# Intelligent Circuit Sensor enabled Fault Detection, Isolation and Restoration for Transmission Lines with T-connection Taps

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***Abstract*—Faults on transmission lines with T-connection taps are difficult to isolate and clear. This is mainly due to the lack of data related to the exact location of the faults at the nearest taps but limited data provided by the protection devices on the substation breakers. The resulting outcome is a manual scheme performed by the operator to perform multiple trial-and-error switching actions along the line in order to isolate the fault and restore the maximum number of customers as fast as possible before fully clearing the faulted section. This paper introduces an innovative and economic solution, called FDIR-T (Fault Detection, Isolation, & Restoration for Transmission line with T-connection Taps). The solution is based on the Intelligent Circuit Sensors (ICS) at individual taps to collect dynamic voltage and current, by which it can effectively detect and isolate the faulted section and then restore service within the normal reclosing cycles of the substation breakers without relying on any communications backbone network.**

***Keywords—Fault Detection, Fault Isolation, Fault Restoration Taps,***

## I. INTRODUCTION

Faults on transmission lines with T-connection taps are difficult to detect or locate and restore quickly. This is because commonly used distance or differential relays do not work well in locating faults on lines with T-connection taps. Such taps generally have 3-way switches that are commonly disconnection switches or load switches, having no capability to clear faults or close to faults. Therefore, when a fault occurs in a line section between two taps or in a tapped off lateral, it is the relay protection schemes at the two ending substations that trip the entire line, resulting in the entire line, along with all loads at the tapped off laterals, being out of service.

It has been a common practice in power utilities to locate a faulted section by a trail-and-error approach, i.e., using a binary searching method to recursively open a switch at the middle of the remaining part of the line and try to energize the two parts from both sides to see which part still sees the fault. Such a searching scheme may take tens or potentially hundreds of switch operations to find out the faulted section. Moreover, communication to these tap points is not common in power utilities, which means that utilities may have to dispatch repair crews to several tap locations to make manual switch operations to determine and isolate the faulted section. This may take hours or even days to restore service to the de-energized loads, without including the repairing work.

There are several existing automation schemes and solutions that tried to speed up the isolation and restoration process. Two of the most common solutions are protection relay scheme and the centralized FDIR approach. While these two existing approaches are good at addressing the issues, they subject to some stringent constraints and limitations. On the other hand, the proposed FDIR-T solution circumvents those constraints and limitations while achieving the desired outcome.

## II. EXISTING AUTOMATION SOLUTIONS

### *A. Distance Protection Relay Scheme*

Distance protection relays allow for custom automation logic to be triggered when it detects a permanent fault. Additionally, it contains the topology of the switches along the transmission line and has the ability to send control signals to them via a communications backbone. As part of the fault detection feature, the relay can provide the distance to fault location as well.

For a line without any T-connection taps, the automation logic simply utilizes the fault distance and the distances to the switches to determine which two switches bounds the fault and opens them between the breakers reclose cycles to perform fault isolation and restoration.

For a line with T-connection taps, the automation logic becomes much more complicated. The logic assigns protection zones to each switch in order to determine which switches to open to isolate the fault. Because of the presence of T-connection taps, the line impedance maps to multiple paths (i.e. a point down a tap and a point along the line are equidistant), the detected fault distance can denote multiple possible fault locations. Moreover, each of the T-connection taps has varying loads, which can introduce significant error in fault distance estimation or incorrect fault zone identification, especially for high impedance faults.

Utilizing the protection zones, the automation logic will attempt to isolate the fault by picking the switches that bounds one of the paths after the second breaker trip. If the breaker trips a third time, then the logic opens the switches that bounds all of the possible fault paths. Additionally, if the control signals fail, the logic will also open the switches bounding all of the fault paths. This essentially creates unreliable restoration process.

### *B. Centralized FDIR*

The centralized solution is a more enhanced approach compared to the distance protection relay scheme. It relies on the communications network to obtain data and information from the relevant field devices (Breakers, switches, fault indicators, etc.) and overlays them with the full electrical network topology to performs optimizations best suited for the given situation.

