted switch is in manual mode, the UDAS no longer considers that switch in the automatic fault isolation and restoration logic. The IED must be in manual and remote mode for the controls available on the HMI to be functional.

F. Hold Tag

A hold tag is a custom IED variable that is used in the automation logic of the recloser controls and dual-feeder protection relays. An active hold tag for a specific IED disables its close command, preventing the closing of an open recloser or line-side switch. The IED hold tag does not prevent local closing of the device.

For the dual-feeder protection relay, a hold tag can be applied in one of the following three ways:

- When an IED is in automatic and remote mode and receives an open command from the UDAS, the IED automatically applies a hold tag to that switch as it executes the command. The reason for this is that under such a condition, the IED only receives an open command when the UDAS is using that specific motor-operated switch to isolate a fault or return the system to its normal state (for NO switches, the UDAS automatically removes the hold tag).
- When an IED is in automatic and remote mode and automatic fault sectionalizing is underway, the UDAS automatically applies a hold tag to the nonmotor-operated switches adjacent to the faulted section. A switch that is not motor-operable but is immediately adjacent to a faulted section can be used by field personnel to manually sectionalize the fault and restore power to nonfaulted sections. The hold tag on the IED front-panel display provides local indication and cautions field crews against closing a switch that may connect a nonfaulted energized section to a de-energized faulted section.
- When an IED is in manual and remote mode, a hold tag can be applied or removed via its respective HMI screen control buttons. This provides the operator with the ability to remotely control the hold tag function as needed.

For the recloser control, a hold tag can be applied in the following two ways:

- When an IED is in manual and remote mode, a hold tag can be remotely applied or removed via its respective HMI screen control buttons.
- When an IED is in manual and local mode, a hold tag can be applied via the IED front-panel pushbuttons. This provides the field crews with the ability to locally control the hold tag function as needed.

A hold tag can only be removed by the means by which it was applied. In other words, if a hold tag is applied remotely, it can only be removed via a command from the HMI or by the UDAS. If a hold tag is applied locally, it can only be removed via front-panel pushbutton controls.

IV. The UDAS Operating Sequence

Once turned on and operational, the UDAS is always in one of three system states: Initialize, Unarmed, or Armed, as shown in Fig. 3.

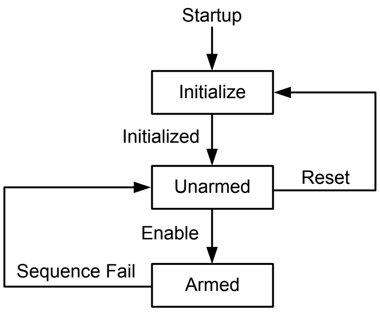

Fig. 3. The UDAS Operating States

A. Initialize State

The UDAS enters the Initialize state when it is turned on or when a reset command is issued by an operator while the UDAS is unarmed. During initialization, the UDAS resets the internal variables and alarm conditions. It determines the distribution system configuration and switch status under normal operating conditions. Once initialization is complete, the UDAS transitions to the Unarmed state.

B. Unarmed State

The UDAS enters the Unarmed state after system initialization is completed or when an automatic reconfiguration sequence failure occurs during the Armed state. In the Unarmed state, the UDAS monitors the DA enable or reset commands issued by an operator from the HMI. If the DA enable command is detected, the UDAS transitions to the Armed state. If the reset command is detected, the UDAS resets some of the internal latched variables. While in the Unarmed state, the UDAS is disabled and DA functionality is not active. The system continues to receive data from the IEDs and display information (analog and discrete values) on the HMI screens. The UDAS must be enabled to make the DA logic functional.

C. Armed State

The UDAS enters the Armed state when an operator issues the DA enable command from the HMI. In the Armed state, the UDAS continuously monitors the distribution system for any fault indications. If a fault is detected, the system initiates an automatic reconfiguration sequence, as shown in Fig. 4. The UDAS supervises the distribution system to ensure that events are ignored if they correlate with abnormal conditions on the related circuit so as to avoid any undesired network reconfiguration.

The steps involved in the automatic reconfiguration sequence are described in the following subsections.

