FAULT DETECTION ISOLATION AND RESTORATION ON THE FEEDER (FDIR): PICK YOUR TECHNOLOGY

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ABSTRACT

SMART Grid 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 automatic 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.

This paper presents an on-line method for the automated power restoration application previously described. The developed method conducts an analysis to achieve back-feed power restoration, i.e., healthy load zones that have lost power will be restored through their boundary tie switching devices from neighboring sources, and no reconfiguration beyond the tie devices will be considered. The back-feed restoration should not overload any part of the back-feeding network.

INTRODUCTION

Traditionally, electric utilities use the trouble call system to detect power outages. Specifically, when a fault occurs and customers experience power outages, they call and report the power outage. The distribution system control center then dispatches a maintenance crew to the field. The crew first investigates the fault location, and then implement the switching scheme(s) to conduct fault isolation and power restoration. This traditional procedure for power restoration may take several hours to complete, depending on how fast customers report the power outage and the maintenance crew can locate the fault point and conduct the power restoration.

In recent years, utilities have deployed the feeder switching devices (reclosers, circuit breakers, and so on) 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. As a result, the power outage duration and the system reliability can be improved significantly.

Based on the information provided by IEDs, automated fault location identification and fault isolation are relatively easy to achieve. In contrast, automated power restoration is a challenging task, with considerable research having focused on this area to tackle this application, to consider the operating constraints, load balancing, and any other practical concerns. This paper will present three different solutions on how to minimize outage time and restore the power to the non-served loads.

FAULT DETECTION ISOLATION AND RESTORATION (FDIR) USING LOOP CONTROL SCHEME

The distribution one line diagram in Figure 1 represents a simple loop system that will be used for analysis of FDIR. This system consists of the following components:

- Source
- Sectionalizing recloser
- Midpoint recloser
- Tie Point recloser

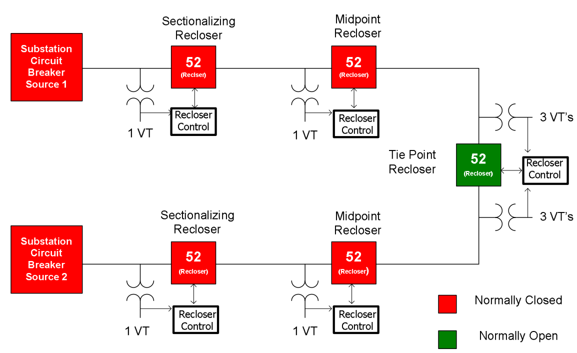

Figure 1: Example Distribution Circuit

Sources

A source is a substation feeder with breaker and ancillary equipment such as CT, IED etc. The substation source is not normally included in the loop scheme logic system; it is only intended to supply the power for the loop control system down the feeder. All loop control systems assume a minimum of two sources. These sources may be supplied by the same or different distribution substation feeders, with different feeders permitting a higher level of service during some fault conditions. The selection of these substations it is recommended that the following be considered:

- Both sources supply power of the same phase rotation
- The voltage level of each source are similar

Sectionalizing recloser

The Sectionalizing recloser is a normally closed recloser that opens in response to a downstream fault condition or to a loss of phase voltage from an upstream circuit. The sectionalizer is typically the first protective device on the distribution line outside the substation..

Midpoint recloser

The Midpoint recloser also is normally closed. Unlike the Sectionalizing recloser, however, it does not open in response to phase voltage loss. Instead, it supports loop control by automatically altering the IED settings in accordance with changing voltage conditions. Specifically, upon the expiration of its undervoltage timer, it will switch to an alternate setting group to prepare for a backfeed condition and for a period will go into non-reclose mode. The reason for the non-reclose is that in the event the fault is between the Sectionalizing unit and the Midpoint, it would be undesirable to have the recloser sequence through multiple operations.