In the case of a permanent fault, the system receives a trip flag and the fault distance from the breaker relay. It will then trace the network topology to find the possible fault locations and the bounding switches for each location. For each pair of bounding switches, it will add to a switching plan that opens both switches and closes the tripped breaker/s to perform restoration. After the breaker/s locks out after the reclose cycles, the system will execute the actions in the switching plan one-by-one. When the breaker/s close is performed and no further trips happen, then the isolation and restoration is complete and all subsequent items in the switching plan is nullified as those actions are no longer necessary. This method of isolation and restoration can be seen as automated trial-and-error since the system tries all the possible fault location scenarios until one succeeds.

A more advanced method is possible if there are fault direction indicators installed on the line with the switches. As the name implies, fault direction indicators provide the direction of the fault when it detects a fault. With this extra piece of data, the logic no longer needs to perform the trial-and-error checks. When the system sees that the fault direction of 2 adjacent indicators are pointed towards each other, it creates a switching plan that opens just the switches associated with the 2 indicators and closes the tripped breakers. Effectively, this method will isolate the fault and restore the line on the first try.

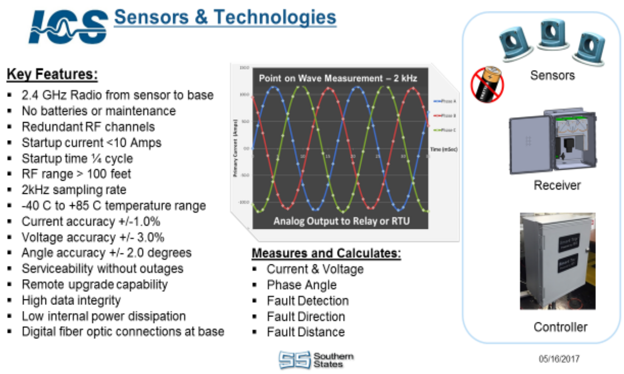
Although the centralized FDIR seems to be the better approach in that it always isolates the smallest segment, but it does have pertinent limitations and drawbacks. First, it is much slower since it can only perform the actions after the reclosing cycles of the breakers, which can be upwards of tens of minutes. Secondly, as with any system that is built on top of another system, the reliability of the top system is only as good as the reliability of the underlying system. In this case, the Achilles heel of the centralized system is its reliance on the communications network. If communications to the field devices are spotty or none-existent, which it often is in rural areas, then the entire solution is rendered useless since the system isn't receiving the trip flags, the fault distances, and the fault directions (or it is receiving them after a long delay which makes the data potentially invalid).

## III. FDIR-T Solution

Compared to either of the existing FDIR solutions, the FDIR-T solution achieves the benefits of both solutions without any of the drawbacks.

The proposed solution in this paper is based on a set of wireless Intelligent Circuit Sensors (ICS) and a Smart Tap Unit (STU) installed at the taps. Usually, a set of 3 sensors is needed for each side of the tap and none is needed down the tap lateral (Fig 1 and Fig 2). Each sensor is capable of measuring the phase current and voltage of the line.

An ICS sensor can be installed at a tap switch terminal connecting to the line. It is powered through self-power harvesting fro line current, with which it takes digital samples of line current and voltage in 2KHz. The sampled current and voltage data are transmitted by 2.4 GHz radio to a STU at the ground which synthesizes and processes the data from the individual sensors to perform fault detection and isolation. The following picture shows the key technical features of the ICS and STU:



When a fault occurs, the STU determines  the fault direction and distance based on the measured currents and voltages from the ICS sensors. Fig. 1 and Fig.2 depict Fig. 2. Depict an actual installation of ICSs and STU on a transmission line tap junction.