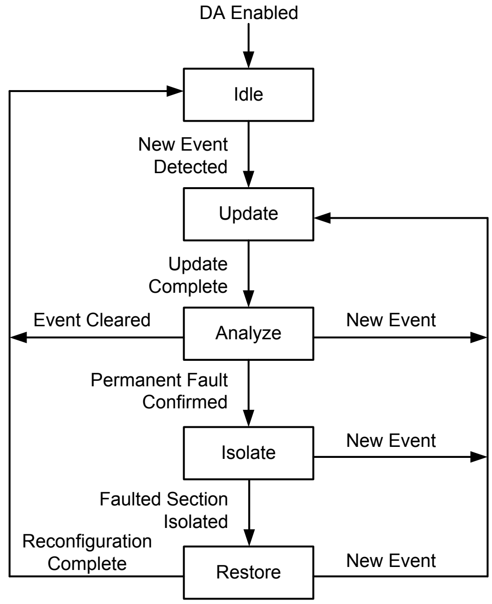

Fig. 4. Automatic Reconfiguration Sequence

1) Idle Step

When the UDAS is armed, it stays in the Idle step and monitors the system for an event. Once an event is detected, the system transitions to the Update step. If, during the Analyze step, the UDAS determines that the event has cleared and no permanent fault exists in the system, the UDAS returns to the Idle step. The sequence also returns to the Idle step after a successful fault isolation and system restoration.

2) Update Step

When an event occurs downstream on the feeder, the recloser control protection element picks up and trips the respective recloser to clear the fault. Meanwhile, one or more devices report the event condition (fault indication, loss of voltage, or high current) to the UDAS. On detecting a new event, the UDAS enters the Update step and responds by polling all the devices on the event feeder and adjacent feeders. The UDAS is updated with the most recent state of the feeders involved and also checks the health of the devices involved. If an IED does not respond within a predefined time, the UDAS generates a communications alarm, flags an abnormal condition for that feeder, and transitions to the Idle step.

New events can be detected during the execution of any of the steps of the automatic reconfiguration sequence (Update, Analyze, Isolate, or Restore). Under such a condition, the sequence returns to the Update step for another poll of the IEDs to gather the most up-to-date distribution system information. The UDAS remains in the Update step until all the devices have responded to a newly initiated poll or until the update time-out setting has been exceeded. Once the integrity poll is complete, the sequence transitions to the Analyze step.

3) Analyze Step

The Analyze step is executed after the system completes the Update step successfully. The purpose of the Analyze step is to verify the presence of a permanent fault or an open-phase condition in the distribution system. If the UDAS finds that the event condition no longer exists, the sequence returns to the Idle step. On confirming the existence of a permanent fault, the UDAS transitions to the Isolate step.

The UDAS also analyzes the data received during the Update step for any abnormal conditions (i.e., local control, disabled UDAS, recloser control diagnostic failure, and communications failures) to avoid undesired operations. If an abnormal condition is present on any switching device associated with a feeder, the entire feeder is considered to have an abnormal condition. The UDAS will not operate any device on a feeder that has an abnormal condition.

If the UDAS cannot determine the nature of the event, then the sequence fails due to exceeding the analyze time-out setting and the system flags an abnormal condition on that feeder and transitions to the Idle step.

4) Isolate Step

After the UDAS confirms a permanent fault or open-phase condition, it identifies the affected circuit components and operates controllable points (reclosers and motor-operated switches) in the network to isolate faulted segments. It executes a search algorithm to find an acceptable solution that results in the maximum load being re-energized. The UDAS identifies all viable open switches that could potentially be closed to supply all, or part, of the de-energized load downstream of the affected section.

The UDAS iterates through the combinations of the open and close possibilities and evaluates the alternative feed options based on voltage health and abnormal conditions on the circuit. It sends the open commands to the selected devices and waits for the status indications from each device to confirm that the operations have been completed successfully and the fault has been isolated.

5) Restore Step

After the faulted feeder section is successfully isolated, the UDAS transitions to the Restore step, where it attempts to restore the zones of the feeder that are not faulted but have been left de-energized due to the event. De-energized zones upstream from the faulted zone are restored from the original source by closing switching devices upstream from the affected zone. The de-energized zones downstream from the faulted zone are restored from an alternate source by closing an NO tie point connection to an adjacent feeder. If the alternate feed has an abnormal condition or does not have a live indication (i.e., it has less than 80 percent nominal voltage), the alternate feed is blocked and does not take part in system reconfiguration. If the UDAS cannot execute the necessary action, then the sequence fails due to exceeding the reconfiguration time-out setting. The system places an abnormal condition flag on that feeder due to a command failure and transitions to the Idle step.