Tiepoint recloser

The Tiepoint recloser, unlike the Sectionalizing and Midpoint recloser is normally open. It closes in response to a loss of all phase voltages from one source if the other source phase voltages are live. Once closed, the TiePoint recloser will trip automatically if a downstream overcurrent condition exists and is not isolated by the midpoint recloser first. The TiePoint recloser can be set to employ different fault thresholds depending on which side of the loop it is supplying, i.e., which side is downstream. After the close operation, it also is set to go into non-reclose mode for a period of time in the event the fault is between the Midpoint and Tiepoint.

There are three potential fault locations on each side of the Tiepoint recloser:

1. between Source and Sectionalizing recloser;
2. between Sectionalizing and Midpoint recloser ;
3. between Midpoint and TiePoint recloser.

Fault between Source and Sectionalizing recloser

In Figure 1 there is a permanent fault between the Source 1 circuit breaker and the sectionalizing recloser.
The Source 1 circuit breaker will recognize the fault and go through its reclosing shots to lockout (for illustration purposes we will assume 3 operations to lockout for all devices). Sectionalizing recloser will recognize a loss of voltage after the first circuit breaker operation, and if the voltage does not return for the LiveBus timer setting, it will automatically trip after t1 seconds (see Figure 2), isolating the faulted zone on the source side of the recloser.

The Midpoint recloser senses the same loss of voltage, and if the voltage does not return for the LiveBus timer setting will request the IED to start its Switch-on-to-fault (SWOTF) timer and, if programmed, to use Setting group2 settings after t2 seconds (typically set around 10 seconds after the Sectionalizer is set to lockout).

The tie-point recloser at the same instant will recognize a loss of 3-phase voltage on the Source 1 side of its recloser VTs. After a delay time of t3 seconds from the initial fault at Source 1 the tie-point recloser T will close, and if programmed, switch to Setting group2 settings. This establishes service from Source 2, recloser and through the tie-point recloser to the faulted sectionalizing recloser.

The non-faulted portion of the distribution feeder circuit between Sectionalizing recloser and TiePoint recloser is picked back up..

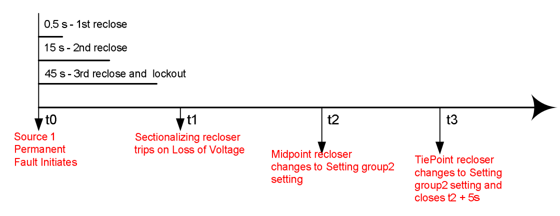

Figure 2: Sequence of Events

Fault between Sectionalizing and Midpoint recloser

In Figure 1. there is a permanent fault between the Sectionalizing and Midpoint recloser. If there is a permanent fault between the Sectionalizing recloser and the Midpoint recloser, the sectionalizing recloser will recognize the fault and go through its reclosing shots to lockout (assuming proper coordination with the circuit breaker at Source 1). Midpoint recloser will recognize a loss of voltage after the first sectionalizing recloser operation, and if the voltage does not return for the LiveBus timer setting, will request the IED to start its SWOTF timer and, if programmed, to use Setting group2 settings after t2 seconds (typically set around 10 seconds after the Sectionalizer is set to trip). See Figure 3.. for sequence of events.

The tie-point recloser at the same instant will recognize a loss of 3-phase voltage on the Source 1 side of its recloser VTs. After a delay time of t3 seconds from the initial fault at Source 1 the tie-point recloser will close, and if programmed, switch to Setting group2 settings. Since the fault is permanent, fault current will flow from the alternate source. With proper coordination in this direction, the mid-point recloser will trip on overcurrent (one shot due to its SWOTF mode), isolating the faulted section between Sectionalizing and Midpoint Reclosers. This establishes service from Source 2 to Midpoint Recloser.

The non-faulted portion of the distribution feeder circuit from Source 2 to the Sectionalizing recloser never loses service, and from Midpoint recloser to the tie-point recloser the load is picked back up.