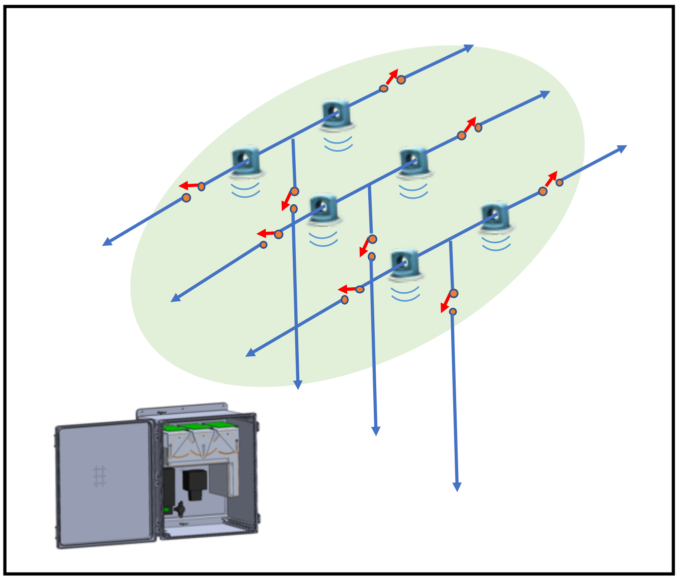


Fig. 1.   Conceptual installation of ICS' and STU on a transmission line tap junction

Fig. 2.   Actual installation of ICS' and STU on a transmission line tap junction

Similar to the protection relay scheme, protection fault zones are configured for each STU on each side of the line.  The zones are defined as follows:

1. Zone 1 – The fault distance is less than a user defined base percentage (e.g., 80%) of the distance to the adjacent tap. The fault is definitely within the coverage of this STU.
2. Zone 2 – The fault distance is between the base percentage and extended percentage (e.g., 80% and 120%) of the distance to the adjacent tap. The fault is maybe within the line segment to the adjacent tap.
3. Zone Null – The fault distance is greater than the extended percentage (e.g., 120%) of the distance to the adjacent tap. The fault is definitely not within the line segment to the adjacent tap.
4. Zone 4 – The fault directions from both sets of sensors are pointing towards each other, which is the down direction. Fault is in the tap lateral, within the coverage of this STU.

With each STU's fault zone configured, the following decision logic is utilized by each STU independently when the breakers at the two ending substations are tripped due to the presence of a fault.

1. Current reading is 0 and a fault is detected. Proceed to the next step.
2. Is this the second trip? If yes then proceed to the next step else proceed to step 5.
3. From the calculated fault distance and direction, which zone is activated? If Zone 1 then open the switch on the side of the switch indicated by the fault direction. If Zone 4 then open the switch down the tap. If Zone 2 or Zone 3,proceed the next step.
4. Wait for breaker/s to perform the 2nd reclose.
5. Does the breaker/s trip again (3rd time)? If yes then proceed to next step else do nothing.
6. From the calculated fault distance and direction, which zone is activated? If Zone 1 or Zone 2 then open the switch on the side of the switch indicated by the fault direction. If Zone 3 then do nothing. Proceed to next step
7. Wait for breaker/s to perform the final reclose.

As the logic shows, each STU contains its own set of configurations and operates independently. The system as a whole doesn't rely on a communication network to exchange data/information among the individual taps and the control center. We can walk through three scenarios on a simple line with four taps to demonstrate the switching operations each STU would generate in order to isolate the fault and restore the line as fast as possible.

### *A. Scenario A - Fault is equidistant between two taps*

As shown on Fig 3, the fault occurred approximately at 50% of the distance between Tap 2 and Tap 3. Utilizing the defined FDIR-T logic for each of the STUs on the 4 taps, the following is what would occur on each STU.

After the 2nd trip, both Tap 1 STU and Tap 4 STU detected the fault in Zone 2, therefore they have to wait for the 3rd breaker/s trip to take any action (Fig 4). On the other hand, Tap 2 STU detected the fault in the right-side Zone 1 and will open the right-side switch. Tap 3 STU detected the fault to be in the left-side Zone 1 and will open the left-side switch. The fault is now isolated (Fig 5). The breakers then automatically performs a 2rd reclose and all line sections are back online except for the isolated section between Tap 2 and Tap 3. Tap1 and Tap4 did not see the 3rd trip occurring and then rest its detection logic following the 2nd reclosing successfully.