After successfully completing the Restore step, the sequence returns to the Idle step and continues to monitor for a new event. It will respond to subsequent events that require reconfiguration actions. Additionally, if multiple simultaneous faults occur at different locations in the distribution system, the UDAS will respond to address all situations and reevaluate them in order to determine the best reconfiguration alternative. Events occurring within approximately 10 seconds of each other are considered simultaneous events by the UDAS.

There are indications on the HMI screen that inform the operator of the type of event (permanent fault or open phase) and of any failure (closed loop, communications failure, abnormal condition, or time-out) that has occurred. The HMI also informs the operator which step the UDAS is executing during the automatic reconfiguration sequence. The alarm indications can be reset by issuing a reset command from the HMI.

V. Fault Identification, Isolation, and Power Restoration Example

This section provides an example to further illustrate the automatic reconfiguration sequence that the UDAS executes for fault identification, isolation, and power restoration. When the UDAS is enabled and the system has no fault condition, the UDAS will be in the Idle step, monitoring for any new event. Fig. 5 shows the distribution system topology under normal conditions.

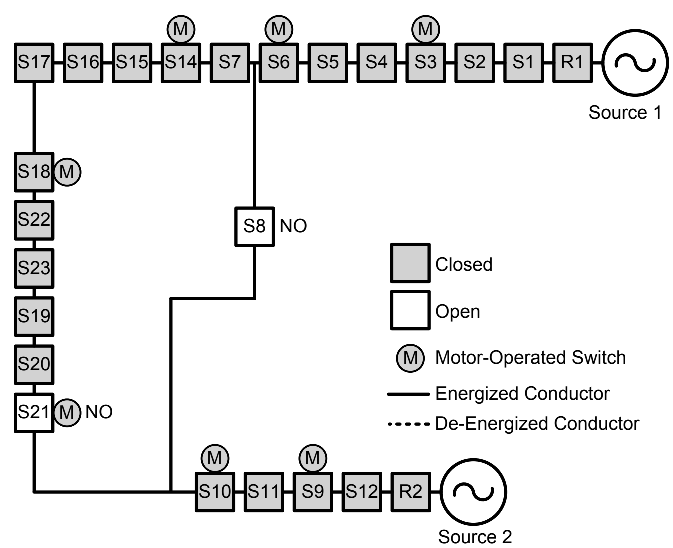

Fig. 5. Example Idle Step

If a fault occurs in the feeder section between S17 and S18, the protection element of the recloser control picks up and takes action to open the recloser R1 at Source 1. All the feeders between R1 and S21 that are fed from Source 1 lose power. Fig. 6 shows the permanent fault present in the feeder section between S17 and S18. All of the IEDs from S1 to S17, along with the recloser control at R1, see the fault and report an event to the UDAS. On detecting an event, the UDAS enters the Update step and polls data from all of the IEDs in the affected section to be updated with the latest state of the distribution system and also check the health of all the devices.

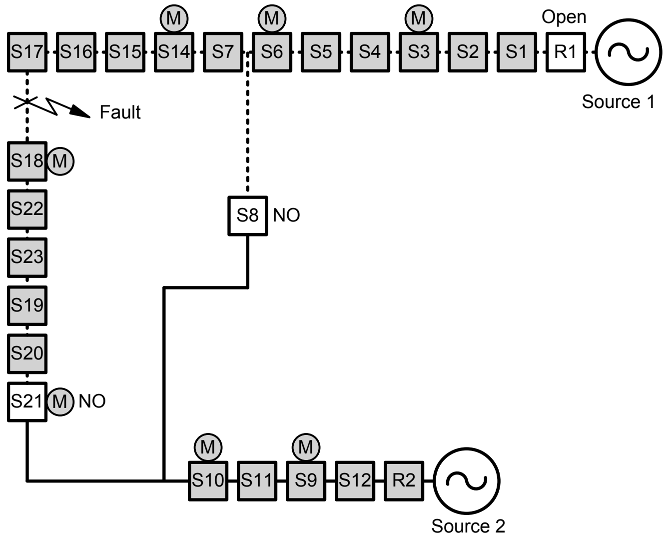

Fig. 6. Example Update Step

Once the update is complete, the UDAS enters the Analyze step, where it confirms a permanent fault between S17 and S18. It also confirms that there is no abnormal condition present on the related circuits. The UDAS determines the motor-operated switches closest to the faulted section (in this case, S14 and S18) that can be controlled remotely to isolate the faulted section. It also determines the NO switch (S21) that can be closed to re-energize the unaffected feeder section downstream of the faulted section from alternate Source 2, if available.