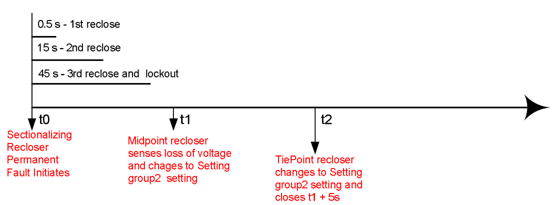

Figure 3: Sequence of Events

Fault between Midpoint and TiePoint recloser

In Figure 1. there is a permanent fault between the Midpoint and TiePoint recloser. If there is a permanent fault between Midpoint and TiePoint reclosers, the following sequence occurs: Midpoint recloser proceeds through its reclosing sequence of overcurrent protection (again, assume 3 operations to lockout). Upon tripping of Midpoint recloser , TiePoint recloser senses loss of voltage and after its time delay of t1 seconds, closes onto the permanent fault. Since this fault is permanent and TiePoint recloser has closed into the fault, TiePoint recloser goes directly to lockout. The non-faulted portion of the distribution feeder circuit between Source 1 to Midpoint recloser remains in service as does Source 2 to TiePoint recloser. See Figure 4. for sequence of events.

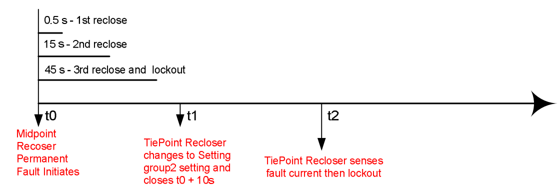

Figure 4: Sequence of Events

FAULT DETECTION ISOLATION AND RESTORATION (FDIR) USING IEC 61850 PEER-TO-PEER SCHEME

The distribution one line diagram in Figure 5 represents a simple loop system that will be used for analysis of FDIR. This system consists of the following components:

- Source
- Sectionalizing recloser
- Midpoint recloser
- Tie Point recloser

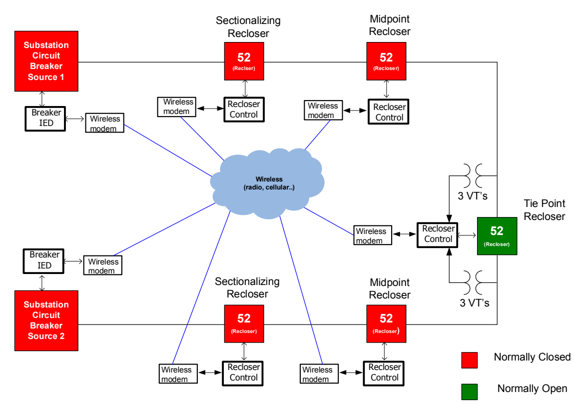

Figure 5: Example Distribution Circuit

There are three potential fault locations on each side of the Tiepoint recloser:

1. between Source and Sectionalizing recloser;
2. between Sectionalizing and Midpoint recloser ;
3. between Midpoint and TiePoint recloser.

IEC 61850 peer-to-peer communication

All Recloser controllers in Figure 5 are IEC 61850 capable. One of the most important benefits IEC 61850 provides is use of Generic Object Oriented Substation Event – GOOSE messaging between recloser controls. Data sending between recloser controls is event based and when a change in GOOSE data occurs, a message is sent a multiple times to the network. Data exchange between recloser controls is based on publisher/subscriber mechanism. The publisher recloser control multicast data over the local area network to different subscribing recloser controls. The content of GOOSE message allows the receiving recloser controls to perform processing of the data in order to execute required actions.

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Fault between Source and Sectionalizing recloser

In Figure 5 there is a permanent fault between the Source1 circuit breaker and the sectionalizing recloser. The Source 1 circuit breaker will recognize the fault and go through its reclosing shots to lockout (for illustration purposes we will assume 3 operations to lockout for all devices). At the same time, Source 1 circuit breaker will multicast GOOSE message that contains Lock out information. Sectionalizing recloser will receive a Lock Out message and it will automatically trip after t1 seconds (see Figure 6), isolating the faulted zone on the source side of the recloser. To enhance the security, using an advanced logic programming capability in the recloser control, received Lock Out GOOSE can be supervised by other conditions prior the open command is send to Sectionalizing recloser, see Figure 7:

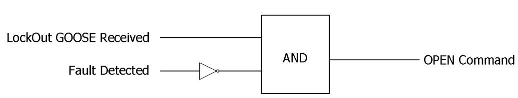

Figure 7: Example of logic for Sectionalizing recloser

Lock Out GOOSE from Source 1 breaker and Open position GOOSE from Sectionalizing recloser will be used as inputs for Midpoint recloser. Two GOOSE messages from Source 1 breaker and sectionalizing recloser will request the Midpoint recloser control to start its Switch-on-to-fault (SWOTF) timer, Figure 8., and if programmed, to use Setting group2 settings after t2 seconds.

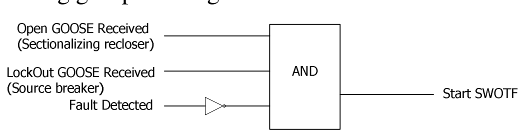

Figure 8: Example of logic for Midpoint recloser

Lock Out GOOSE from Source 1 breaker and Open position GOOSE from Sectionalizing recloser will be used as inputs for TiePoint recloser. Two GOOSE messages from Source 1 breaker and sectionalizing recloser will request the TiePoint recloser control if programmed, to use Setting group2 settings after t3 seconds. To enhance the security, using an advanced logic programming capability in the recloser control, received Lock Out and Open position GOOSE can be supervised by other conditions prior the Close command is send to Tiepoint recloser, see Figure 9:

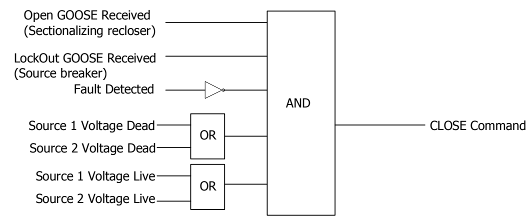

Figure 9: Example of logic for TiePoint recloser

The non-faulted portion of the distribution feeder circuit between Sectionalizing recloser and TiePoint recloser is picked back up.

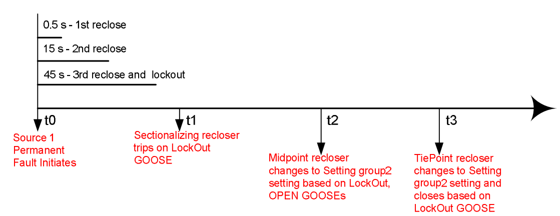

Figure 10: Sequence of Events

Fault between Sectionalizing and Midpoint recloser

In Figure 5 there is a permanent fault between the Sectionalizing and Midpoint reclosers. The Sectionalizing recloser will recognize the fault and go through its reclosing shots to lockout (for illustration purposes we will assume 3 operations to lockout for all devices). At the same time, Sectionalizing recloser will multicast GOOSE message that contains Lock out information. Midpoint recloser will receive a Lock Out message and it will automatically trip after t1 seconds (see Figure 13), isolating the faulted zone on the source side of the recloser. To enhance the security, using an advanced logic programming capability in the recloser control, received Lock Out GOOSE can be supervised by other conditions prior the open command is send to Midpoint recloser, see Figure 11:

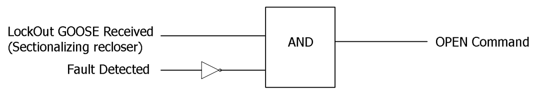

Figure 11: Example of logic for Midpoint recloser

Lock Out GOOSE from Sectionalizing recloser and Open position GOOSE from Midpoint recloser will be used as inputs for TiePoint recloser. Two GOOSE messages from Sectionalizing and Midpoint reclosers will request the TiePoint recloser control if programmed, to use Setting group2 settings after t2 seconds. To enhance the security, using an advanced logic programming capability in the recloser control, received Lock Out and Open position GOOSE can be supervised by other conditions prior the Close command is send to Tiepoint recloser, see Figure 12