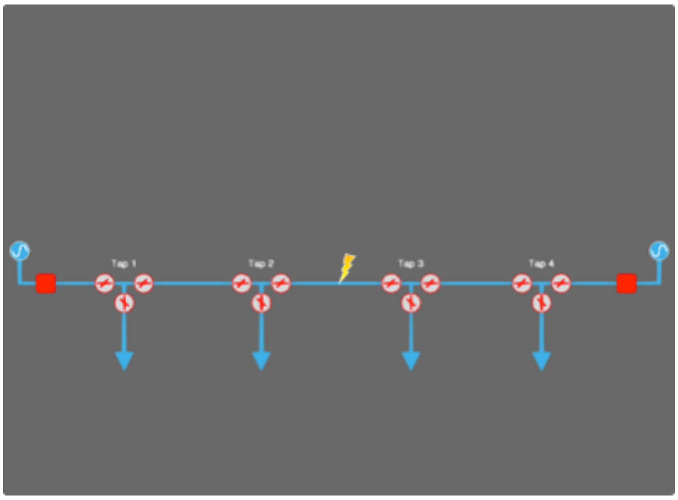


Fig. 3. Fault scenario A – fault is equidistant between Tap 2 and Tap 3

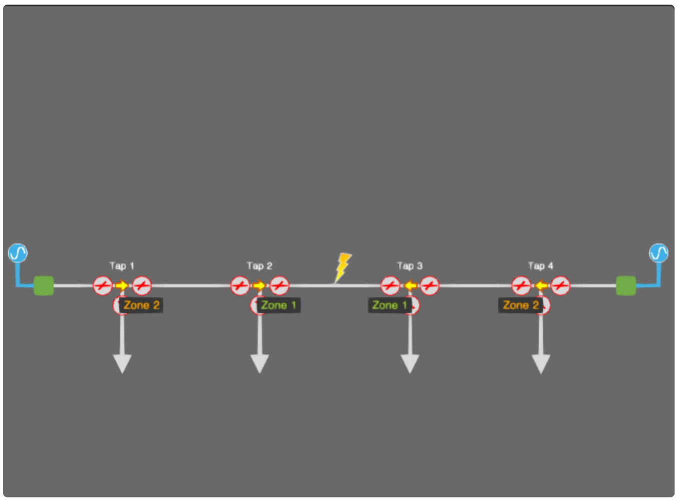



Fig. 4. Fault scenario A – computed fault zones of each tap

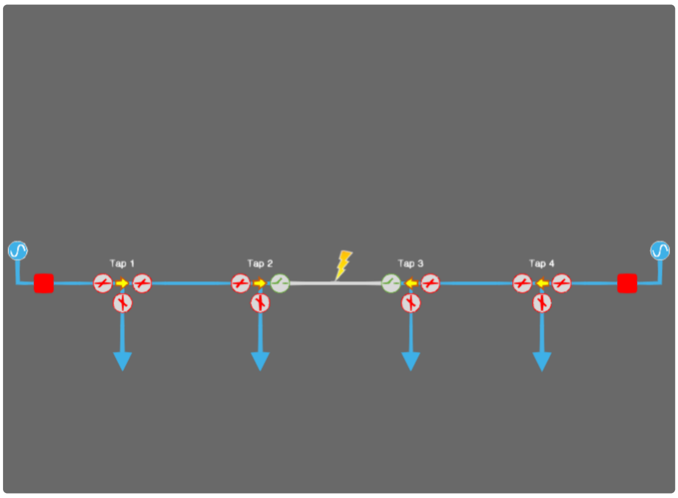



Fig. 5. Fault scenario A – fault is isolated by openning the Tap 2 right-side switch and Tap 3 left-side switch. Restoration is completed by closing the breakers.

*B. Scenario B - Fault is between two taps but closer to one tap*

As shown on Fig 6, the fault occurred approximately at 10% of the distance between Tap 2 and Tap 3. Utilizing the defined FDIR-T logic for each of the STUs on the 4 taps, the following is what would occur on each STU.

After the 2$^{nd}$ breaker/s trip, both Tap 1 STU and Tap 3 STU detected the fault in Zone 2, therefore they have to wait for the 3$^{rd}$ breaker/s trip to take any action (Fig 7). Tap 2 STU detected the fault in the right-side Zone 1 and will open the right-side switch, which isolates the fault from the left side source. Tap 4 STU detected the fault to be in Zone Null, so it will do nothing. The breakers on either side then automatically performs a 2$^{nd}$ reclose. The left-side breaker will not trip as the fault is isolated from that side, however, the right-side breaker will trip again. This right-side 3$^{rd}$ trip will trigger the Tap 3 STU to open the left-side switch because it detected the fault in Zone 2. Now, the fault is fully isolated. The right-side breaker automatically performs a 3$^{rd}$ reclose and all line sections are back online except for the isolated section between Tap 2 and Tap 3 (Fig 8).