After the Analyze step is completed, the UDAS transitions to the Isolate step, where it sends open commands to the motor-operated switches at S14 and S18 and isolates the faulted section (see Fig. 7). It waits for the status indications from each switch to confirm that the operations have been completed successfully. After isolating the faulted section, the UDAS enters the Restore step, where it sends close commands to recloser R1 and the motor-operated switch at S21 to restore power to the unaffected feeder sections both upstream and downstream from the faulted zone. The power to the feeder section between R1 and S7 is restored from the original Source 1, and the power to the feeder section between S21 and S22 is restored from an alternate source (Source 2), as shown in Fig. 8.

After the successful and rapid fault identification, isolation, and system power restoration, the UDAS returns to the Idle step and waits for the next event to occur. With the automatic reconfiguration capabilities of the UDAS, the restoration times on nonfaulted lines are significantly reduced from hours (for manual restoration) to seconds.

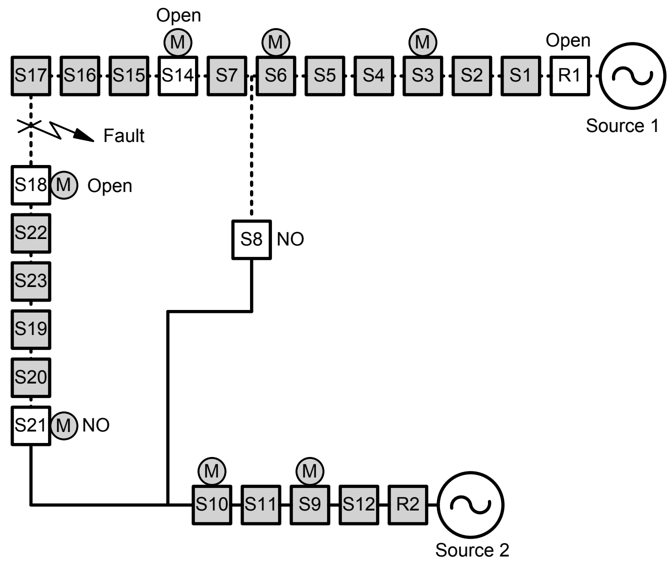

Fig. 7. Example Isolate Step

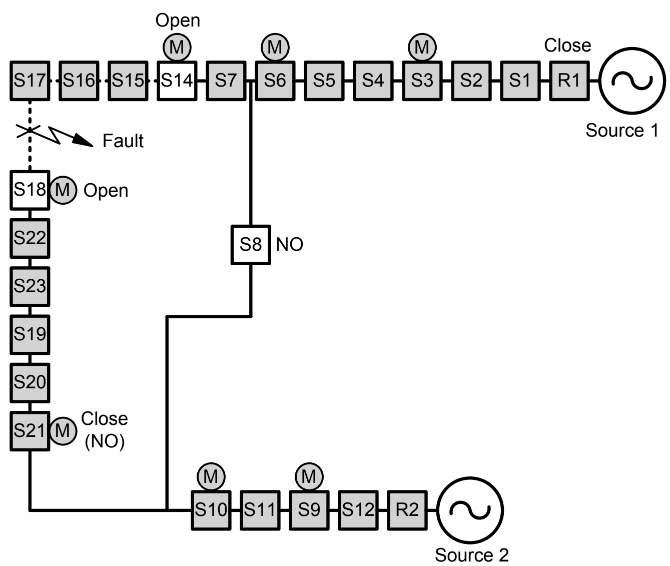

Fig. 8. Example Restore Step

VI. Abnormal Conditions

There are some conditions that can be detected in the system that will inhibit an automatic reconfiguration operation initiated by the UDAS. The following conditions are considered to be abnormal by the UDAS:

- A dual-feeder protection relay or recloser control is set to local control.
- The UDAS is disabled.
- A device experiences a diagnostic failure.
- A communications failure has occurred.
- A command failure is reported.
- A hold tag is present on a device.

If the UDAS observes an abnormal condition on any of the switching devices, the feeder associated with that switching device will be considered abnormal by the UDAS and no automatic reconfiguration will occur. For example, if the IED at pad-mounted switch S3 in Fig. 1 is in local mode, the radial feeder associated with Source 1 is considered to have an abnormal condition. The UDAS will omit the entire feeder circuit with the abnormal condition from its reconfiguration algorithm and will not respond to any event detected on that feeder circuit. It also excludes the abnormal feeder circuit source from being considered as an available alternate source [4].