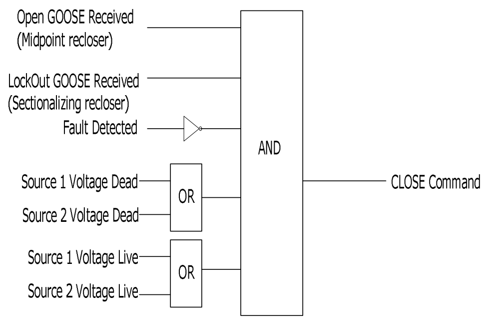

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Figure 12: Example of logic for TiePoint recloser

The non-faulted portion of the distribution feeder circuit from Source 1 to Sectionalizing recloser never loses service, and from Midpoint recloser to the tie-point recloser the load is picked back up.

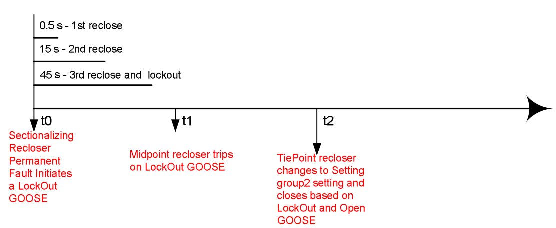

Figure 13: Sequence of Events

Fault between Midpoint and TiePoint recloser

In Figure 5 there is a permanent fault between the Midpoint and TiePoint reclosers.

The MidPoint recloser will recognize the fault and go through its reclosing shots to lockout (for illustration purposes we will assume 3 operations to lockout for all devices). At the same time, MidPoint recloser will multicast GOOSE message that contains Lock out information. TiePoint recloser will receive a Lock Out message.

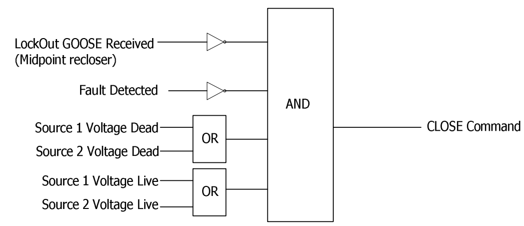

Figure 14: Example of logic for TiePoint recloser

From Figure 14, Close command to TiePoint recloser will not be issued because of LockOut GOOSE that was sent from the Midpoint recloser. Thus, TiePoint recloser closing will be prevented in the event of a permanent fault between MidPoint and TiePoint reclosers, thus saving the life of the recloser.

The non-faulted portion of the distribution feeder circuit between Source breaker and MidPoint recloser is picked back up.(it is never lost)

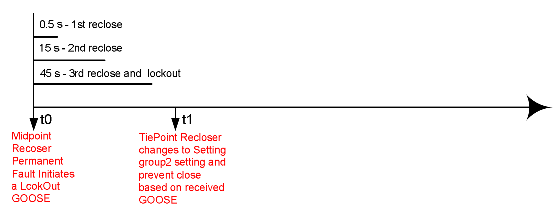

Figure 15: Sequence of Events

FAULT DETECTION ISOLATION AND RESTORATION(FDIR)USING DECENTRALIZED SCHEME

The distribution one line diagram in Figure 16 represents a simple distribution system that will be used for analysis of FDIR using decentralized concept.

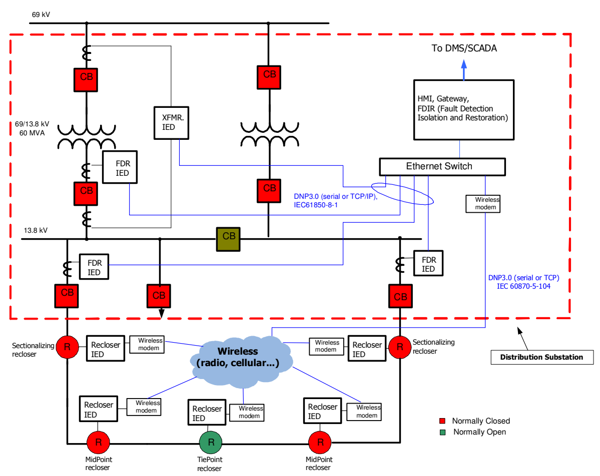

Figure 16: Example Distribution Circuit

This system consists of the following components:

- Source breakers
- Sectionalizing recloser
- Midpoint recloser
- Tie Point recloser
- Substation HMI, Gateway with FDIR

Substation HMI and Gateway with FDIR

In Figure 16., substation IEDs are connected to the Substation HMI and gateway via Ethernet switch. Substation HMI and gateway support a variety of different communication protocols such as DNP3.0, IEC 61850, IEC 60870-103 etc. Feeder devices i.e. reclosers from Figure 16. are connected to the Substation HMI and gateway via wireless communication. Recloser controllers support different SCADA protocols such as DNP3.0, IEC 60870-5-101/104 and IEC 61850 peer-to-peer communications. Both SCADA and IEC 61850 protocols are supported simultaneously. If necessary, Substation HMI and gateway can be connected to the centralized DMS or SCADA systems.

Network Model

For the sake of decentralized FDIR description, a simplified network model is considered, Figure 16, that includes three types of components: sources, switching devices (a.k.a. reclosers), and loads.

Sources are assumed to have limited capacity (ampere rating) but constant voltage. Switches are assumed to have limited loading capability (in amperes). Loads are assumed to be constant, aggregated lumps that connect to switches over zero-impedance feeder conductors.

Network Connectivity

The connectivity of the network model must be known in order to achieve successful fault isolation and service restoration. The switching devices, loads, and sources, as well as how these different components are connected, are required for the isolation and restoration method. By creating a Network Single Line Diagram – SLD of Figure 16 at the Substation HMI and gateway, network connectivity is automatically presented to the FDIR algorithm that resides in the same HMI and gateway. Thus, avoiding lengthy engineering for creating FDIR is avoided.

FDIR Algorithm Description

The algorithm starts with a back-feeding isolation switch search. This search is done on the pre-fault network's tree structure, with the tripped breaker as the root. The search traces down the tree, finds the most downstream switch that passed the fault current, and names it the forward-feed isolation switch. It then traces down further for the first layer of downstream switches, and names them the back-feed isolation switches.

Then, the algorithm applies the following recursive steps:

1. For each isolation switch, the algorithm traces downstream and finds the first T-node (multi-connection load node), which is the load node that connects with more than one downstream switch;
2. After finding the first T-node, the following judgment is made: if one or more single back-feed path exists to restore all loads in the particular isolated network by itself, then the back-feed path with the maximum available capacity will be selected; the restoration algorithm then returns to the Step 1 to process the next isolation switch. Otherwise, when no single back-feed path has sufficient capacity, the algorithm searches all the immediate downstream switches that connect to this T-node and stores them as an "other switch";
3. The algorithm continues to trace all the downstream closed switches between the first T-node and a downstream tie-switch or a

downstream second T- node and stores them in a vector S;

4. By opening each switch in vector S, the algorithm determines whether the network will be divided into two sub-networks, and which out-of-service loads can be restored respectively. If so, the switch that can best balance the loading levels of the back-feeding sources will be selected as the switch that should be opened in the final restoration strategy;
5. Otherwise, in the case that no such switch in vector S can be found, for each "other switch" stored, if the number of its downstream tie-switches is greater than 1 (meaning that another T-node exists downstream of this switch), this switch is treated as an isolation switch and the algorithm goes back to Step 1;
6. If no switch in vector S can be found to have more than one downstream tie-switch, the downstream tie-switch will be searched for instead, and the out-of-service loads will be restored from the alternative back-feed path that connects from the tie-switch up to an isolation switch or "other switch" by closing the tie-switch. If the algorithm stops before it can reach an isolation switch or "other switch" because the validation check didn't pass, the algorithm will go back to Step 1 or 2;
7. If more than one path can be restored up to its corresponding "other switch", the one with more remaining capacity will be selected, and the restoration will proceed upstream via the T- node to the corresponding "isolation switch";
8. If the restoration can reach an "isolation switch" and still have remaining capacity, it will start from the T-node and try to restore any loads downstream of the T-node that are still out-of-service.