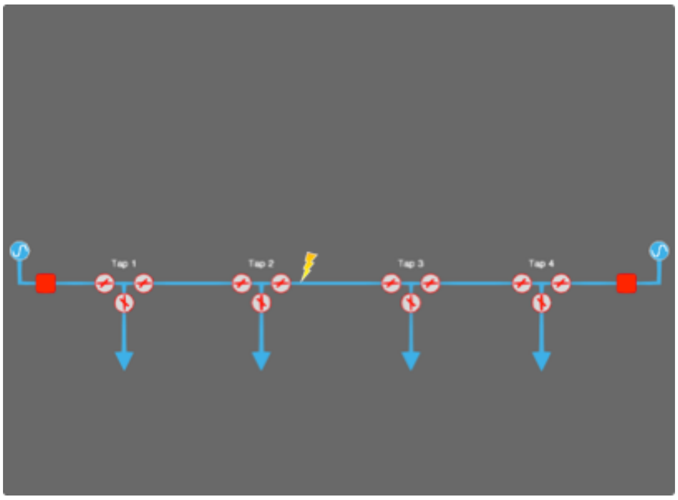



Fig. 6. Fault scenario B – fault is between Tap 2 and Tap 3 but is much closer to Tap 2

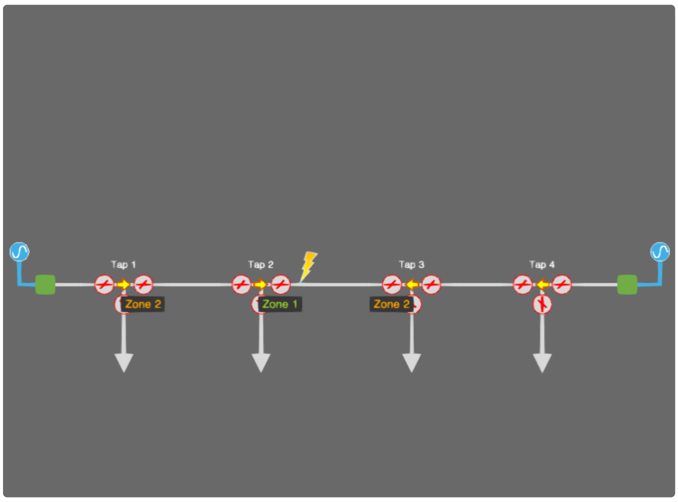



Fig. 7. Fault scenario B – computed fault zones of each tap

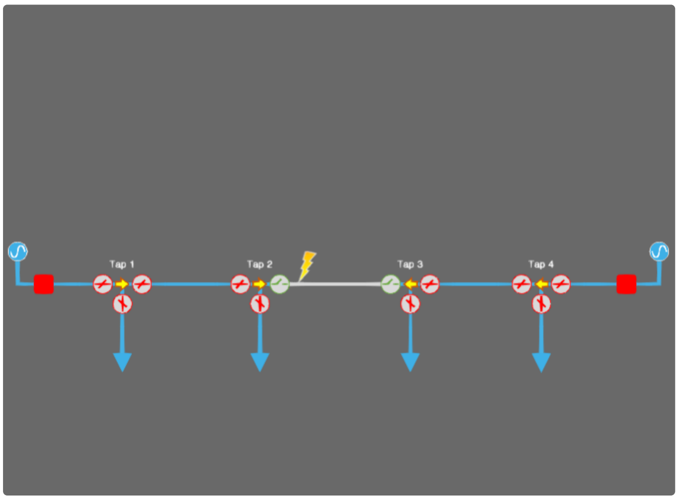



Fig. 8. Fault scenario B – fault is isolated by openning the Tap 2 right-side switch and Tap 3 left-side switch. Restoration is completed by closing the breakers.

*C. Scenario C - Fault is down a tap*

As shown on Fig 9, the fault occurred down the tap at Tap 2. Utilizing the defined FDIR-T logic for each of the STUs on the 4 taps, the following is what would occur on each STU.