VII. Return to Normal

Once a crew repairs the faulted zone, operators can issue a single command from the HMI to systematically return the feeders to their normal configuration. The UDAS RTN capability automatically reconfigures the distribution network topology to restore the de-energized load and set the switches to their normal state. Reconfiguration may include several switch operations. These operations are executed in a specific sequence in order to avoid unnecessary outages. The UDAS performs validation checks to ensure that system limits are not exceeded and that safety is not compromised.

The RTN mode is set for closed transition return, where the UDAS will first send close commands to NC switches and reclosers followed by open commands to NO switches. This temporarily connects the two radial feeders together as zones are transferred between adjacent radial feeders.

The UDAS responds to the RTN command only if it is armed. After the RTN sequence is completed successfully, the sequence returns to the Idle step. The RTN function is also useful when returning to a normal configuration from a temporary reconfiguration of a feeder for maintenance or a line section outage. If a manual feeder reconfiguration becomes permanent rather than temporary, the dispatcher can issue a command to the controls on the feeder to make this configuration the normal configuration. This feature avoids any UDAS reprogramming.

VIII. Automatic Source Transfer Scheme

The UDAS implements an ASTS to further improve the system reliability. The ASTS can be enabled only if the UDAS is enabled; otherwise, the ASTS remains disabled. By default, the ASTS is disabled and should be enabled by the operator from the HMI for the scheme to work.

If a loss of voltage is sensed at the normal source, the UDAS executes the ASTS for open transition rollover to re-energize the affected feeder from the alternate source. The UDAS continues to monitor the voltage at the unhealthy source. Once the good voltage (i.e., 90 percent of nominal voltage) is sensed for more than the set time, the source is considered to be healthy. The UDAS initiates the ASTS for closed transition rollback to restore the radial feeder back to its normal source. Table I explains the open transition rollover and closed transition rollback scenarios and the action initiated by the UDAS.

The following conditions may cause the ASTS to be inhibited:

- The UDAS is in reconfiguration or return mode.
- An active fault occurred in the system and has not yet cleared.
- A fault occurs at any of the source sides.
- Either of the two recloser controls is inhibited because the IED is in local and/or manual mode.
- Dual-feeder protection relays at any of the pad-mounted switches are in local control or manual mode.
- Either of the two radial feeders has an abnormal condition.
- An invalid contact fault or switch fault occurs for any of the NO pad-mounted switches (S8 or S21).

Table I
ASTS Settings

ASTS Function	Source Condition	Action Initiated by the UDAS
Open transition rollover	At the primary source, the UDAS senses low voltage for more than 3 seconds at both overhead and underground sides. The threshold voltage is set to 90% (31.05 kV) of the system nominal voltage (34.5 kV). If any of the line voltages for the overhead side (Z side) and the underground side (Y side) drop below the threshold value (31.05 kV), the source will be considered unhealthy and the UDAS will initiate open transition rollover.	The UDAS sends an open command to the recloser with low voltage. After the recloser opens, the UDAS then sends a close command to one of the available NO switches. All of the feeders are energized from the alternate source, if available.
Closed transition rollback	After open transition rollover has occurred, the UDAS senses good voltage at a primary source for more than 20 seconds (both overhead and underground sides). The threshold voltage is set to 90% (31.05 kV) of the system nominal voltage (34.5 kV). If all the line voltages for the overhead side (Z side) and the underground side (Y side) are above the threshold value (31.05 kV), the source will be considered healthy and the UDAS will initiate closed transition rollback.	The UDAS sends a close command to the primary recloser. After the recloser closes, the UDAS then sends an open command to the NO switch. Normal configuration of the network is restored.

The following three cases describe the functionality of the ASTS implemented in the UDAS.

A. Case 1

If the voltage at the primary source becomes unhealthy, the UDAS executes an open transition rollover to the alternate source, if available. The UDAS identifies and analyzes the condition and sends an open command to the unhealthy recloser control source. It then sends the close command to one of the available NO switches and restores power to the de-energized feeders from the alternate source.

The UDAS continues to monitor the condition of the faulted source. When the voltage is restored at the primary source, a closed transition rollback occurs. A close command is sent by the UDAS to close the primary recloser after sensing good voltage for a set time. The open command is sent to the NO switch after the primary recloser has been closed.

After rollover, the ASTS may be inhibited for any of the reasons mentioned previously. Under such conditions, the UDAS will not initiate rollback and the primary recloser will remain open even when healthy voltage returns. If for some reason one of the NO switches is not available, the UDAS will automatically shift to the other available NO switch to complete the rollover and rollback transfer schemes.