Demonstration of FDIR algorithm will be shown for the fault between Sectionalizing and Midpoint reclosers.

Fault between Sectionalizing and Midpoint recloser

1. Permanent Fault occurs on the section between Sectionalizing and Midpoint reclosers
2. The Sectionalizing recloser will recognize the fault and go through its reclosing shots to lockout (for illustration purposes we will assume 3 operations to lockout for all devices).
3. Lockout information from Sectionalizing recloser will be send to Substation HMI and Gateway using SCADA protocols: DNP3.0, IEC 60870-5-101/104
4. Upon receiving the Lockout information, FDIR algorithm will complete fault isolation by sending the Open command to MidPoint recloser
5. Opened MidPoint recloser will be treated as the "isolating switch" and FDIR will search for the most optimum part to restore the power to the unserved loads between MidPoint and TiePoint reclosers. In the simple example shown in Figure 16, there is only one path to restore service, i.e. close TiePoint
6. FDIR will send Close command to TiePoint recloser. Thus service is restored between MdiPoint and TiePoint reclosers.

A restoration switching analysis method produces a switching sequence that when executed, will reach a valid post-restoration network that satisfies the following requirements: 1) it is radial; 2) there is no current violation at any network component. Other optimization requirements are also considered in the algorithm.

The FDIR scheme at Substation HMI and gateway presents a deterministic algorithm that identifies a restoration strategy to restore the out-of-service load due to fault isolation while ensuring that the post-restoration network has a valid configuration. The algorithm is based on the concepts of network tracing and it supports both single-path and multi-path restoration. In case the network components are too stressed and even the multi-path restoration cannot restore all the out-of-service loads, the algorithm tries to shed minimal load while restoring as many other loads as possible.

FDIR ALGORITHMS COMPARISON

Each FDIR algorithm has been compared considering different criteria, Table 1.

	External VTs @ Sectionalzing, Midpoint	Remote (Wireless, wired) communication	Scalability	Current violation check for reclosers	Operational Flexibility
FDIR - Loop Scheme	YES	NO	LOW	NO	LOW
FDIR – IEC 61850 peer-to-peer SCEME	NO	YES	MEDIUM	NO	MEDIUM
FDIR – Substation based Scheme	NO	YES	HIGH	YES	HIGH

Note: All reclosers require external VT for control power.

Table 1: Comparison of different FDIR solutions

Although each FDIR algorithm will contribute to the improved feeder reliability, selection and implementation of different FDIR solutions depends on many factors, just to mention a couple of them: Smart Grid strategy utility is considering, communication infrastructure, recloser infrastructure, cost etc.

CONCLUSION

Reclosers are the primary device that utilities have available to improve reliability. This paper demonstrates three methods of Fault Detection Isolation and restoration (FDIR). These methods have applications based on conditions needed for each distribution loop.

- Loop Control (voltage and time) has the advantages of being simple, doesn't require communications. It is limited in its application since system loading is not reviewed. It will also close an unfaulted source into a faulted source under certain conditions and stressing the system.
- Peer to Peer Scheme offers the advantages and restoration using loop control but since communications are utilized, has the advantage of not closing into a permanent fault from another source.
- Decentralized Scheme is the most flexible scheme and can be deployed to a greater number of devices. It also has an advantage of checking for current so will allow restoration based on loading at the nodes.

As Smart Grid solutions are implemented evaluations of which scheme is right at specific locations is a decision that must be made. This decision should be looking at what the grid will look like in 5-10 years.

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[1] ABB, 2004, *PCD Power Control Device Instruction Book*

[2] Fahrudin Mekic, Zhenyuan Wang, Vaibhav Donde, Fang Yang, James Stoupis, 2009, "Distributed Automation for Back-Feed Network Power Restoration", 20th International Conference on Electricity Distribution *CIRED*