After the 2nd breaker/s tripped, Tap 1 STU detected the fault in Zone 2, therefore it has to wait for the 3rd breaker/s trip to take any action (Fig 10). Tap 3 STU and Tap 4 STU detected the fault in their Zone Null, so they will do nothing. Tap 2 STU detected the fault in Zone 4 will open the down-tap switch, which completely isolates the fault from both sources. The breakers then automatically perform a 2rd reclose and all line sections are back online except for the isolated section down Tap 2 (Fig 11).


Fig. 9. Fault scenario C – fault is down Tap 2

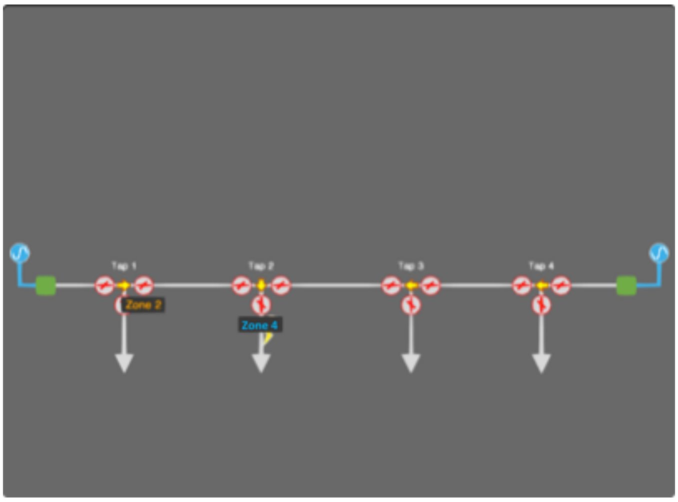



Fig. 10. Fault scenario C – computed fault zones of each tap

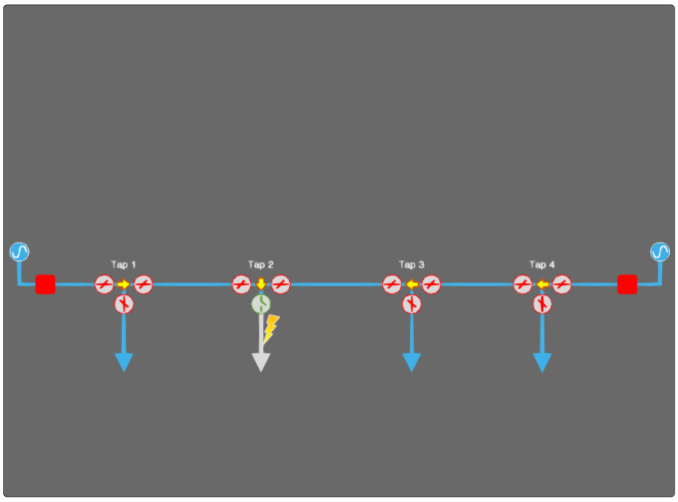



Fig. 11. Fault scenario B – fault is isolated by openning the Tap 2 down-tap switch. Restoration is completed by closing the breakers.

### D. *Benefits*

As indicated earlier, the FDIR-T solution has the following characteristics that make it a more attractive FDIR solution for transmission systems with t-connected taps.

1. It requires no communications; therefore, it isn't affected by the reliability of the communications backbone and is cheaper to install and setup.
2. It doesn't require full network topology modeling. Each tap operates independently by following the common rules, which makes it simple to configure implement.
3. It operates very quickly. The entire fault detection and isolation process is done within the breaker\s reclosing cycles and can isolate down to the smallest segment possible. Therefore it can achieve 10X-20X improvements in system reliability metrics (SAIDI, SAIFI, CAIDI, CAIFI) compared to the traditional methods.
4. It operates between the reclosing cycles of breakers, therefore, requiring minimal reconfiguration of existing reclosing schemes.
5. It does not make any operation to close a switch but open only; therefore, it can never close into a fault if any data error or device mal-operation.

## IV CONCLUSION

This paper presented a practical FDIR solution for T-transmission lines with T-connected taps. The solution is based on ICS sensors and a STU unit installed at each tap. A set of common operation rules is developed and implemented in each STU to detect and isolate faults within breaker reclosing cycles. No communication systems is needed in the entire process of fault detection, isolation and restoration and no changes are needed for the existing breaker reclosing logic. Three typical operation scenarios are presented to demonstrate the effectiveness of the FDIR solution for transmission lines with T-connected taps.

## V REFERENCES

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