B. Case 2

If the alternate source loses overhead and underground voltages after rollover has occurred from an unhealthy primary source to the alternate source, then the UDAS issues an open command to the secondary-side recloser and the NO switch remains closed. This is the condition of a totally dead distribution system. If voltages come back at both sources simultaneously, then the UDAS opens the NO switch first before closing the reclosers at both end sources.

C. Case 3

In Case 3, both end sources have lost overhead and underground voltages and both reclosers are in the closed position. If one source restores healthy voltage under such a condition, then an open transition rollover is executed. The UDAS opens the recloser for the unhealthy source and then closes the NO switch to restore power to the complete feeder loop from the available healthy source.

IX. UDAS EXPANSION

The UDAS is scalable, and the system was designed keeping future expansion in mind. The UDAS is very flexible and automatically detects and accommodates changes made to the present system topology. For instance, the addition of more motor-operated line-side switches was automatically detected (based on the status information from IEDs) by the UDAS with no additional reconfiguration required. As part of the system expansion, more pad-mounted switches were added to the distribution feeders. The new distribution network topology was easily modified in the automation controllers with a drag-and-drop feature to incorporate the changes in the power system. With minimal configuration changes and with no additional equipment, the operational efficiency and reliability of the UDAS were maintained for the new distribution system.

The UDAS has been deployed, and the system is being optimized. Tests have been conducted to study the performance of the UDAS to accomplish the tasks formerly performed manually or left undone. In the near future, more system quantitative data (such as the frequency of outages, time duration for power outages, number of customers affected, restoration times, and operations and maintenance costs) and performance results will be recorded and analyzed for greater understanding of the improvements in system reliability and efficiency.

X. CONCLUSION

This paper explains the operating principles of a centralized and automated UDAS developed for CenterPoint Energy to improve the reliability of their underground distribution system. The UDAS was applied to ensure the reliable delivery of electric power for a looped distribution system with two electrically separated radial feeders. The UDAS objective is to rapidly identify faults, isolate the faulted sections, and automatically restore power to the unaffected feeder sections from the normal source or an alternate source, if available. The system efficiency is highly improved with reduced power interruptions and outage times along with lower maintenance costs. The fiber-optic communications network acts as a backbone for the UDAS to observe the power system state by polling information and sending faster control signals to the field IEDs distributed over a large area.

On detecting an event, the UDAS executes an automatic reconfiguration sequence in which the system updates itself with the most recent state of the power system. It evaluates the system and determines the most feasible solution to re-energize the maximum feeder loads. The UDAS takes corrective action by sending control signals to switching devices to isolate a faulted zone and restore power to unaffected zones. Abnormal system conditions are monitored by the UDAS to avoid undesirable reconfiguration. The UDAS RTN capability and ASTS functionality were implemented to further improve the reliability of the distribution system.

XI. REFERENCES

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XII. Biographies

David Gomes, P.E., received his B.S. (Hons) in Electrical Engineering from the University of the West Indies, Trinidad, in 1976 and an M.S. in Electrical Power Systems from Manchester University, England, in 1982. Upon graduating, he served nearly 14 years at the national electric utility in Guyana. He joined CenterPoint Energy in 1991. He is now responsible for providing engineering support to the major underground department for protection and automation systems, power quality, reliability, and material evaluation. He is a licensed Professional Engineer in Texas.

Richard Colunga is an engineer at CenterPoint Energy. He is responsible for supporting the major underground department with relay protection, power reliability, and material evaluation. Richard received his bachelor's degree from Texas A&M University and joined the CenterPoint Energy team in December 2011.

Payal Gupta received her master's degree in electrical engineering from the University of Houston in 2011 and her bachelor's degree in electrical engineering from the National Institute of Technology, India, in 2007. She is presently working as an automation engineer at Schweitzer Engineering Laboratories, Inc. in Houston, Texas. She has been involved in the design, engineering, and implementation of power management systems and distribution automation systems for electric utilities and industrial projects.

Ashok Balasubramanian, P.E., received his BE degree in electrical and electronics engineering from the University of Madras, India, in 2004 and an MS in power systems from the University of Alaska, Fairbanks, in 2006. Upon graduation, he worked in the process automation industry in Alaska for more than three years, where he worked on process automation projects and gained experience integrating programmable logic controllers with microprocessor-based protective relays. He joined Schweitzer Engineering Laboratories, Inc. in January 2010 and is currently an automation engineer in the engineering services division.

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